Journal of Atmospheric and Solar-Terrestrial Physics 138-139 (2016) 169–178

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Radiative analysis of global mean temperature trends in the middle atmosphere: Effects of non-locality and secondary absorption bands

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ARTICLE INFO

Article history:
Received 19 August 2015
Received in revised form
13 January 2016
Accepted 13 January 2016
Available online 14 January 2016

Keywords:
Middle atmosphere
Modeling
Climate change
Radiative balance

ABSTRACT

In this paper, we provide a refined and extended assignment of past and future temperature changes relative to previous analyses and describe and evaluate the relevance of vertical coupling and non-linear and secondary radiative mechanisms for the interpretation of climatic temperature variations in the middle atmosphere. Because of their nature, the latter mechanisms are not adequately accounted for in most regression analyses of temperature trends as a function of local constituent variations. These mechanisms are examined using (1) globally averaged profiles from transient simulations with the Canadian Middle Atmosphere Model (CMAM) forced by changes in greenhouse gases and ozone depleting substances and (2) a one-dimensional radiative-equilibrium model forced using the diagnosed global mean changes in radiatively active constituents as derived from the CMAM model runs. The conditions during the periods 1975 to 1995 and 2010 to 2040 (during which the rates of change in ozone and CO_2 differ) provide a suitable contrast for the role of the non-linear and non-local mechanisms being evaluated in this paper to be clearly differentiated and evaluated. Vertical coupling of radiative transfer effects and the influence of secondary absorption bands are important enough to render the results of multiple linear regression analyses between the temperature response and constituent changes misleading. These effects are evaluated in detail using the 1D radiative-equilibrium model using profiles from the CMAM runs as inputs. In order to explain the differences in the CMAM temperature trends prior to and after 2000 these other radiative effects must be considered in addition to local changes in the radiatively active species. The middle atmosphere temperature cools in response to CO_2 and water vapor increases, but past and future trends are modulated by ozone changes.

1. Introduction

Middle atmosphere temperatures have been decreasing in recent decades (Beig et al., 2003; WMO, 2007; Randel et al., 2009; Austin et al., 2009; Seidel et al., 2011) and are expected to decrease further in the future (WMO, 2007; Jonsson et al., 2009). Randel et al. (2009) show statistically significant negative trends of near-global (60°S to 60°N) mean temperature over the period 1979–2005 throughout the stratosphere with a maximum trend that exceeds -1 K/decade in the upper stratosphere. As the thermal regime of the middle atmosphere is determined to a great extent by the balance between the incoming solar and outgoing infrared radiation, the observed cooling has generally been attributed to changes in the abundance of radiatively active gases (Shine et al., 2003; Seidel et al., 2011) through multiple linear regressions analyses (MLR) of the temperature fields relative to the constituent fields. As Seidel et al. (2011) point out in their conclusions, recent work while improving our understanding of temperature trends in the stratosphere has also “revealed considerable uncertainty in analysis of observations and in knowledge of the mechanisms that drive temperature changes”. Our paper is devoted to addressing the latter point and in addition extends consideration of these mechanisms into the mesosphere. In addition, since MLR analyses have been the sole approach to these analyses (by necessity for observational analyses), we evaluate the extent to which non-linear effects and vertical coupling of radiative effects (both of which cannot be determined using MLR analyses) contribute to the modelled trends.

The radiatively active gases that provide the major contribution to the energy budget of the middle atmosphere are O_3, CO_2, and H_2O. Absorption of solar energy by ozone is the main source of radiative heating, whereas radiative cooling is provided mainly by radiative transfer in the 15 μm CO_2 band with secondary contributions from the 9.6 μm O_3 and rotational H_2O bands. Non-

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http://dx.doi.org/10.1016/j.jastp.2016.01.010
1364-6826/

negligible solar heating in the mesosphere is also provided by absorption in the near-infrared (NIR) CO_2 bands (e.g., Fomichev 2009).

Changes in the concentration of radiatively active gases lead to changes in the energy balance which, in turn, affect the temperature distribution. Shine et al. (2003) analyzed the radiative contributions of different radiatively active gases to recent stratospheric temperature changes. This was accomplished by prescribing observed changes in CO_2, ozone, and water vapor into a suite of models. They found that upper stratospheric trends in temperature during 1980–2000 were due roughly in half to CO_2 increases and in half to ozone reductions. However, while observed ozone changes were primarily forced by changes in ozone depleting substances (ODSs) over this period, they were also partly affected by CO_2 induced cooling, so the exact separation between the CO_2 and ozone induced effects is not clear. Strictly in terms of external forcings, the contribution from changes in ODS to upper stratospheric temperature changes over 1975–1995 is roughly 30% greater than the contribution from CO_2 changes for the same period (Jonsson et al., 2009).

In the current paper we examine the radiative attribution of global mean past and future temperature trends in the middle atmosphere (between approximately 25 and 80 km) obtained from transient simulations with the Canadian Middle Atmosphere Model (CMAM) forced by changes in greenhouse gases (GHGs) and ODSs. In order to focus on the radiative effects underlying these forcings, the analysis is carried out on globally and annually averaged fields. This minimizes the effects of dynamical changes, since the middle atmosphere to first order is near radiative equilibrium up to the upper mesosphere (e.g. Fomichev and Shved, 1994) and dynamical changes will have minimal effects on globally averaged temperatures (Seidel et al., 2011). The two time periods used in this analysis (1975 to 1995 and 2010 to 2040) are chosen because of the differing rates of change of ozone and CO_2 during these periods which allow the roles of each to be suitablly contrasted. In order to attribute the impact of different radiatively active gases and absorption bands, changes in ozone, CO_2, H_2O and other globally averaged profiles of other GHGs extracted from the CMAM simulations are applied to a one-dimensional (1D) radiative-equilibrium model (REM). This analysis is complemented by an analysis of changes in the radiative energy budget resulting from these diagnosed changes in atmospheric composition.

The purpose of this work is three-fold. First, it provides a radiative attribution of simulated past and future temperature changes up to 80 km, and thereby updates and extends the work of Shine et al. (2003) and Seidel et al. (2011) who focused primarily on the recent changes in the stratosphere.

Second, some details on these attributions are provided. For example, to better understand the overall impact of changes in the various gases, we separate their contribution into their short-wave and long-wave effects. In addition, in consideration of the significantly non-linear effect of CO_2 changes on heating rates over multi-decadal time scales (see Jonsson et al., 2009), we investigate the additivity of the radiative effects of the simulated changes in ozone and the various GHGs considered. While the primary radiative effects of CO_2 and ozone are through infrared (IR) cooling and solar heating respectively, both molecules also have secondary absorption bands which provide second order effects. We calculate these secondary effects and discuss their relevance for past and future temperature changes.

Third, since the middle atmosphere can be optically thin in the major radiative heating and cooling bands, vertical coupling of radiative transfer effects between different altitude regions (termed non-local radiative effects in this paper) can play an important role. These effects cannot generally be captured by multiple linear regression (MLR) techniques which intrinsically assume locality and linearity. In order to highlight this fact we show that a correct attribution of temperature changes in the mesosphere must take into account ozone changes near the stratopause.

2. Model description and simulations

The Canadian Middle Atmosphere Model (CMAM) is an interactive coupled chemistry climate model incorporating comprehensive tropospheric physics, wave-driven dynamics, interactive middle atmosphere chemistry and a detailed representation of radiation throughout the atmosphere (de Grandpré et al., 2000; Fomichev et al., 2004; Scinocca et al., 2008). As such it has the capability to simulate the response of the middle atmosphere to perturbations in GHGs and ODSs, including dynamical, chemical and radiative feedbacks. A detailed description of the model components and its capabilities are provided in SPARC CCMVal (2010).

For the current study, the CMAM CCMVal REF-B2 simulations (for a detailed description see SPARC CCMVal, Eyring et al., 2008; Scinocca et al., 2009) are analyzed. These are transient simulations over 1960–2100 including GHG loading from IPCC scenario A1B (Houghton et al., 2001) and halogen loading from WMO scenario A1 (WMO, 2007). Fig. 1 shows the surface boundary values applied in these simulations for the period from 1960 to 2050. The mixing ratios of CO_2, CH_4 and N_2O all increase secularly throughout this period, whereas chlorofluorocarbons (CFCs) decrease after reaching a maximum in the mid-1990s. According to the A1B scenario CO_2 increases more rapidly after 2000 than before 2000. The CFCs' decline after the mid-1990s is markedly slower than the increase during the buildup period.

The CCMVal-2 runs used here were coupled to an ocean model so that sea surface temperatures and sea ice were calculated by the model itself. A solar cycle was not included in the CMAM runs (medium conditions of solar activity were used) and an annually repeating cycle of profiles of stratospheric aerosol surface area density was created from the CCMVal-2 specified aerosol fields. The stratospheric aerosols were specified using clean background conditions (i.e. excluding periods when the effects of volcanos aerosols were present) and an average around the year 2000 was used.

The results analyzed in this paper are based on an ensemble of three REF-B2 simulations covering the period 1960–2100. The CMAM performance for these simulations is assessed in SPARC CCMVal (2010). The global mean climatology for the REF-B2 simulations and the REF-B1 simulations (the latter including additional forcings such as volcanic aerosols and variable solar cycle) over 1980–1999 for temperature, ozone and water vapor is realistic. Although the CMAM climatology shows a warm bias of up to 9 K in the upper stratosphere and a low bias of water vapor of 1–2 ppmv throughout the stratosphere (see Fig. 3.1 in SPARC CCMVal, 2010), the global mean temperature trends simulated by the CMAM show very close agreement with observations (see Fig. 3.2 in SPARC CCMVal, 2010), which confirms that the model's sensitivity to perturbations in radiatively active gases is realistic. Analyses with the 1D model indicate that the model biases result in variations of $\sim 5\%$ in the model trends.

Two time periods are selected for analysis. The first period, from 1975 to 1995, is characterized by rapid ozone depletion. The second period, from 2010 to 2040, is characterized by ozone recovery. These are the same periods as analysed by Shepherd and Jonsson (2008) and Jonsson et al. (2009). For convenience the two periods are generally referred to in the paper as the "past" and "future" periods, respectively. Both periods are characterized by nearly linear changes in the forcings (Fig. 1). The CO_2 trend during