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Role of external factors in the evolution of the ozone layer and stratospheric circulation in 21st century

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Abstract

The chemistry-climate model (CCM) SOCOL has been used to evaluate the contribution of the main anthropogenic factors to the simulated changes of ozone and stratospheric dynamics during the 21st century. As the main anthropogenic factors we consider atmospheric concentration of the greenhouse gases (GHG), ozone depleting substances (ODS) and sea surface temperature and sea ice (SST/SI) distribution. The last one is considered here as an independent factor because the majority of the CCMs prescribe its evolution. We have performed three sets of "time-slice" numerical experiments with CCM SOCOL for the years 2000, 2050, and 2100 taking into account all factors separately and all together. It was established that the total column ozone increase during the first half of the 21st century is caused by the ODS, especially in the middle and high latitudes of both hemispheres. In the tropics and the extra tropical region of the Northern Hemisphere (NH) the SST/SI forcing plays very important role in the evolution of ozone atmospheric content during the second half of the 21st century. The GHG affect the temperature and ozone mainly in the upper stratosphere and in the lower stratosphere of the high latitudes of the Southern Hemisphere (SH). In the lower tropical stratosphere of the NH the long-term changes of the temperature, zonal wind velocity and the meridional circulation intensity are controlled mainly by the SST/SI. The strong contribution of the SST/SI to the ozone and circulation changes in the future implies that some differences between the simulated results could be caused by the applied SST/SI rather than by the CCM's deficiencies. We suggest taking this issue into account for the planning of the future model evaluation campaigns.

1 Introduction

During the last decade substantial efforts of the atmospheric research community were focused on the modeling of the global stratospheric ozone and climate changes throughout the 21st century caused by the anthropogenic factors (SPARC CCMVal, 2010, Chapter 9; WMO, 2011, Chapter 4) using chemistry-climate models (CCM). A typical CCM consists of a general circulation model and a three-dimensional global chemistry-transport model. These model components interact by exchanging the global fields of gas species and dynamics parameters. Thus, according to their formulations CCMs inherently take into account main feedbacks between climate and chemical atmospheric quantities existing in the real atmosphere (Morgenstern et al., 2010). To enhance the confidence of the projection outputs the most of state-of-the-art CCMs have been evaluated and improved using the process-oriented evaluation procedures in the framework of the comprehensive SPARC Chemistry-Climate Model validation activities – CCMVal-1 and CCMVal-2 (Eyring et al., 2006; SPARC CCMVal, 2010).

The main anthropogenic factors affecting the long-term variability of stratospheric ozone, temperature and circulation of the atmosphere can be divided into three following groups: (1) increasing of the greenhouse gas concentrations (GHG) as the result of the world economic development (IPCC, 2001, 2007); (2) the reduction of the atmospheric content of ozone depleting substances (ODS) resulting from the Montreal Protocol limitations (WMO, 2007) and (3) the changes of sea surface temperature and the sea ice parameters (SST/SI). Last one is the direct consequence of the GHG influence, but the majority of the CCMs involved in the assessment of the ozone layer evolution exploit SST/SI distribution prescribed from atmosphere-ocean general circulation models (Morgenstern et al., 2010). Therefore the SST/SI can be considered as an external factor together with the other two main factors (GHG and ODS).

The atmospheric composition and climate changes in the current century simulated with different CCMs taking into account GHG, SST/IS and ODS have been presented recently in a number of publications (e.g. Austin et al., 2010; Gettelman et al., 2010; Austin et al., 2011; Zubov et al., 2011). Main conclusions and findings of these studies have been summarized in two assessments (SPARC CCMVal, 2010; WMO, 2011). According to these publications the process of the ozone layer recovery caused by the decreasing halogen loading in the atmosphere will proceed with different rates in the various atmospheric regions and depends also on the temperature and circulation changes. It is concluded that in the year 2100 the simulated total column ozone will reach nearly its 1960 yr ("unperturbed") values in the southern polar latitudes and Antarctic ozone "hole" will almost disappear. In the middle and high latitudes of the Northern Hemisphere (NH) and the middle latitudes of the Southern Hemisphere (SH) the total column ozone in the year 2100 will exceed their "unperturbed" state, while tropical ozone layer will not recover even in 2100. It should be noted that the above mentioned differences in the future ozone behavior occur mainly in the lower stratosphere/upper troposphere and are strongly model dependent, while in the upper stratosphere all CCMs simulate almost identical ozone recovery during the next 100 yr.

It is of substantial interest to evaluate the contributions of the main external factors to the total tendency of ozone layer and dynamics throughout 21st century and to establish what role is played by the basic physical and chemical processes such as heating/cooling, photochemical lost/production and transport. To address this problem Oman et al. (2010a) applied multi-linear regression analysis (MLR) technique to estimate the contributions of the chemical processes and the temperature tendency to the simulated ozone changes in the upper stratosphere (SPARC CCMVal, 2010; WMO, 2010). However, this method cannot be applied for the evaluation of the main external anthropogenic factors contribution. There are other limitations of the MLR approach applicability to attribute the ozone changes in the middle and lower stratosphere discussed in detail by Oman et al. (2010a, 2010b) which inspires to exploit different approaches because these regions play crucial role in the understanding of the long-term total column ozone tendency in the CCMs model projections.

From our point of view the evaluation of the external factors affecting the long-term atmospheric changes has some priority, because the external forcings constitute the ultimate cause of the all atmospheric long-term changes in the future. They operate in the atmosphere via the acceleration or suppression of the main physical and chemical processes, which play only secondary role. Thus the attribution of the atmospheric changes to the external anthropogenic factors is the more important task in comparison with any other types of the attributions. Understanding of the main driving factors is very important for further model improvements. It was mentioned in several publications (e.g., Eyring et al., 2010; Charlton-Perez et al., 2010; Strahan et al., 2011) that there is a substantial scatter among CCMs in the projection of the future ozone layer, however the reasons for this uncertainty have not been clearly identified. There are no strong evidences whether this is caused by some model deficiencies in the representation of the chemical, dynamical and transport processes or by the some differences in the prescribed external forcing. It seems that the prescribed evolution of GHG and ODS cannot be the cause of the intermodel scatter in the ozone projections because all CCMs participated in CCMVal-2 activity applied almost identical scenarios (Morgenstern et al., 2010). However, it is not the case for the future SST/SI distributions taken from different models participated in IPCC AR4 assessment (IPCC, 2007) which are characterized by substantially different magnitude and pattern of the future climate change. For the CCM community this is crucial problem, because if the prescribed SST/SI is responsible for large scatter among model predictions any model improvements would not help to reduce the scatter.

In this paper we estimate the contribution of the main anthropogenic external factors to the 21st century evolutions of the ozone layer, temperature and circulation of the stratosphere exploiting CCM SOCOL (version 2.0), which participated in the CCMval-1/2 model intercomparison campaigns (Eyring et al., 2007; SPARC CCMVal, 2010). To avoid the shortcoming of the MLR attribution approach in the middle and lower stratosphere the method of “idealized” experiments is used (e.g. Kodama et al., 2007). According to this method we have performed one reference experiment changing all considered factors together and three additional ensemble simulations taking into account long-term evolution of either SST/SI or GHG or ODS separately. For the later experiments two external factors are fixed on the present day level. Comparison of the results of the numerical experiments allows us to evaluate the contribution of each external factor to the evolution of the ozone layer, temperature and circulation over 21st century. Ensemble approach provides a possibility to estimate the statistical significance of the contributions against the inter-annual natural variability of the model atmosphere.

In the Sect. 2 the model description and design of the numerical experiments are presented. The Sect. 3 contains the analysis of the simulation results. The summary and conclusions of the paper are given in the Sect. 4.

2 Model design and description of numerical experiments

2.1 Model description

The simulations discussed below have been performed using the global three-dimensional CCM SOCOL version 2.0. The model has been developed at the PMOD/WRC (Davos, Switzerland) in collaboration with ETH Zurich (Switzerland) and Voeikov Main Geophysical Observatory (St. Petersburg, Russia; Egorova et al., 2005). The CCM SOCOL consists of the middle atmosphere version of the European Center/Hamburg Model (MA-ECHAM4) (Manzini et al., 1997) and the three-dimensional chemistry-transport model (CTM) for the Evaluation of Ozone Trends (MEZON) (Egorova et al., 2003). Vertical model structure includes 39 levels of a hybrid sigma/pressure coordinate system and extends from the surface up to 0.01 hPa (~ 80 km). The horizontal model resolution (3.75° × 3.75°) is defined by the horizontal spectral truncation of the MA-ECHAM4 (T30).

The time-space distributions of the 45 trace gases from the major atmospheric groups are calculated by the CTM MEZON taking into account 118 gas phase reactions, 33 photolytic reactions, and 16 heterogeneous reactions. The space-resolved transport of the model species is computed using the hybrid advection scheme (Zubov et al., 1999).

Main modules of the CCM SOCOL (MEZON and MA-ECHAM4) are exchanging meteorological and chemical species fields every 2 h. The mixing ratios of ozone, methane, nitrous oxide, chlorofluorocarbons, and water vapor are passed from MEZON to MA-ECHAM4, and the global three-dimensional distributions of temperature, water vapor concentration, and zonal, meridional, and vertical components of wind velocity are transferred from MA-ECHAM4 to MEZON. The chemical transformations of the water vapor are treated in the MEZON, while the water vapor tendencies related to physical processes are calculated in MA-ECHAM4. Thus, the CCM SOCOL accounts inherently the interactive properties and basic feedbacks between dynamical, transport, photochemical, and radiative processes. The original description of SOCOL is presented more thoroughly in Egorova et al. (2005). The CCM SOCOL was applied to investigate the influence of the shortwave solar irradiance variability during the 11-yr solar cycle on the composition and dynamics of the middle and lower atmosphere (Egorova et al., 2004) and to analyze the additional heating of the polar lower stratosphere from galactic cosmic rays and its plausible impact on atmospheric ozone, temperature, and circulation (Zubov et al., 2005, 2006). To verify and increase the confidence of the model results the CCM SOCOL participated in the International Chemistry–Climate Model Validation Activity (CCMval-1,2) of the Stratospheric Processes and Their Role in Climate (SPARC) program. CCMval-1, 2 are the most extensive CCMs intercomparison and validation campaigns in the recent decade (Eyring et al., 2007; SPARC CCMVal, 2010). The comparisons and verifications performed in the framework of CCMval-1 provided an opportunity to put together the new improved version of CCM SOCOL version 2.0 (Schraner et al., 2008). The results published in the final CCMval-2 report (SPARC CCMVal, 2010) allow us to conclude that CCM SOCOL 2.0 is comparable to the most of other CCMs.

2.2 Description of numerical experiments

To attribute the ozone and atmospheric dynamics changes over the 21st century we have performed three sets of time-slice numerical experiments with the CCM SOCOL 2.0, for the 2000, 2050, and 2100 conditions, respectively. As driving factors we consider long-term evolution of the ODS, GHG and SST/SI quantities (Table 1).

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The mixing ratio of ODSs in the lower troposphere evolves according to the World Meteorological Organization (WMO) A1 scenario (WMO, 2007). The atmospheric mixing ratio changes of the main GHGs (CO_2 CH_4, and N_2O) are taken from the "most plausible" SRES scenario A1B IPCC (IPCC, 2001; IPCC, 2007). The SST/SI fields for the 21st century are adopted from the relevant simulations of the ECHAM5/MPIOM model (Jungclaus et al., 2006) using the SRES A1B IPCC scenario for the GHG long-term variations. Therefore, the SST/SI and GHG fields utilized in our numerical runs with the CCM SOCOL 2.0 are consistent.

Each experiment set includes four 20-yr model runs (excluding the set for the 2000 yr conditions). The first run (FULL) takes into account the impact of all external factors (i.e., evolutions of the GHG, ODS and SST/SI). The second run (GHG) simulates the influence of the GHG long-term changes only (ODS and SST/SI represent the year 2000 conditions). The third run (ODS) represents the influence of the ODS long-term evolution (GHG and SST/SI represent the year 2000 conditions). Finally, the fourth run (SST/SI) takes into account only the SST/SI long-term changes keeping GHG and ODS at the year 2000 level. The experiment set of the 2000 yr conditions includes only one run (FULL) and all considered forcings are prescribed for the year 2000. The Table 1 presents the summary of the undertaken model experiments.

Each 20-yr time-slice model run consists of 10-yr spin-up calculations, which is necessary for the adaptation of the chemical composition and dynamics of the model atmosphere to the specific boundary conditions. Then, the last two years of the run are "recalculated" five times with the slightly (within ± 0.01 %) changed CO_2 mixing ratio to generate five ensemble members. The ensemble approach allows us to estimate the natural variability of the model atmosphere and to define the statistical significance of the atmospheric responses to the considered external forcings against the background model variability. The level of the significance is estimated by Student's test (von Storch and Zwiers, 1999). A comparison of the model run results is used to estimate the contribution of external factors to the evolution of the ozone layer, temperature and circulation of the stratosphere throughout 21st century. For example the difference between the outputs of “GHG-2050” and “FULL-2000” runs (Table 1) elucidates the role of the GHG factor in the atmospheric changes over the first half of the current century (from 2000 to 2050).

On the other hand, some interaction between the factors can exist. It means that the influence of one factor on the atmospheric changes depends on whether other factors operate together with it or not. Particularly, this dependency leads to nonequivalence between the total effect (FULL) of all factors and the sum of the separate effects (GHG + ODS + SST/SI) of the factors taken separately for the same time period. The residual term (RES) can be then introduced as:

$$\text{RES} = \text{FULL} - (\text{GHG} + \text{ODS} + \text{SST/SI}) \qquad (1)$$

The RES value can be calculated for all model cells and for each time step of the runs according to this equation. The magnitude and sign of the RES term allow us to find the areas of the atmosphere where the interplay between factors enhances ($|\text{RES}| > 0$) or compensates ($|\text{RES}| < 0$) the combined effect.

In the discussions of the model results presented below we analyze not only the FULL, GHG, ODS and SST/SI impacts on the atmosphere during the 21st century, but also the relevant values of the RES term. We estimate the statistical significance of the RES term and find the atmospheric regions in which this term cannot be masked by the interannual variability of the model atmosphere.

3 Results

The main external factors (GHG, ODS, SST/SI) affect the composition and dynamics of the atmosphere by a multitude of the physical and chemical mechanisms: an additional heating and cooling of the atmospheric air and surface, changes of the gas-phase and heterogeneous chemical reaction rates, changes of the atmospheric circulation followed by alteration of the gas transport and others. However, here we do not present the detailed analysis of all mechanisms paying main attention to the relative contributions of the external factors to the atmospheric parameter evolution over 21st century.

Figure 1 presents the zonal-mean annually averaged ensemble-mean changes of temperature from 2000 to 2100 due to the influence of the ODS, GHG, SST/SI factors and their combination (FULL). Figure 1 shows that GHG increase constitutes the main contribution to the cooling in the upper stratosphere. In this case the cooling over Antarctica is much more pronounced as result of the radiative exchange of the additional GHG molecules with cool ice covered surface of the Antarctic. Below 20 hPa the SST/SI factor plays dominant role in the long-term temperature changes. Convective processes redistribute ocean warming vertically leading to a pronounced (up to 8 K) temperature rise in the upper tropical troposphere followed by the tropic/extra-tropic temperature gradient increase, acceleration of the extra-tropical jets (see also below), intensification of the Brewer-Dobson circulation (BDC). More intensive upward motions in the lower BDC branch produces pronounced cooling due to adiabatic extension of the rising air (Fig. 1c). The SST/SI variations are also responsible for the additional heating in the extra tropical regions of NH. The drop of ODS concentration results in the ozone increase followed by a small heating which partially compensates GHG induced cooling in the stratosphere. The lower stratosphere over the South Pole is an exception because the ODS induced heating exceeds the GHG cooling values there.

The zonal and annual-mean changes of the zonal wind velocity from 2000 to 2100 are presented in Fig. 2. In the upper stratosphere the ODS and GHG produce some acceleration of the westerlies in the middle latitudes of the both hemispheres. The SST/SI factor has quite different effects on the zonal wind in the SH and NH which consist of the eastward wind acceleration in the middle latitudes of the SH and deceleration in the NH. In the lower stratosphere the SST/SI forcing is mostly responsible for the zonal wind changes. The comparison of the Fig. 2c, d shows that the SST/SI weaken the westerly wind over the middle and high latitudes of the SH and NH and substantially strengthens the both subtropical jets extending their upper flanks in vertical direction, and. As it was discussed in the literature (Deckert and Dameris, 2008; Calvo and Garcia, 2009;

McLandress and Shepherd, 2009; Shepherd and McLandress, 2011) such changes of subtropical jets are accompanied by intensification of the BDC. Additional warming of the polar lower stratosphere caused by the ODS forcing (see Fig. 1a) also contributes to the statistically significant deceleration of the Polar Night Jet over Antarctica (see Fig. 2a).

Figure 3 displays zonal and annual mean ozone mixing ratio changes from 2000 to 2100 due to impacts of the ODS, GHG, SST/SI and FULL factors. Decline of the halogen loading (ODS factor) plays a major role in the ozone increase in the entire upper stratosphere and in the lower stratosphere of the southern high latitudes (Fig. 3a). The ODS factor is important over the both poles, but in the tropics of the upper stratosphere the GHG forcing is responsible for about a half of the ozone mixing ratio increase (see Fig. 3a, b). Below 20 hPa the SST/SI forcing is the main driver of the ozone long-term evolution in the NH. Strengthening of the Brewer-Dobson circulation mentioned earlier caused by SST/SI produces substantial ozone decrease in the tropics due to intensified upwelling of the tropospheric air with rather low ozone mixing ratio and its additional accumulation over the northern extra-tropics (Fig. 3c).

Zonal-mean monthly total column ozone changes from 2000 to 2100 are illustrated in Fig. 4. Figure 4a, c shows that the long-term column ozone changes are determined mainly by the ODS and SST/SI factors. The ODS decline leads to the total column ozone increase over all latitudes with the maximum of growth in the Antarctic ozone “hole” region and the minimum in the tropics. The SST/SI contribution to the total column ozone tendency over 21st century is the most pronounced in the tropics and substantial in the extra-tropical latitudes. The influence of the GHG factor on the column ozone variations during the century is rather small, except the lower south polar stratosphere where the GHG induced cooling slightly increases the area of the Antarctic ozone hole.

The zonal mean RES term (see Eq. 1) is presented in Fig. 5 for the annual mean temperature (a), zonal wind (b) and ozone concentration (c) changes as well as for the monthly mean total column ozone (d) changes during the 21st century. The interaction between the factors (RES term) leads to the polar stratosphere warming for the 21st century. In agreement with these temperature changes the eastward zonal wind velocities of the polar stratosphere are weaker in FULL experiment in comparison with the sum of the relevant wind velocity changes of GHG, ODS and SST/SI experiments. The statistical significance of the RES term for the temperature and zonal wind velocity changes are not very high (less than 95 % for most of the atmosphere) while the RES term values for the column ozone variations are statistically significant in the lower polar stratosphere. The interactions among the ODS, GHG and SST/SI factor over these areas lead to the acceleration of the ozone recovery which is the most pronounced over the Antarctic ozone "hole" region.

It is of interest to evaluate the timing of the ozone and dynamics changes throughout the 21st century. Comparison of the model runs for the years 2000, 2050 and 2100 allows us to evaluate these changes separately for the first and for the second half of the 21st century. Figure 6 presents the zonally averaged annual mean changes of the zonal wind velocity (Fig. 6a) and monthly averaged total column ozone changes (Fig. 6c) from 2000 to 2050 under FULL forcing conditions. Figures 6b and 6d illustrate changes in these variables for the time period from 2050 to 2100. From Figures 6a, b we can conclude that the main changes in the stratospheric dynamics occur in the second half of the 21st century and can be attributed to the SST/SI forcing influence (see Fig. 2c, d). SST/SI factor also has dominant contribution to the deceleration of the stratospheric westerly winds in the extra-tropical latitudes of the NH from 2000 to 2050 (Fig. 6a). Figures 6c and 6d display the total column ozone changes in the 21st century under FULL forcing condition and reveal that it increases over all latitudes in the first half of the century. This increase is much more pronounced at the middle and high latitudes of both hemispheres and depends mainly on the removal of ODS (compare Figs. 6c and 4a). In the second half of the century the column ozone changes are controlled by the SST/SI. The SST/SI driven circulation changes are so strong in the tropical lower stratosphere, that their negative influence on the ozone concentration completely overcame the effects of ODS.

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4 Summary and discussion

We have exploited chemistry-climate model SOCOL 2.0 to evaluate the ozone, temperature and circulation changes of the stratosphere over 21st century due to main external forcings (GHG, ODS, SST/SI). Several 20-yr long time-slice ensemble runs have been performed with the CCM SOCOL using boundary conditions taken from IPCC A1B scenario for the GHG long-term evolution and the WMO A1 scenario for the century-long tendency of the ODS for the years 2000, 2050 and 2100. In these runs the SST/SI values are adopted from the model simulations with the ocean-atmosphere general circulation model (ECHAM5/MPIOM) driven also by the IPCC A1B scenario for the GHG long-term evolution (Table 1).

Analysis of the differences between the total effect (FULL) of all factors and the sum of the effects of the separate factors (GHG + ODS + SST/SI) leads us to the conclusion that the synergy of different factors is visible only in the southern polar region. In the other atmospheric regions the influence of this interaction does not exceed internal variability of the atmosphere and can be ignored. This fact confirms that the influence of considered factors can be evaluated with the applied set of experiments.

Comparison of the model experiments allows us to attribute the variability of the stratospheric ozone, temperature and circulation during the 21st century to the main anthropogenic factors (GHG, ODS, SST/SI). The GHG factor provides the main part of cooling of the upper and middle stratosphere, especially over the southern polar region. The upper stratospheric westerlies are accelerated mainly in the SH. All these atmospheric changes are responsible for about a half of the century ozone concentration increase in the upper stratosphere and ozone decline over the Antarctic area. The impact of the ODS consists of the ozone increase in the upper stratosphere (especially over the poles) and dissipation of the Antarctic ozone “hole”. These processes lead to additional heating of the upper stratosphere and the polar lower stratosphere in the SH. The westerlies are decelerated in the Polar Night Jet region. Thus, the ODS is the main factor of the ozone layer recovery in the first half of the century especially in the extra-tropical latitudes of the both hemispheres. The forcing from SST/SI leads to the tropical tropopause lifting, ozone depletion and cooling in the tropical lower stratosphere, acceleration of the subtropical jets and deceleration of the westerly flow in the northern stratosphere. It should be noted that these effects are more pronounced in the second half of the century. The SST/SI factor plays a dominant role in the atmospheric century-long changes in the lower stratosphere together with the ODS forcing. The long-term tendency of the total column ozone depends mainly on the ODS and SST/SI forcing. The ODS is the main driver of the total column ozone changes over the Antarctic and it is responsible for about 50 % of these changes in the middle and high latitudes of the NH basically in the first half of the 21st century. The SST/SI factor is the main contributor to the total column ozone depletion in the tropics and is responsible for a half of total column ozone increase over the northern extra-tropical latitudes. This effect of SST/SI factor appears mainly in the second half of century. The influence of GHG forcing on the evolution of the ozone layer can be found in the upper stratosphere and does not contribute substantially to the relevant column ozone changes.

A strong impact of the SST/SI on the ozone and circulation changes in the future has important implications for the analysis of the uncertainties in the total column ozone projections and their causes. Some differences between the simulated results could be caused by the applied SST/SI rather than by model features. For example, Oman et al. (2010a) showed that CCM SOCOL simulates very strong acceleration of the BDC in the future and estimated the tropical residual vertical velocity increase from 1960 to 2100 in CCM SOCOL to be as high as 0.21 mm s^{-1} while this increase in the other CCMs is within 0.04–0.12 mm s^{-1}. Strong increase of the BDC results in the strong cooling in the lower tropical stratosphere, pronounced tropical total column ozone depletion and faster total column ozone recovery over the middle and high-latitudes. Our results suggest that such a strong increase of BDC intensity is caused by the applied SST/SI from MPI-OM model, rather than simulated by the CCM in response to changing concentrations of GHG and ODS. To confirm this hypothesis we have rerun FULL-2000 and 2100 experiments using SST/SI acquired from the NCAR ESM output and found that the intensification of the tropical residual vertical velocity at 70 hPa drops from 0.16 mm s^{-1} for the run driven by MPI-OM SST/SI to 0.1 mm s^{-1}, which is in a reasonable agreement with other models (see Fig. 6 of Oman et al., 2010a). We think that the choice of SST/SI should be done more carefully for the future model evaluation campaigns.

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Table 1. The list of the numerical experiments performed with CCM SOCOL 2.0.

	Factor/scenario/year		
Experiment	GHG-A1B	ODS-A1	SST/SI-A1B
FULL-2000	2000	2000	2000
FULL-2050	2050	2050	2050
FULL-2100	2100	2100	2100
GHG-2050	**2050**	2000	2000
GHG-2100	**2100**	2000	2000
ODS-2050	2000	**2050**	2000
ODS-2100	2000	**2100**	2000
SST/SI-2050	2000	2000	**2050**
SST/SI-2100	2000	2000	**2100**

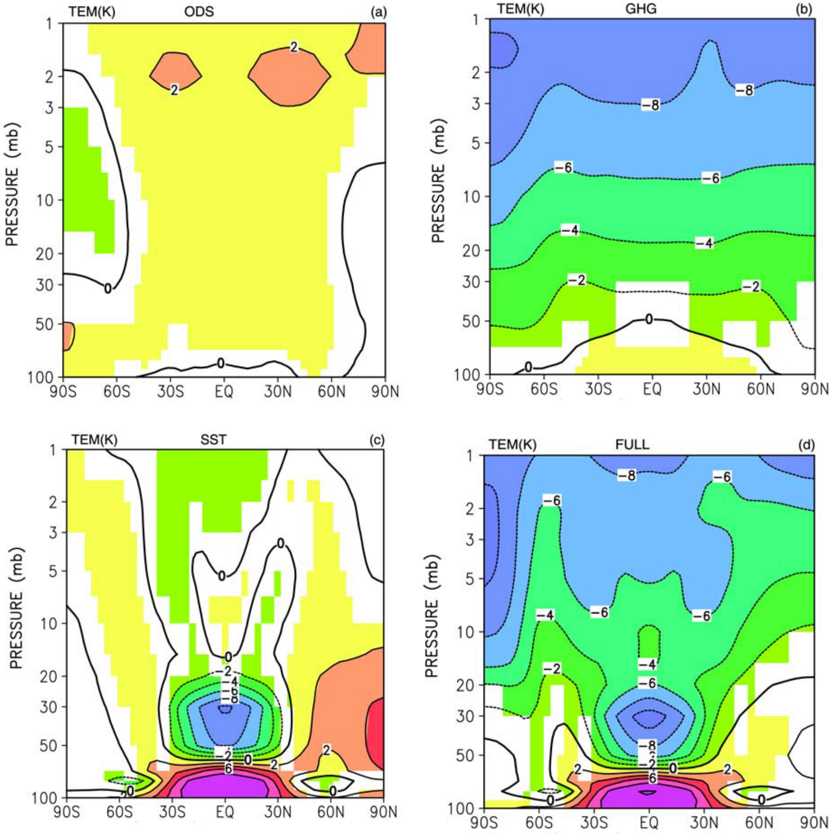

Fig. 1. Zonal, annual and ensemble mean changes of the temperature (K) from 2000 to 2100 caused by: **(a)** ODS; **(b)** GHG; **(c)** SST/SI; **(d)** all factors (ODS, GHG, and SST/SI). Color pattern indicates the regions where the changes are judged statistically significant at or better than 5 % level.

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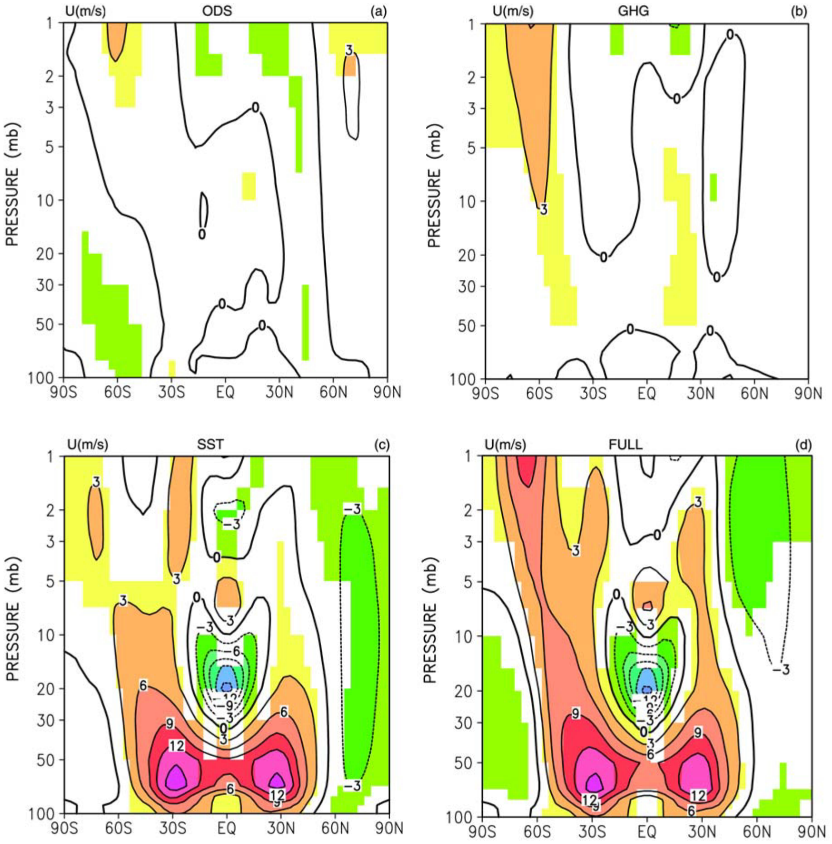

Fig. 2. Zonal, annual and ensemble mean changes of the zonal wind ($\text{m}\,\text{s}^{-1}$) from 2000 to 2100 caused by: **(a)** ODS; **(b)** GHG; **(c)** SST/SI; **(d)** all factors (ODS, GHG, and SST/SI). Color pattern indicates the regions where the changes are judged statistically significant at or better than 5 % level.

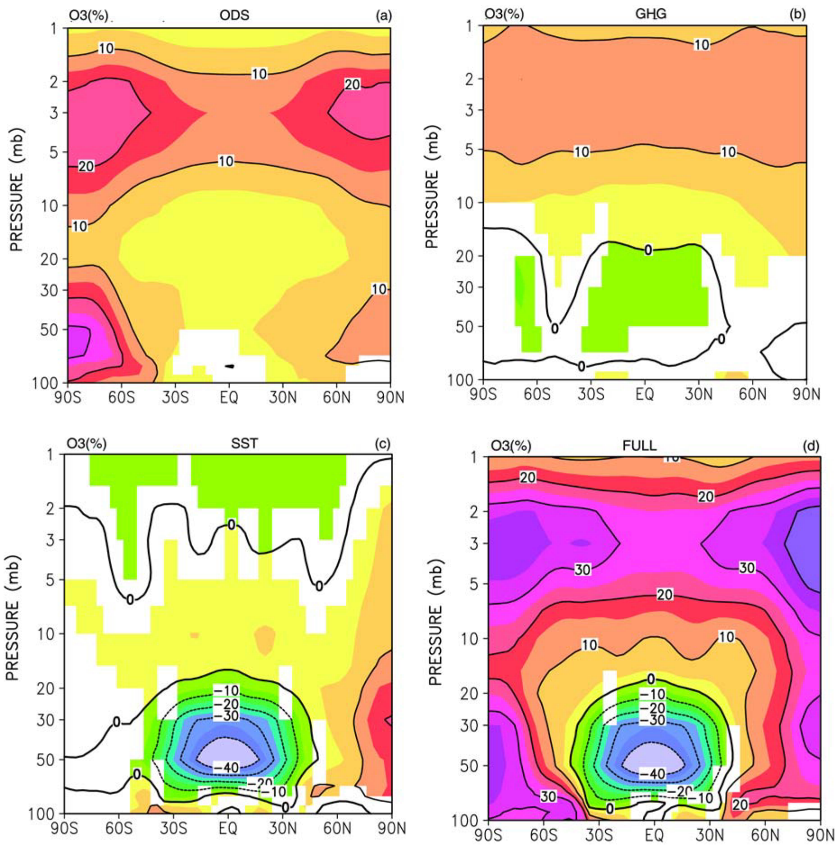

Fig. 3. Zonal, annual and ensemble mean changes of the ozone mixing ratio (%) from 2000 to 2100 caused by: **(a)** ODS; **(b)** GHG; **(c)** SST/SI; **(d)** all factors (ODS, GHG, and SST/SI). Color pattern indicates the regions where the changes are judged statistically significant at or better than 5 % level.

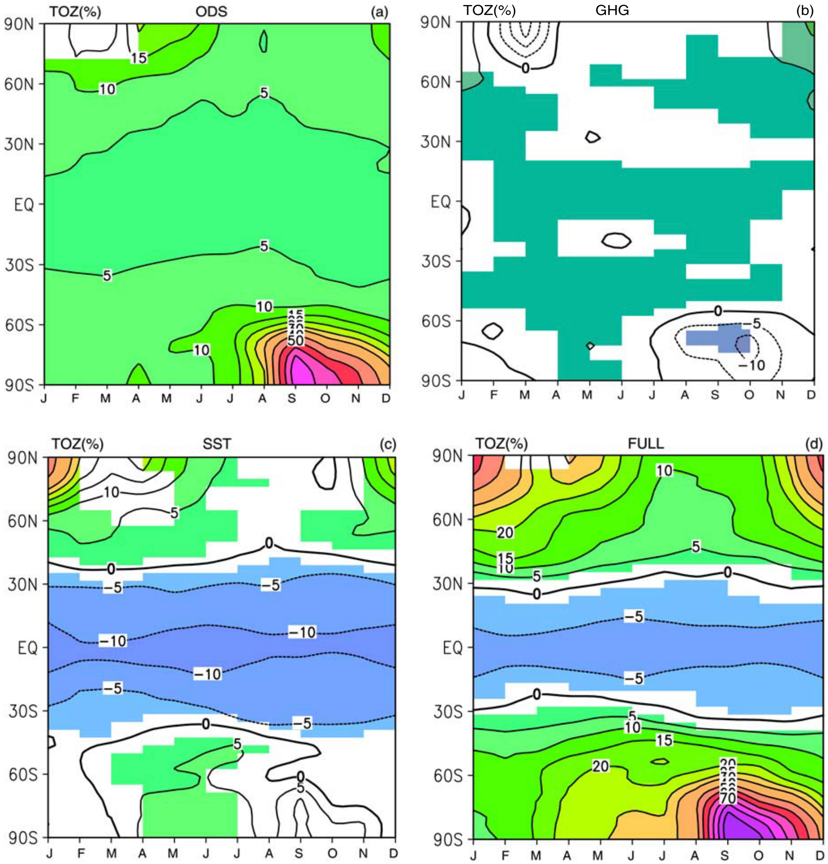

Fig. 4. Zonal and ensemble mean changes of the total column ozone (%) from 2000 to 2100 caused by: **(a)** ODS; **(b)** GHG; **(c)** SST/SI; **(d)** all factors (ODS, GHG, and SST/SI). Color pattern indicates the regions where the changes are judged statistically significant at or better than 5 % level.

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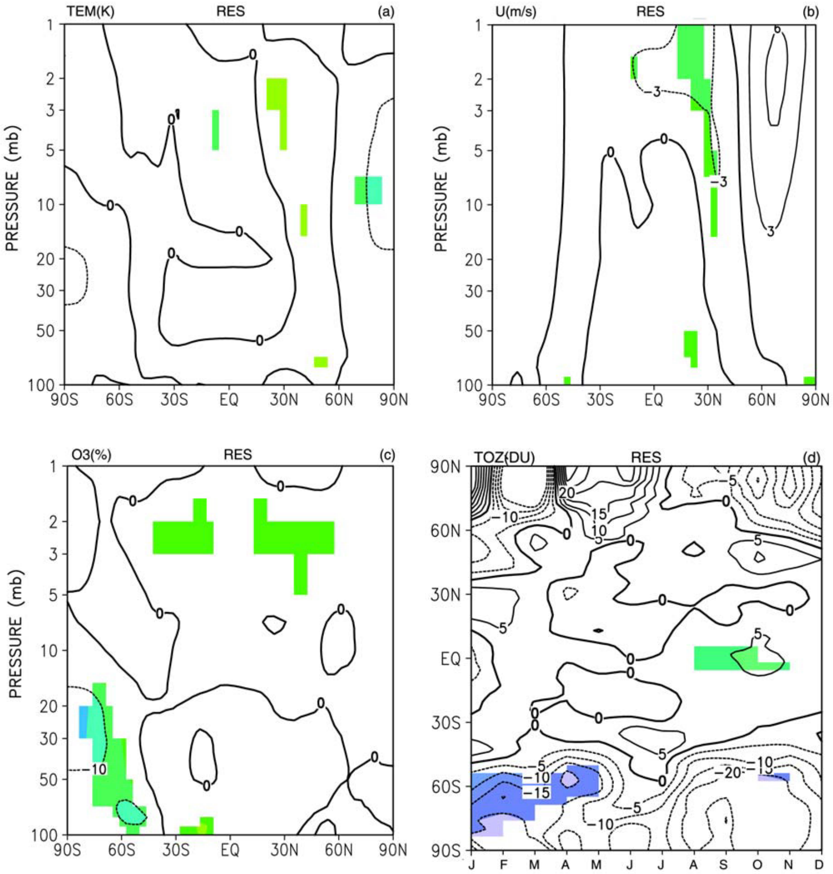

Fig. 5. Zonal and ensemble mean RES term (see the Eq. (1) for the changes of **(a)** annual mean temperature (K); **(b)** annual mean zonal wind (m s^{-1}); **(c)** annual mean ozone mixing ratio (%); **(d)** total column ozone (D.U.) from 2000 to 2100. Color pattern indicates the regions where the changes are judged statistically significant at or better than 5 % level.

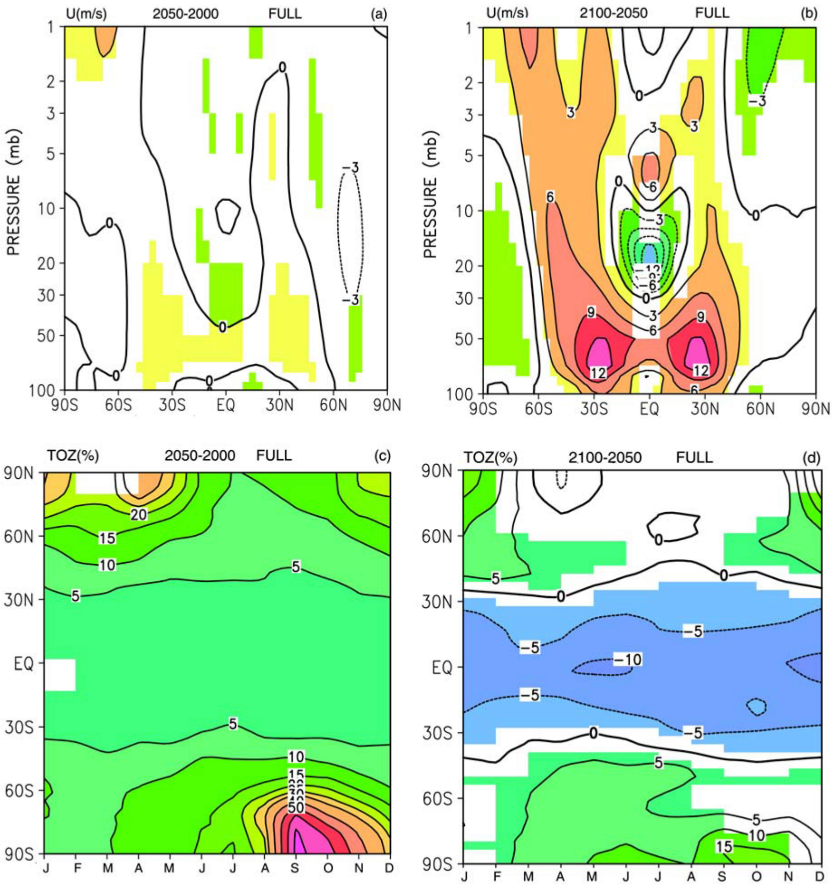

Fig. 6. Zonal and ensemble mean changes of annual mean zonal wind ($\mathrm{m\,s^{-1}}$): **(a)** from 2000 to 2050; **(b)** from 2050 to 2100 and total column ozone (%): **(c)** from 2000 to 2050; **(d)** from 2050 to 2100. Color pattern indicates the regions where the changes are judged statistically significant at or better than 5 % level.