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Interannual variation, decadal trend, and future change in ozone outflow from East Asia

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Abstract. We examine the past and future changes in O_3 outflow from East Asia using a global three-dimensional chemical transport model GEOS-Chem. The simulations of Asian O_3 outflow for 1986–2006 are driven by the assimilated GEOS-4 meteorological fields, and those for 2000–2050 are driven by the meteorological fields archived from the Goddard Institute for Space Studies (GISS) General Circulation Model (GCM) 3 under the IPCC SRES A1B scenario. Sensitivity studies are conducted to examine the respective impacts of meteorological parameters and emissions on the variations in the outflow flux of O_3. When both meteorological parameters and anthropogenic emissions varied during 1986–2006, the simulated Asian O_3 outflow fluxes exhibited a small and statistically insignificant decadal trend of −2.2 % decade^{-1}, but large interannual variations (IAVs) with seasonal absolute percent departure from the mean (APDM) values of 4–9 % and annual APDM value of 3.3 %. Sensitivity simulations indicated that the large IAVs of O_3 outflow fluxes were mainly caused by the variations in meteorological conditions. The simulations of the 2000–2050 changes show that the annual outflow flux of O_3 will increase by 2.0 %, 7.9 %, and 12.2 %, respectively, owing to climate change alone, emissions change alone, and changes in both climate and emissions. Therefore, climate change will aggravate the effects of the increases in anthropogenic emissions on future changes in the Asian O_3 outflow. Future climate change is predicted to greatly increase Asian O_3 outflow in the spring and summer seasons as a result of the projected increases in zonal winds. Findings from the present study help to understand the variations in tropospheric O_3 in the downwind regions of East Asia on different timescales, and have important implications for long-term air quality planning.

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1 Introduction

Tropospheric ozone (O_3) is an important air pollutant, which has a detrimental effect on human health (Fann et al., 2012; Jhun et al., 2014), crops (Wilkinson et al., 2011; Tai et al., 2014), and ecosystems (Fuentes et al., 2013; Yue and Unger, 2014). It is also an important greenhouse gas that directly contributes to global warming (IPCC, 2013). O_3 has a relatively long lifetime of weeks in the free troposphere (Young et al., 2013; Monks et al., 2015), which makes intercontinental transport of O_3 an important issue for understanding O_3 concentrations and planning emission control measures.

A number of previous studies have shown that Asian continental outflow impacts the global O_3 budget (Liu et al., 2002), and influences O_3 air quality in the downwind regions, such as the United States and Canada (Zhang et al., 2008; Chiang et al., 2009; Huang et al., 2010; Walker et al., 2010; Ambrose et al., 2011; Lin et al., 2012; Ou-Yang et al., 2013). Liu et al. (2002) reported that boundary-layer O_3 pollution was lifted into the upper troposphere by deep convection over the Asian maritime continent, from where it was transported northward along the upper branch of the local Hadley circulation and into the mid-latitude westerlies, influencing the global O_3 budget. Using a global 3-D chemical transport model GEOS-Chem, Zhang et al. (2008) estimated that Asian pollution enhanced surface-layer O_3 concentrations by 5–7 ppbv over western North America in spring 2006. Walker et al. (2010) used the same model (GEOS-Chem) to evaluate sensitivities of tropospheric O_3 over Canada to Asian anthropogenic emissions, and reported that the contribution from Asian emissions to O_3 profiles above Whistler, Canada, was 6–8 ppbv in spring 2006. Through an integrated analysis of in situ and satellite measurements in May–June 2010 with a global chemistry-climate model GFDL AM3, Lin et al. (2012) reported that Asian emissions could contribute 8–15 ppbv O_3 over the western United States on days when the observed daily maximum 8-h average O_3 (MDA8 O_3) exceeded 60 ppbv, and that 20 % of MDA8 O_3 exceedances of 60 ppbv would not have occurred in the southwestern United States in the absence of Asian anthropogenic emissions.

Asian O_3 outflow exhibits seasonal variations (Liu et al., 2002; Han et al., 2015). Using a global 3-D chemical transport model GEOS-Chem, Liu et al. (2002) simulated the seasonal variations of the Asian outflow flux of O_3 over the Pacific, which was defined as the eastward flux integrated for the tropospheric column through a wall located at 150 °E between 10 °N and 60 °N. They found that the Asian O_3 outflow flux reached the maximum in early spring (March) and the minimum in summer (July). Han et al. (2015) examined O_3 measurements at Ieodo Ocean Research Station, which was located in the East China Sea and regarded as an ideal place to observe Asian outflow without local effects. They reported that the seasonal variation of O_3 was distinct, with a minimum in August and two peaks in April and October, and was greatly affected by the seasonal wind pattern over East Asia.

Continental outflow of O_3 is expected to vary on interannual to decadal timescales, because tropospheric O_3

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concentrations and meteorological parameters have variations on these timescales. Large interannual variations (IAVs) of tropospheric O_3 concentrations have been reported in previous observational studies (Kurokawa et al. 2009; Zhou et al., 2013). Analyzing 11 years of ozonesonde data over Hong Kong, Zhou et al. (2013) reported that observed tropospheric O_3 levels during 2000–2010 exhibited high IAV, with an annual averaged amplitude [defined as (maximum + 2nd maximum − minimum − 2nd minimum) × 0.5 / the average during 2000–2010] up to 30 % of the averaged concentrations at 3–8 km altitude. Kurokawa et al. (2009) analyzed observed springtime O_3 over Japan during 1985–2005, and found that the observed O_3 showed greater year-to-year variations than the annual rate of the long-term trend. Decadal trends of tropospheric O_3 concentrations have been reported for different locations on the basis of observations (Ding et al., 2008a; Xu et al., 2008; Tang et al., 2009; Wang et al., 2009b; Cooper et al., 2010; Wang et al., 2012; Lin et al., 2014; Zhang et al., 2014), such as −0.56 ppbv yr^{-1} over Linan in eastern China (Xu et al., 2008), +0.58 ppbv yr^{-1} over Hong Kong in southern China (Wang et al., 2009b), and +0.35 ppbv yr^{-1} over Hawaii in North Pacific (for autumn O_3; Lin et al., 2014). Future changes of tropospheric O_3 concentrations have also been predicted by modeling studies (Racherla and Adams, 2006; Lin et al., 2008; Wu et al., 2008a; Racherla and Adams, 2009; Lam et al., 2011; Wild et al., 2012; Gao et al., 2013; Liu et al., 2013; Wang et al., 2013; Lee et al., 2015; Val Martin et al., 2015; Zhu and Liao, 2016). Wang et al. (2013), using the NASA GISS GCM/GEOS-Chem model combination, reported that the summer surface-layer O_3 levels averaged over China would increase by 11.9 ppbv due to the combined changes in climate and emissions over 2000–2050 under the SRES A1B scenario. Meteorological parameters, especially winds that are important for O_3 outflow, also exhibit variations on different time scales (Chang et al., 2000; Ding et al., 2008b; Sun et al., 2009; Zhang and Guo, 2010; Hirahara et al., 2012). Large IAVs of the East Asian summer monsoon (EASM) have been reported in previous studies (Zhu et al., 2012; Yang et al., 2014). The decadal-scale weakening of the EASM since the 1950s has also been reported by many previous studies, and anomalous northeasterlies during the weak monsoon years were found over the western North Pacific near 40 ° N, which did not favor the outflow of pollutants from northern China (Chang et al., 2000; Ding et al., 2008b; Zhu et al., 2012). On the basis of NCEP/NCAR reanalysis data, Sun et al. (2009) showed that the axis location of the East Asia subtropical westerly jet (EASWJ) had displaced southward since the end of the 1970s, intensifying the westerly wind over 25–35 ° N and weakening it over 42–50 ° N, and therefore influencing the outflow of pollutants. Most of the Coupled Model Intercomparison Project Phase 3 (CMIP3) models projected that the Asian jet would be intensified on its equatorward side by the end of the 21st century (Zhang and Guo, 2010; Hirahara et al., 2012).

Few previous studies have examined the IAVs, decadal trends, and future changes in O_3 outflow. In this work, we examine the historical (1986–2006) and future (2000–2050) changes of O_3 outflow from East Asia, and systematically quantify the roles of meteorological parameters and/or anthropogenic emissions on the changes. The descriptions of

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the model, emissions, and numerical simulations are presented in Sect. 2. Section 3 evaluates the model performance for tropospheric O_3. Section 4 discusses the IAVs and decadal trends in the O_3 outflow from East Asia over 1986–2006. Future changes in O_3 outflow from East Asia for 2000–2050 are presented in Sect. 5.

2 Methods

2.1 Model description

We apply the global 3-D chemical transport model GEOS-Chem to simulate O_3 outflow fluxes. The GEOS-Chem model includes a detailed simulation of O_3–NOx–hydrocarbon (~80 species, ~300 chemical reactions) (Bey et al., 2001) and aerosol chemistry. Aerosol species include sulfate (SO_4^{2-}), nitrate (NO_3^-), ammonium (NH_4^+) (Park et al., 2004; Pye et al., 2009), black carbon (BC) and organic carbon (OC) (Park et al., 2003), mineral dust (Fairlie et al., 2007), and sea salt (Alexander et al., 2005). The simulations account for the impacts of aerosols on the distributions and concentrations of O_3 through heterogeneous reactions and changes in photolysis rates (Lou et al., 2014).

To simulate historical changes in the Asian outflow of O_3, the GEOS-Chem model is driven by the assimilated GEOS-4 meteorological fields from the Goddard Earth Observing System (GEOS) of NASA Global Modeling and Assimilation Office (GMAO). We perform simulations for 1986–2006, which are the years with available GEOS-4 meteorological datasets. The version of the model used here has a horizontal resolution of 2 ° (latitude) × 2.5 ° (longitude), with 30 vertical layers.

To simulate future changes of O_3 outflow fluxes during 2000–2050, the GEOS-Chem simulation is driven by meteorological data from the National Aeronautics and Space Administration/Goddard Institute for Space Studies (NASA/GISS) general circulation model (GCM) 3 (Rind et al., 2007) for both the present day (1996–2005) and future (2046–2055), following Wu et al. (2008b), Pye et al. (2009), Wang et al. (2013), and Jiang et al. (2013). Both the GISS and GEOS-Chem models used here have a horizontal resolution of 4 °latitude by 5 °longitude, with 23 vertical layers.

2.2 Emissions

For simulations during 1986–2006, the global anthropogenic emissions of reactive nitrogen oxides (NO_x), carbon monoxide (CO), and sulfur dioxide (SO_2) in the model are from the Emission Database for Global Atmospheric Research (EDGAR) inventory (Olivier and Berdowski, 2001). The global emissions of non-methane volatile organic compounds (NMVOCs) are from the Global Emissions Inventory Activity (GEIA) inventory (Piccot et al., 1992). Global emissions of carbonaceous aerosols (BC and OC) follow Bond et al. (2007). Anthropogenic emissions of reactive NO_x, CO, SO_2, NH_3, and NMVOCs over East Asia are overwritten by the emissions inventory of Streets et al.

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(2003) and Zhang et al. (2009). IAVs of anthropogenic emissions are represented by global-gridded annual scaling factors as described by van Donkelaar et al. (2008) for NO_x, CO, and NMVOCs. Biomass burning emissions are taken from the Global Fire Emissions Database-3 (GFED-3) inventory (van der Werf et al., 2010) for 1997–2006. The biomass burning emissions before 1997 are unavailable because of the lack of datasets.

Figure 1 shows the evolution of anthropogenic and biomass burning emissions of O_3 precursors (NO_x, CO, NMVOCs) summed over the globe and Asia (60–150 ° E, 10 ° S–55 ° N) over 1986–2006. Global anthropogenic emissions of these precursors exhibited no significant trends, while the Asian anthropogenic emissions showed large increases over the past two decades. Relative to year 1986, the Asian anthropogenic emissions of NO_x, CO, and NMVOCs in 2006 increased by 70.0 %, 42.1 %, and 50.9 %, respectively. Compared with anthropogenic emissions, biomass burning emissions had greater IAVs during 1997–2006. Figure 1 also shows the pathway for the global CH_4 abundance used in our simulations of O_3. The CH_4 mixing ratio in 1986 was 1672 ppb, which increased by 6.3 % in 2006.

For future simulations during 2000–2050, anthropogenic emissions of O_3 precursors, including NO_x, CO, and NMVOCs, are taken from Wu et al. (2008b), and those of NH_3 and SO_2 follow those in Pye et al. (2009). The future anthropogenic emissions of O_3 precursors, aerosol precursors, and aerosols under the SRES A1B scenario are generated by the Integrated Model to Assess the Greenhouse Effect (IMAGE) socioeconomic model using growth factors for different species and countries (Streets et al., 2004). Table 1 shows the present-day (year 2000) and future (year 2050) anthropogenic emissions of O_3 precursors under the SRES A1B scenario. The global emissions of NO_x, CO, and NMVOCs are projected to increase by 78.4 %, 26.4 %, and 89.4 % over 2000–2050; and the Asian emissions are projected to increase by 159.6 %, 23.7 %, and 118.6 %, respectively. Present-day methane mixing ratios are specified as 1750 ppbv on the basis of observations (Wu et al., 2008b). The future methane concentrations are set to 2400 ppbv, following the SRES A1B scenario (Pye et al., 2009).

The natural emissions of O_3 precursors, including NO_x from lighting and soil, and NMVOCs from vegetation, are calculated on the basis of the assimilated GEOS-4 meteorological fields and GISS Model 3 meteorological parameters. The lightning NO_x emissions follow Price and Rind (1992), with the NO_x vertical profile proposed by Pickering et al. (1998). The soil NO_x emissions scheme in the GEOS-Chem model is based on the work of Yienger and Levy (1995) and Wang et al. (1998). Biogenic emissions of NMVOCs are calculated according to the Model of Emissions of Gases and Aerosols from Nature (MEGAN) (Guenther et al., 2006). Figure 2 shows the evolution of natural emissions summed over the globe and Asia over 1986–2006. Both global and Asian NO_x emissions from lightning exhibited large IAVs and significant increasing trends. It has been shown that warming climate leads to increased lightning NO_x (IPCC, 2013). Compared with lightning NO_x emissions, NO_x emissions from soil showed smaller IAVs and no

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significant decadal trend. Both global and Asian biogenic emissions of NMVOCs have been shown to have large IAVs, as a result of the changes in both vegetation and meteorological parameters (Fu and Liao, 2012). For future simulations during 2000–2050, the natural emissions of O_3 precursors are listed in Table 2. The simulated emissions of lightning NO_x, soil NO_x, and biogenic VOCs are projected to increase by 18.8 %, 14.9 %, and 22.1 % for the globe, and by 16.7 %, 21.4 %, and 18.9 % for Asia, respectively.

The effects of changes in stratosphere–troposphere exchange (STE) of O_3 are not included in this study for both past and future simulations. The cross-tropopause O_3 flux is represented by the synthetic O_3 (Synoz) method (McLinden et al., 2000), which imposes a global annual mean cross-tropopause O_3 flux of 500 Tg yr^{-1}.

2.3 Numerical experiments

To examine the respective and combined impacts of meteorological parameters, anthropogenic emissions, and biomass burning emissions on the IAVs and decadal trends of O_3 outflow from East Asia during 1986–2006, we perform simulations for four cases (Table 3):

(a) Met: The simulation of O_3 outflow for 1986–2006, to examine the effect of variations in meteorological parameters alone. The meteorological parameters vary from 1986 to 2006, and the anthropogenic emissions are fixed at year 2006 levels. Biomass burning emissions are turned off.

(b) Emis: The simulation of O_3 outflow for 1986–2006, to examine the effect of variations in anthropogenic emissions alone. The anthropogenic emissions vary from 1986 to 2006, and the meteorological parameters are fixed at year 2006 levels. Biomass burning emissions are turned off.

(c) MetEmis: The simulation of O_3 outflow for 1986–2006, with variations in both meteorological parameters and anthropogenic emissions during 1986–2006. Biomass burning emissions are turned off.

(d) MetEmisB: The simulation of O_3 outflow for 1997–2006, with variations in meteorological parameters, anthropogenic emissions, and biomass burning emissions during 1997–2006. Note that biomass burning emissions in the model are not available before 1997.

To identify the relative roles of future changes in meteorological parameters and emissions in 2000–2050 changes in Asian O_3 outflow flux, another four simulations are carried out: (a) Met2000Emis2000: present-day climate and emissions; (b) Met2050Emis2000: future climate and present-day anthropogenic emissions; (c) Met2000Emis2050: present-day climate and future anthropogenic emissions; and (d) Met2050Emis2050: future climate and emissions. Both the future climate and anthropogenic emissions follow the IPCC SRES A1B scenario.

The mass flux of O_3 through the vertical plane along 135 °E from 20 °N to 55 °N from the surface to 100 hPa

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(marked in Fig. 3a) is used to quantify Asian O_3 outflow. The metric of mass flux through a vertical plane was also used by Liu et al. (2002) to represent Asian O_3 outflow, and by Jiang et al. (2013) and Yang et al. (2015) to represent Asian aerosol outflow. It should be noted that the O_3 outflow flux from East Asia includes the effects of emissions in different regions of the world owing to the relatively long lifetime (~3 weeks) of O_3 (Fiore et al., 2002; Liao et al., 2006). However, Liu et al. (2002) found that anthropogenic sources in Asia made the largest contribution to the Asian outflow flux of O_3.

3 Model evaluation

The GEOS-Chem simulations of O_3 have been evaluated extensively for the U.S. (Liu et al., 2006; Wu et al., 2008b; Zhang et al., 2008), Europe (Auvray and Bey, 2005; Liu et al., 2006; Kim et al., 2015), and China (Wang et al., 2013; Lou et al., 2014; Yang et al., 2014; Zhu and Liao, 2016). These studies showed that the GEOS-Chem model captured the magnitude and distribution of the surface-layer concentration and column burden of tropospheric O_3 fairly well. The vertical distributions of O_3 have also been evaluated by aircraft campaigns and ozonesonde measurements (Zhang et al., 2008; Walker et al., 2010; Wang et al., 2011), showing that the GEOS-Chem model closely reproduced the observed O_3 profiles.

Here, we conduct comparisons with measurements to evaluate whether the version of the GEOS-Chem model used in this study can capture the Asian outflow of tropospheric O_3. We use tropospheric column O_3 (TCO) products retrieved from TOMS/SBUV (Total Ozone Mapping Spectrometer/Solar Backscattered Ultraviolet instruments) to evaluate model performance for tropospheric O_3 over China and regions downwind. The TOMS/SBUV retrievals are available for 1997–2005. In 2001, it was discovered that the TOMS had experienced instrument problems, and the quality of the total O_3 measurements had degraded (Fishman et al., 2003). Therefore, we show in Fig. 3 the maps of TCO retrieved from TOMS/SBUV and those simulated by the model (in the MetEmisB simulation) averaged over 1997–2005 (excluding year 2001). The TOMS/SBUV retrievals exhibit high values exceeding 40 Dobson units (DU) over the North China Plain and Sichuan Basin, and low values of 25–35 DU over the Tibetan Plateau. The spatial distribution of TCO is mostly captured by the model. The differences between the GEOS-Chem simulation and TOMS/SBUV observation indicate that the model underestimates the TCO over the Tibetan Plateau by ~10 DU and overestimates the TCO over central and eastern China by ~10 DU. Zhang et al. (2010) attributed the overestimation of TCO in the northern subtropics in the GEOS-Chem model to an excessive stratospheric influx of O_3.

We then compare the simulated monthly and yearly variations in TCO averaged over a selected region (30–50 °N, 130–150 °E, downwind of China; Fig. 4) in the western Pacific Ocean in the MetEmisB simulation with those obtained

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from TOMS/SBUV. The GEOS-Chem model generally overestimates TCO values, especially during winter/spring months. Chandra et al. (2003) also reported that the TCO values simulated by the GEOS-Chem model tended to be higher by 5–10 DU compared with sonde values at Naha, Japan (26 °N, 128 °E) during winter months. The satellite measurements suggest that TCO has a maximum in July and a minimum in January. The seasonality in TCO is reproduced fairly well by the model, with a correlation coefficient of +0.90 between simulated and TOMS/SBUV TCO. However, the maximum in the model occurs two months earlier than in TOMS/SBUV. Wang et al. (2011) also reported that the maximum of TCO averaged over East China simulated by the GEOS-Chem model occurred two months earlier than Tropospheric Emission Spectrometer (TES) retrievals. On the interannual scale, for 1997–2005, the model mostly captures the years with maximum or minimum TCO values, with a correlation coefficient of +0.56.

Although GEOS-Chem overestimates TCO values over eastern China and the western Pacific Ocean, the model exhibits reasonable performance in simulating the spatiotemporal distributions of the tropospheric O_3 column burden over China and downwind regions, which lends us confidence to simulate the temporal evolutions of the Asian O_3 outflow.

4 Simulated Asian O_3 outflow during 1986–2006

4.1 Seasonal patterns of Asian O_3 outflow

Figure 5 shows the pressure–latitude cross-sections along 135 °E of the seasonal O_3 outflow fluxes averaged over 1997–2006 in the MetEmisB simulation. The maximum O_3 fluxes were found in the middle-upper troposphere, in consistent with Liu et al. (2002) and Wang et al. (2009a), and it could be attributed to the vertical distributions of both zonal winds and O_3 concentrations. The westerlies strengthen with altitudes with the strongest winds occurring around 200 hPa (known as the East Asia subtropical westerly jet) (Ren et al., 2011). Concentrations of O_3 are high in the upper troposphere over the mid-latitudes (Wang, 1999).

The seasonal mass fluxes through the meridional plane (along 135 °E from 20 °N to 55 °N, and from the surface to 100 hPa) were calculated to be 509.6, 437.6, 126.6, and 268.7 Tg season^{-1} for December–January–February (DJF), March–April–May (MAM), June–July–August (JJA), and September–October–November (SON), respectively. Although the seasonal flux was highest in DJF, the monthly O_3 flux through the panel peaked in March and reached the nadir in July (not shown in Fig. 5). Such monthly variations of the Asian O_3 outflow flux agreed with those in Liu et al. (2002). The maximum O_3 outflow in March was caused by the combined effects of meteorological conditions, biomass burning emissions, and stratospheric O_3 intrusion. The “warm conveyor belt” (WCB) airstreams that export pollution from the Asian boundary layer to the free troposphere, and the mid-latitude prevailing westerly winds in the free

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troposphere that transport pollution from Asia to the Northwest Pacific, were strongest during the early spring period (Eckhardt et al., 2004; Pochanart et al., 2004). The contribution from Asian biomass burning emissions on O_3 outflow was maximum in the spring and insignificant during other seasons (Liu et al., 2002). The stratospheric O_3 intrusion was also found to be most effective in late winter and early spring (Danielsen and Mohnen, 1977; Mahlman and Moxim, 1978).

4.2 IAVs and decadal trends of Asian O_3 outflow

Figure 6a shows the simulated annual O_3 outflow fluxes through the meridional plane along 135 °E from 20 °N to 55 °N, from the surface to 100 hPa, during 1986–2006 in the Met, Emis, and MetEmis simulations, and Fig. 6b shows the associated deviations from the mean (DEV). The simulations of the O_3 outflow in Met, Emis, and MetEmis examined, respectively, the effects of variations in meteorological parameters alone, anthropogenic emissions alone, and both meteorological parameters and anthropogenic emissions. The outflow fluxes of O_3 with changes in anthropogenic emissions alone (the Emis simulation) exhibited a statistically significant ($P < 0.001$) increasing trend. However, the magnitude of the increasing trend was very small; the decadal trend of the Asian O_3 outflow flux in the Emis simulation was calculated to be +16.7 Tg decade^{-1} (i.e., +1.2 % decade^{-1}) using the linear fit with least-squares method. The DEV, defined as

$$\mathrm{DEV} = 100\% \times \left(C_i - \frac{1}{n}\sum_{i=1}^{n} C_i\right) / \left(\frac{1}{n}\sum_{i=1}^{n} C_i\right),$$

where n is the number of years examined (n = 21 for 1986–2006) and C_i is the simulated O_3 outflow flux in year i, changed from −1.3 % (in 1986) to +1.4 % (in 2006), also indicating a small increasing trend in the O_3 outflow flux. With variations in meteorological parameters alone (the Met simulation), simulated O_3 outflow fluxes exhibited large IAVs, but a statistically insignificant ($P > 0.05$) decadal trend of −3.4 % decade^{-1}. The DEV values in the Met simulation ranged from −8 % to +16.5 %. With variations in both anthropogenic emissions and meteorological parameters (the MetEmis simulation), the simulated O_3 outflow showed large IAVs, but a statistically insignificant ($P >$ 0.05) decadal trend of −2.2 % decade^{-1}.

To analyze the IAVs of O_3 outflow fluxes, the decadal trend obtained from the linear fit was removed from the time series of simulated O_3 outflow fluxes, following the approach used in previous studies that examined IAVs of aerosol outflow fluxes (Yang et al., 2015) and O_3 concentrations (Camp et al., 2003). The deviations from the mean of the detrended O_3 outflow fluxes from the Met, Emis, and MetEmis simulations over 1986–2006 are shown in Fig. 6c. While the detrended outflow fluxes of O_3 in Met and MetEmis simulations showed large IAVs with DEV values in the range of −7.5 % to +13.5 %, the DEV values in the Emis simulation were very small (in the range of ±0.3 %). The two

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deviation curves from the Met and MetEmis simulations almost coincided with each other, indicating the dominant role of variations in meteorological parameters in the IAVs of the Asian O_3 outflow flux.

The IAVs in the O_3 outflow fluxes were further quantified with statistical variables of mean absolute deviation (MAD) and absolute percent departure from the mean (APDM), which have been used in previous IAV studies, such as Mu and Liao (2014), Lou et al. (2015), and Yang et al. (2015). The absolute IAVs of the O_3 outflow fluxes can be quantified by MAD, defined as

$$\mathrm{MAD} = \frac{1}{n}\sum_{i=1}^{n} |C_i - \frac{1}{n}\sum_{i=1}^{n} C_i\,|,$$

while the IAVs relative to the multi-year average outflow flux can be quantified by APDM, defined as

$$\mathrm{APDM} = 100\% \times \mathrm{MAD} / \left(\frac{1}{n}\sum_{i=1}^{n} C_i\right),$$

where n is the number of years examined (n = 21 for years 1986–2006) and C_i is the detrended O_3 outflow flux in year i. The MAD and APDM values of the detrended seasonal and annual O_3 outflow fluxes across the meridional plane along 135 °E from 20 °N to 55 °N, from the surface to 100 hPa, are shown in Fig. 7. The seasonal MAD and APDM values in the Emis simulation were close to zero, while those in the Met and MetEmis simulations were relatively large. The APDM values in the Met and MetEmis simulations were maximum in JJA and minimum in SON. The MAD and APDM values in the Met simulation were almost identical to those in the MetEmis simulation, which indicated again that the IAVs of the O_3 outflow fluxes were mainly dependent on the variations in meteorological conditions, rather than the variations in anthropogenic emissions. With variations in both meteorological parameters and anthropogenic emissions, the seasonal APDM values were in the range of 4–9 % and the annual APDM value was 3.3 %.

Figure 8 shows the pressure–latitude cross-sections of MAD values along 135 °E for detrended annual O_3 outflow fluxes from the Met, Emis, and MetEmis simulations. The O_3 outflow in the Met simulation exhibited large IAVs throughout the whole troposphere, with MAD values greater than 0.2 kg yr^{-1} m^{-2}. The MAD values increased with altitude, which could be attributed to the vertical distributions of the IAVs in westerly winds (see MAD values of winds in Fig. 8a). The variations in anthropogenic emissions led to very small IAVs, with MAD values less than 0.2 kg yr^{-1} m^{-2} (Fig. 8b) throughout the troposphere. With both variations in meteorological parameters and anthropogenic emissions, the MAD values (Fig. 8c) showed almost identical magnitudes and spatial distributions to those in the Met simulation (Fig. 8a), indicating the dominant role of variations in meteorological conditions in the IAVs of the O_3 outflow.

4.3 Effect of variations in biomass burning emissions

The biomass burning emissions of the O_3 precursors exhibited large IAVs during 1997–2006 (Fig. 1). To analyze

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the impacts of biomass burning emissions on IAVs of O_3 outflow fluxes, we compare the MAD and APDM values of detrended O_3 outflow fluxes during 1997–2006 in the MetEmis and MetEmisB simulations. The MAD (APDM) was calculated to be 31.17 Tg yr^{-1} (2.35 %) in the MetEmis simulation and 31.82 Tg yr^{-1} (2.36 %) in the MetEmisB simulation. The minor influence of biomass burning emissions on the IAVs of the O_3 outflow fluxes from East Asia was also supported by Voulgarakis et al. (2015). Furthermore, Lin et al. (2014) reported that meteorological variability, compared with the variability in biomass burning, was much more important for driving the IAVs in springtime O_3 at the Mauna Loa Observatory, a remote North Pacific site sensitive to Asian pollution outflow.

5 Future changes in Asian O_3 outflow for 2000–2050

In this part of the study, we quantify future decadal changes in Asian O_3 outflow during 2000–2050 under the SRES A1B scenario, and examine the relative impacts of variations in climate and anthropogenic emissions on the changes. We conduct each simulation for 10 years, driven by 1996–2005 meteorology to represent the present-day (year 2000) climate, and by 2046–2055 meteorological fields to represent the future (year 2050) climate, following 1 year of model spin-up. All the results presented below are 10-year averages. Simulated present-day and future changes in seasonal and annual fluxes of O_3 across the vertical plane along 135 °E from 20 °N to 55 °N are summarized in Table 4.

5.1 Present-day O_3 outflow

The pressure–latitude cross-sections along 135 ° E of the simulated present-day (Met2000Emis2000) seasonal O_3 outflow fluxes, driven by the meteorological inputs provided by GISS GCM 3, are shown in Fig. 9a. The magnitudes, spatial distributions, and seasonal variations agree closely with those driven by the assimilated GEOS-4 meteorological fields (Fig. 5). The O_3 outflow flux through the vertical plane is simulated to be 1877.1 Tg yr^{-1} with GISS GCM 3 meteorology, and 1342.5 Tg yr^{-1} with the GEOS-4 assimilated meteorological fields, which indicates the reliability of the simulated present-day O_3 outflow fluxes.

5.2 Effect of future changes in climate alone

Relative to the present-day value, year 2050 annual outflow of O_3 is estimated to increase by 2.0 % (Table 4) as a result of climate change alone (Met2050Emis2000 minus Met2000Emis2000). The outflow of O_3 shows a slight decrease of 1.8 % in DJF and of 3.8 % in SON, but a large increase of 14.5 % in JJA and of 7.3 % in MAM. The spatial distributions of projected changes in O_3 fluxes are well consistent with those of changes in zonal winds (Fig. 9b). The wind speed of the westerlies in DJF and SON decreases across the troposphere over 30–45 °N, leading to the

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reductions in the O_3 outflow fluxes. In contrast, the increases in zonal winds in JJA and MAM lead to the increases of O_3 outflow fluxes throughout the troposphere over 30–45 ° N. Changes in O_3 concentrations also contribute to the changes in O_3 outflow; although the zonal winds are projected to increase north of 40 ° N in the upper troposphere during SON, the O_3 outflow fluxes are simulated to decrease because of the significant decreases of O_3 levels north of 40 °N in the upper troposphere (Fig. S1).

5.3 Effect of future changes in anthropogenic emissions alone

The annual outflow of O_3 through the vertical plane is simulated to increase by 7.9 % relative to the present-day value (Table 4) as a result of the changes in anthropogenic emissions alone (Met2000Emis2050 minus Met2000Emis2000). Considering that the O_3 outflow with changes in anthropogenic emissions alone exhibits an increasing trend of 1.2 % decade^{-1} over 1986–2006 (Sect. 4.2), the increasing trend of 1.2 % decade^{-1} (i.e., 6.0 % half-century^{-1}) is close to the value of 7.9 % over the future half-century.

The projected future O_3 fluxes show increases during all seasons, which can be attributed to the increases in O_3 concentrations at all altitudes over Asia and upwind regions (i.e., Europe and Central Asia; Fig. S1) as a result of the increases in anthropogenic emissions of the O_3 precursors (NO_x and NMVOCs) and CH_4 concentrations. NO_x emissions in 2050 are projected to increase by 159.6% over Asia and by 78.4% globally, while NMVOCs emissions are projected to increase by 118.6% over Asia and by 89.4% globally under the SRES A1B scenario (Table 1). The CH_4 mixing ratios are projected to increase by 37.1% relative to the present-day value. The largest increases of O_3 outflow fluxes are located in the middle-upper troposphere (Fig. 9c) owing to the strong westerlies located here. It is noted that, in spite of the significant increases of emissions, the simulated surface-layer O_3 concentrations show slight decreases over the North China Plain in DJF, which subsequently leads to the small decreases of O_3 outflow fluxes at the surface layer over 30–40 ° N. In DJF, biogenic VOC emissions are especially low over the North China Plain, whereas anthropogenic NO_x emissions are fairly high due to the residential heating, leading to a low VOCs/NO_x ratio in this region (Lou et al., 2010; Fu et al., 2012). Therefore, increases in NO_x emissions lead to decreases in surface-layer O_3 concentrations over the North China Plain.

5.4 Effect of future changes in both climate and anthropogenic emissions

The annual outflow of O_3 through the vertical plane is projected to increase by 12.2 % (Table 4) during 2000–2050 as a consequence of future changes in both climate and anthropogenic emissions (Met2050Emis2050 minus Met2000Emis2000). Climate change in DJF and SON slightly offsets the effects of changes in anthropogenic

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emissions, while climate change in MAM and JJA enhances the effects of variations in anthropogenic emissions. When considering future changes in both emissions and climate, the projected O_3 outflow fluxes show increases throughout almost the entire troposphere along 135 °E during all seasons (Fig. 9d).

6 Conclusions

We quantify the past and future changes in the O_3 outflow from East Asia using the global 3-D chemical transport model GEOS-Chem. The historical (1986–2006) simulations are driven by the assimilated GEOS-4 meteorological fields, and the future (2000–2050) simulations under the IPCC SRES A1B scenario are driven by the meteorological fields archived from GISS GCM 3. Sensitivity studies are conducted to examine the respective impacts of meteorological parameters and emissions on the variations in the outflow flux.

The TCO products retrieved from TOMS/SBUV are used to evaluate model performance in simulating tropospheric O_3. Simulated spatiotemporal distributions of TCO over China and the downwind regions agree fairly well with TOMS/SBUV measurements, which gives us confidence to simulate the temporal evolutions of Asian O_3 outflow. Simulated Asian O_3 outflow flux peaks in early spring, and reaches the nadir in summer. The maximum O_3 fluxes are located in the middle-upper troposphere.

The IAVs and decadal trends of Asian O_3 outflow are examined over 1986–2006. Simulated O_3 outflow fluxes showed large IAVs, but an insignificant decadal trend; with variations in both meteorological parameters and anthropogenic emissions, the seasonal APDM values were in the range of 4–9 % and the decadal trend was −2.2 % decade^{-1} (statistically insignificant). Sensitivity simulations showed that the large IAVs of the O_3 outflow fluxes were mainly caused by the variations in meteorological conditions, rather than the variations in anthropogenic and biomass burning emissions.

The decadal changes in Asian O_3 outflow are also examined during 2000–2050. The present-day annual O_3 flux through the vertical plane is calculated as 1877.1 Tg, which is projected to change over 2000–2050 by +2.0 %, +7.9 %, and +12.2 %, respectively, due to climate change alone, emissions change alone, and changes in both climate and emissions. During MAM and JJA, climate change plays a larger role in the future changes in O_3 outflow compared with emissions changes, owing to the significant increases in zonal winds during these two seasons. It is noted that climate change will aggravate the impacts of increases in anthropogenic emissions on the O_3 outflow from East Asia over 2000–2050 under the SRES A1B scenario.

These findings are helpful for understanding the temporal evolutions of tropospheric O_3 on different timescales in the downwind regions of East Asia. Observed IAVs of tropospheric O_3 on a relatively short timescale can be attributed to variations in meteorological parameters. Furthermore, conclusions from this study will have important implications

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for long-term air quality planning. Since future climate change will increase O_3 outflow from East Asia, extra efforts are needed to reduce anthropogenic emissions of O_3 precursors to offset the adverse effects caused by climate change.

7 Data availability

GEOS-Chem is an open-access model developed collaboratively at Harvard University and other institutes in North America, Europe, and Asia. The source codes can be downloaded from http://acmg.seas.harvard.edu/geos/. The TCO (tropospheric column O_3) data are retrieved from TOMS/SBUV; TOMS total O_3 measurements are available from http://toms.gsfc.nasa.gov; and SBUV stratospheric O_3 measurements are available from http://orbit-net.nesdis.noaa.gov/crad/sit/ozone. All data presented in this study are available upon request from the corresponding author.

Author contributions. H. Liao and J. Zhu conceived the study and designed the experiments. J. Zhu performed the simulations, carried out the data analysis, and prepared the manuscript. Y. Mao provided useful comments on the paper. Y. Yang and H. Jiang helped with performing the experiments.

Competing interests. The authors declare that they have no conflicts of interest.

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Table 1. Anthropogenic emissions[a] of O_3 precursors for the present day (year 2000) and future (year 2050, under the SRES A1B scenario).

Species	Global			Asian[b]		
	2000	2050	Change (%)	2000	2050	Change (%)
NO_x (Tg N yr^{-1})	33.4	59.6	+78.4	10.9	28.3	+159.6
CO (Tg CO yr^{-1})	1054.2	1332.0	+26.4	393.7	487.2	+23.7
NMVOCs (Tg C yr^{-1})	70.8	134.1	+89.4	28.5	62.3	+118.6
CH_4 (ppbv)	1750	2400	+37.1	1750	2400	+37.1

[a] Biomass burning emissions are included.

[b] Asia covers the domain of 60–150 °E, 10 °S–55 °N.

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Table 2. Natural emissions of O_3 precursors for the present day (year 2000) and future (year 2050, under the SRES A1B scenario).

Species	Global			Asian[a]		
	2000	2050	Change (%)	2000	2050	Change (%)
Lightning NO_x (Tg N yr^{-1})	4.8	5.7	+18.8	1.2	1.4	+16.7
Soil NO_x (Tg N yr^{-1})	6.7	7.7	+14.9	1.4	1.7	+21.4
Biogenic VOCs (Tg C yr^{-1})	614.5	750.2	+22.1	106.1	126.2	+18.9

[a] Asia covers the domain of 60–150 °E, 10 °S–55 °N.

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Table 3. Experimental design of the simulations for 1986–2006.

Simulation	Simulated years	Meteorological parameters	Anthropogenic emissions	CH_4 abundance	Biomass burning emissions
Met	1986–2006	Vary over 1986–2006	Fixed at 2006	Fixed at 2006	Turn off
Emis	1986–2006	Fixed at 2006	Vary over 1986–2006	Vary over 1986–2006	Turn off
MetEmis	1986–2006	Vary over 1986–2006	Vary over 1986–2006	Vary over 1986–2006	Turn off
MetEmisB[a]	1997–2006	Vary over 1997–2006	Vary over 1997–2006	Vary over 1997–2006	Vary over 1997–2006

[a] The MetEmisB simulation is conducted for 1997–2006 owing to the unavailability of biomass burning emissions before 1997.

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Table 4. Simulated present-day O_3 fluxes and projected changes from the present day (1996–2005) to the future (2046–2055) through the vertical plane along 135 °E from 20 °N to 55 °N, and from the surface to 100 hPa, due to future climate change alone, change in anthropogenic emissions alone, and changes in both climate and emissions.

	O_3 Fluxes[a]			
	Met2000Emis2000 (present day)	Met2050Emis2000 (climate)	Met2000Emis2050 (emissions)	Met2050Emis2050 (climate + emissions)
DJF	792.9	778.3 (−1.8%)	850.5 (+7.3%)	853.7 (+7.7%)
MAM	597.0	640.4 (+7.3%)	639.0 (+7.0%)	698.0 (+16.9%)
JJA	146.5	167.7 (+14.5%)	161.3 (+10.1%)	187.2 (+27.8%)
SON	340.7	327.8 (−3.8%)	374.1 (+9.8%)	368.1 (+8.0%)
Annual	1877.1	1914.1 (+2.0%)	2024.9 (+7.9%)	2106.9 (+12.2%)

[a] The units are Tg season^{-1} for seasonal fluxes and Tg yr^{-1} for annual fluxes. Values in parentheses are percentage changes relative to the present-day fluxes.

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Figure captions

Figure 1. Evolution of annual anthropogenic and biomass burning emissions summed over the globe and Asia (60–150 ° E, 10 ° S–55 ° N) for NO_x (Tg N yr^{-1}), CO (Tg CO yr^{-1}), and NMVOCs (Tg C yr^{-1}) over 1986–2006. Blue squares represent anthropogenic emissions, and red circles represent the sum of anthropogenic emissions and biomass burning emissions. The last panel shows the evolution of global CH_4 abundance (ppbv) during 1986–2006.

Figure 2. Evolution of annual natural emissions summed over the globe and Asia (60–150 ° E, 10 ° S–55 ° N) for lightning NO_x (Tg N yr^{-1}), soil NO_x (Tg N yr^{-1}), and biogenic VOCs (Tg C yr^{-1}) over 1986–2006.

Figure 3. Comparison of tropospheric column ozone (TCO, units: DU) from the MetEmisB simulation with those retrieved from TOMS/SBUV. Both the model results and the TOMS/SBUV retrievals are averaged over 1997–2005 (excluding year 2001). Also shown in (a) is the location of the meridional plane through which the Asian O_3 outflow flux is calculated.

Figure 4. Monthly and yearly variations of tropospheric column ozone (TCO, units: DU) retrieved from TOMS/SBUV (blue line) and simulated by MetEmisB (red line). Both the retrieved and simulated TCO values are averaged over the selected region (30–50 °N, 130–150 °E) in the western Pacific Ocean.

Figure 5. The pressure–latitude cross-sections along 135 ° E of the simulated seasonal O_3 outflow fluxes and zonal winds during four seasons averaged over 1997–2006 in the MetEmisB simulation. The O_3 mass fluxes are shown by shades (units: kg $season^{-1}$ m^{-2}), and winds are represented by contours (units: m s^{-1}). Positive fluxes represent eastward fluxes, and negative values represent westward fluxes.

Figure 6. Evolution of (a) annual O_3 outflow fluxes (Tg yr^{-1}) across the meridional plane along 135 ° E from 20 ° N to 55 ° N, and from the surface to 100 hPa, over 1986–2006 in the Met, Emis, and MetEmis simulations; (b) the associated deviations from the mean (%); and (c) deviations from the mean (%) of the detrended O_3 outflow fluxes. The deviation from the mean (DEV) is defined in Sect. 4.2.

Figure 7. The MAD and APDM values of the detrended seasonal and annual O_3 outflow fluxes across the meridional plane along 135 °E from 20 °N to 55 °N, and from the surface to 100 hPa, over 1986–2006 in Met, Emis, and MetEmis simulations. Both the MAD and APDM are defined in Sect. 4.2. The units of MAD are Tg $season^{-1}$ for seasonal fluxes and Tg yr^{-1} for annual fluxes.

Figure 8. The pressure–latitude cross-sections along 135 ° E of MAD values for detrended annual O_3 outflow fluxes and zonal winds over 1986–2006 in the Met, Emis, and MetEmis simulations. The MAD values for O_3 mass fluxes are shown by shades (units: kg yr^{-1} m^{-2}), and the MAD values for winds are represented by contours (units: m s^{-1}).

Figure 9. (a) The pressure–latitude cross-sections along 135 ° E of simulated present-day O_3 mass fluxes and zonal winds (Met2000Emis2000). Projected changes in O_3 mass fluxes and zonal winds from the present day (1996–2005) to the future (2046–2055) caused by (b) climate change alone (Met2050Emis2000 minus Met2000Emis2000); (c) changes in anthropogenic emissions alone (Met2000Emis2050 minus Met2000Emis2000); and (d) changes in both climate and anthropogenic emissions (Met2050Emis2050 minus Met2000Emis2000). The O_3 mass fluxes are shown by shades (units: kg $season^{-1}$ m^{-2}), and winds are represented by contours (units: m s^{-1}). The dotted areas are statistically significant at the 95 % level, as determined by a two-sample Student's *t*-test.

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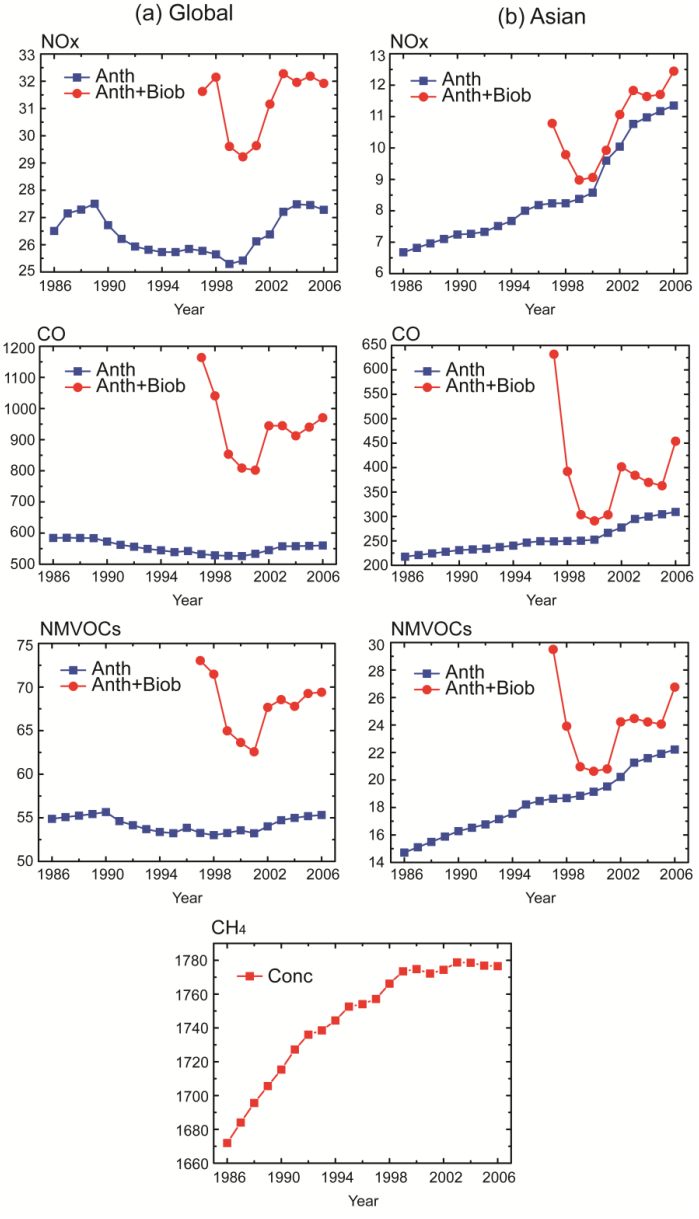

Figure 1. Evolution of annual anthropogenic and biomass burning emissions summed over the globe and Asia (60–150 ° E, 10 ° S–55 ° N) for NO_x (Tg N yr^{-1}), CO (Tg CO yr^{-1}), and NMVOCs (Tg C yr^{-1}) over 1986–2006. Blue squares represent anthropogenic emissions, and red circles represent the sum of anthropogenic emissions and biomass burning emissions. The last panel shows the evolution of global CH_4 abundance (ppbv) during 1986–2006.

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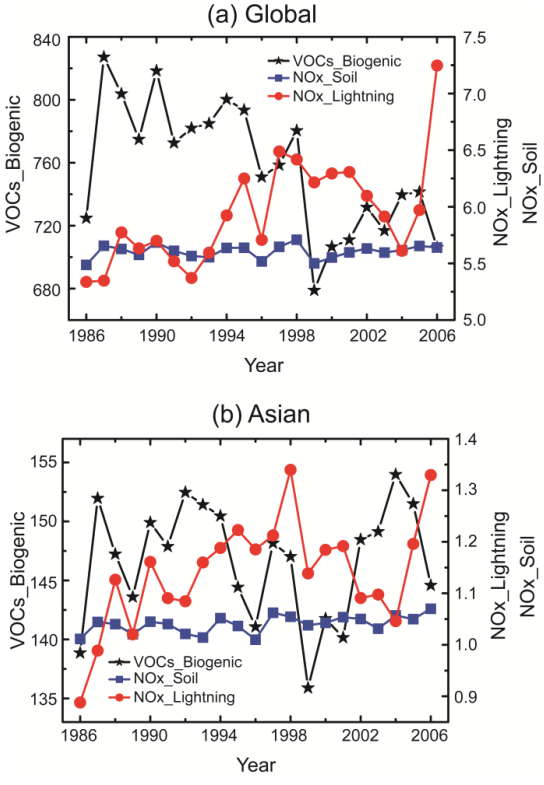

Figure 2. Evolution of annual natural emissions summed over the globe and Asia (60–150 ° E, 10 ° S–55 ° N) for lightning NO_x (Tg N yr^{-1}), soil NO_x (Tg N yr^{-1}), and biogenic VOCs (Tg C yr^{-1}) over 1986–2006.

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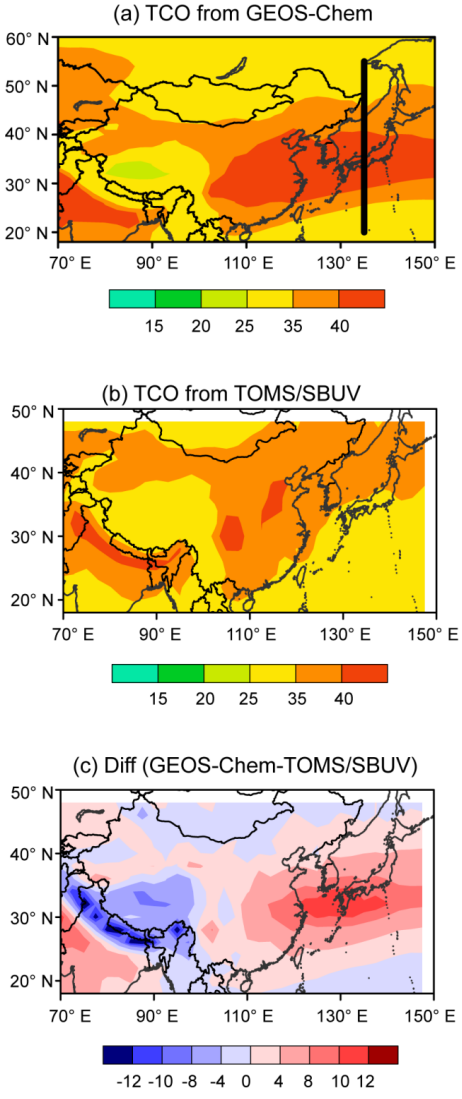

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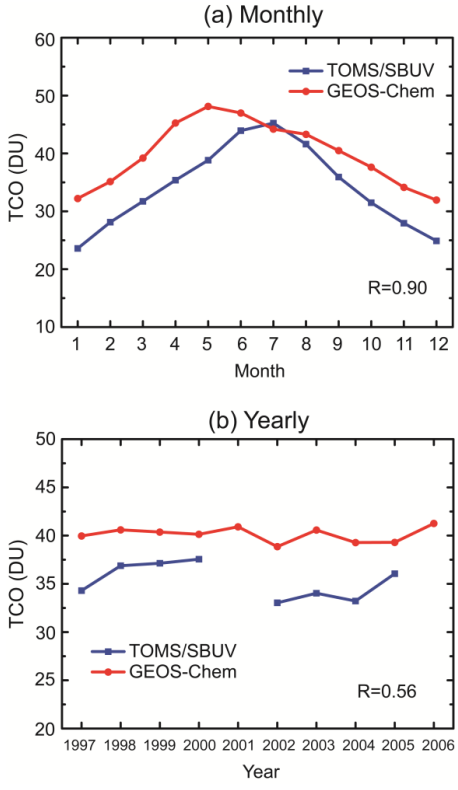

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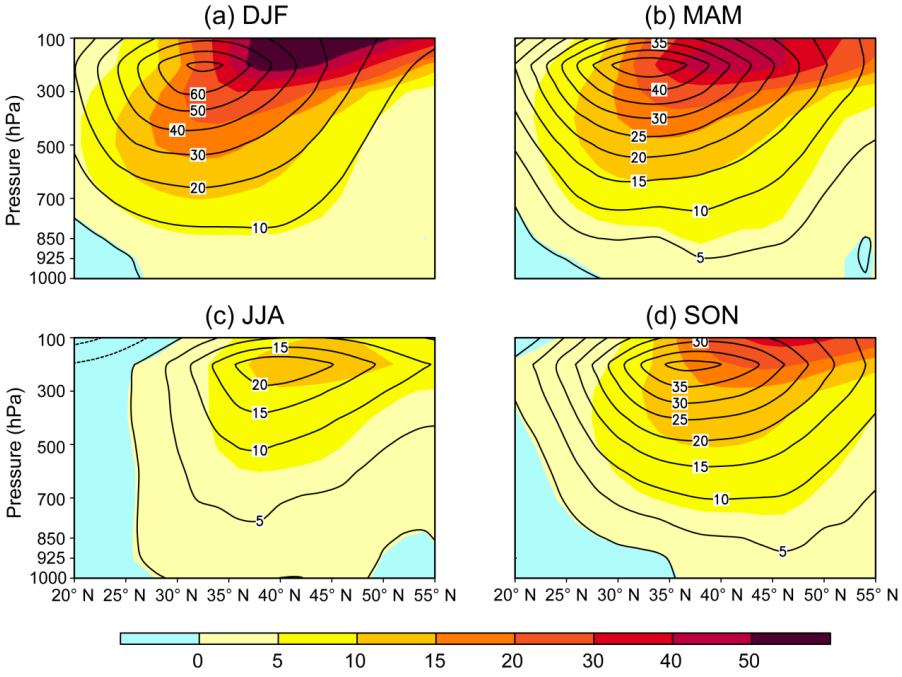

Figure 5. The pressure–latitude cross-sections along 135 ° E of the simulated seasonal O_3 outflow fluxes and zonal winds during four seasons averaged over 1997–2006 in the MetEmisB simulation. The O_3 mass fluxes are shown by shades (units: kg season^{-1} m^{-2}), and winds are represented by contours (units: m s^{-1}). Positive fluxes represent eastward fluxes, and negative values represent westward fluxes.

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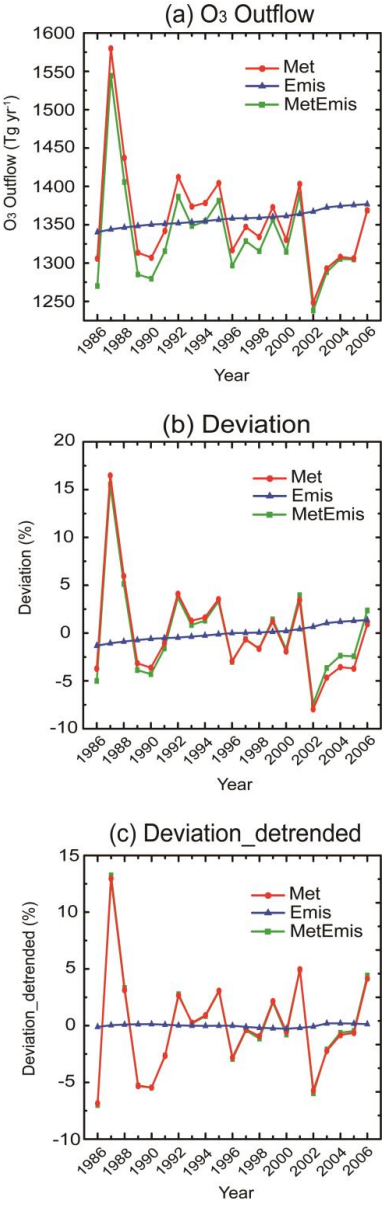

Figure 6. Evolution of (a) annual O_3 outflow fluxes (Tg yr^{-1}) across the meridional plane along 135 °E from 20 °N to 55 ° N, and from the surface to 100 hPa, over 1986–2006 in the Met, Emis, and MetEmis simulations; (b) the associated deviations from the mean (%); and (c) deviations from the mean (%) of the detrended O_3 outflow fluxes. The deviation from the mean (DEV) is defined in Sect. 4.2.

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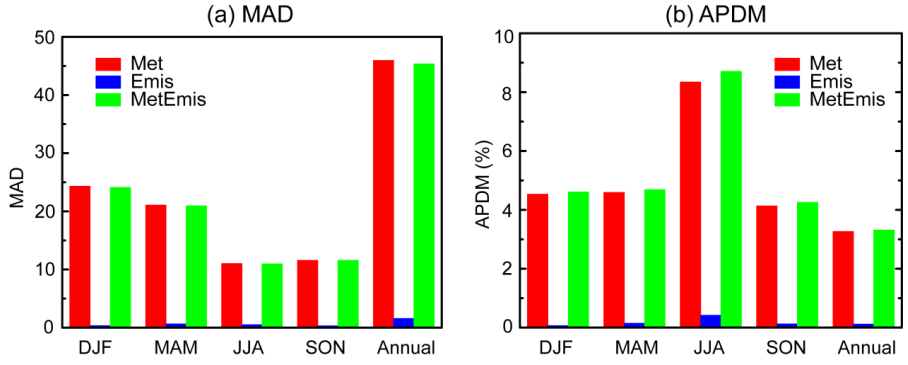

Figure 7. The MAD and APDM values of the detrended seasonal and annual O_3 outflow fluxes across the meridional plane along 135 °E from 20 °N to 55 °N, and from the surface to 100 hPa, over 1986–2006 in Met, Emis, and MetEmis simulations. Both the MAD and APDM are defined in Sect. 4.2. The units of MAD are Tg season^{-1} for seasonal fluxes and Tg yr^{-1} for annual fluxes.

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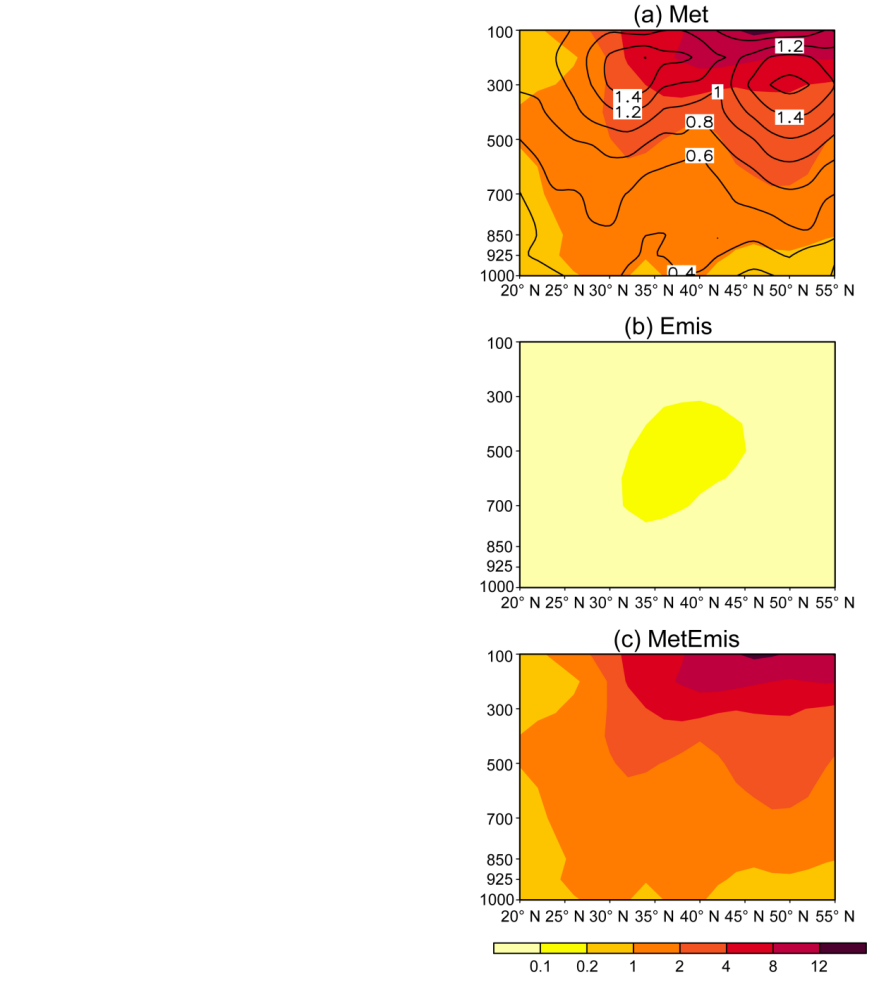

Figure 8. The pressure–latitude cross-sections along 135 °E of MAD values for detrended annual O_3 outflow fluxes and zonal winds over 1986–2006 in the Met, Emis, and MetEmis simulations. The MAD values for O_3 mass fluxes are shown by shades (units: kg yr^{-1} m^{-2}), and the MAD values for winds are represented by contours (units: m s^{-1}).

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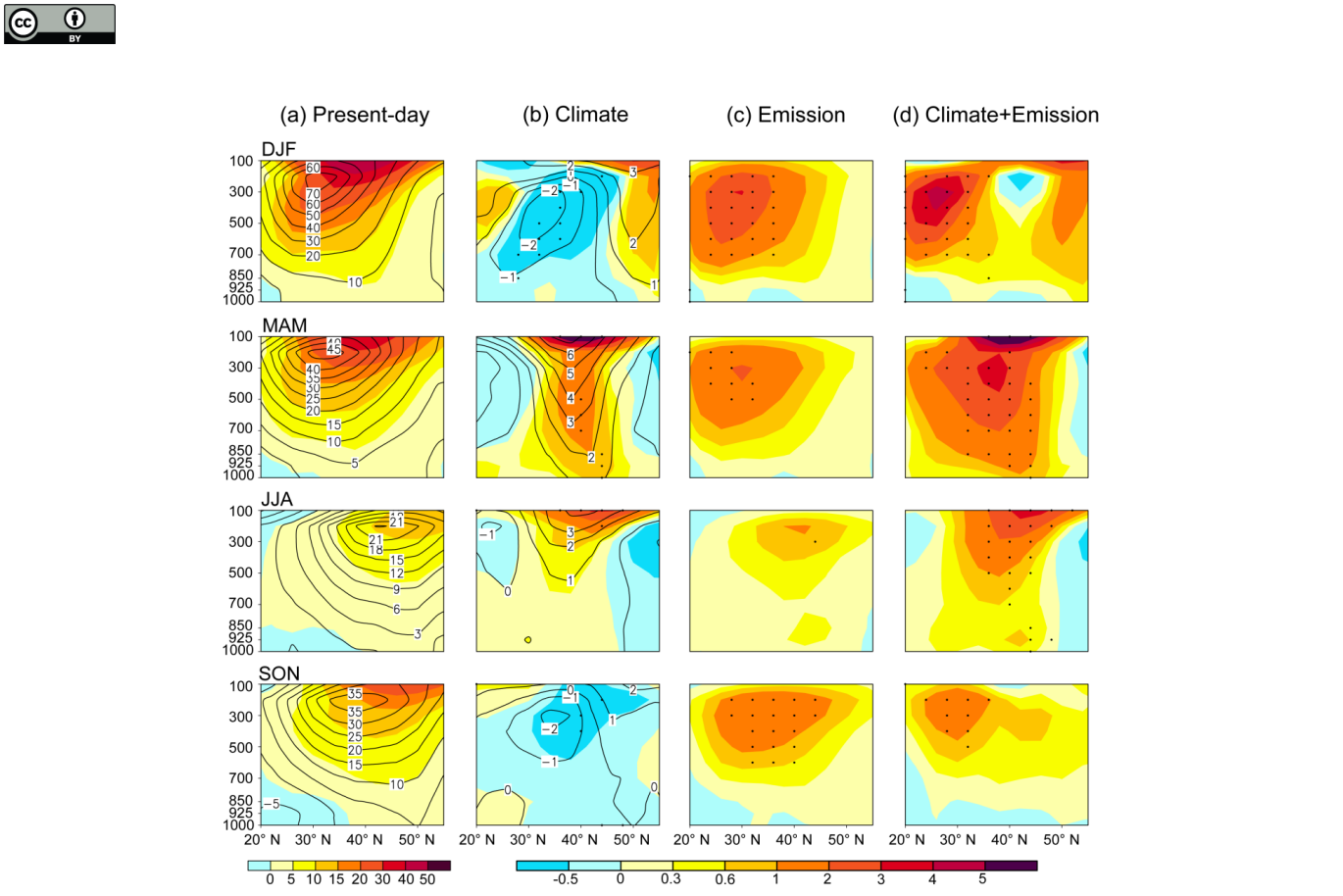

Figure 9. (a) The pressure–latitude cross-sections along 135 °E of simulated present-day O_3 mass fluxes and zonal winds (Met2000Emis2000). Projected changes in O_3 mass fluxes and zonal winds from the present day (1996–2005) to the future (2046–2055) caused by (b) climate change alone (Met2050Emis2000 minus Met2000Emis2000); (c) changes in anthropogenic emissions alone (Met2000Emis2050 minus Met2000Emis2000); and (d) changes in both climate and anthropogenic emissions (Met2050Emis2050 minus Met2000Emis2000). The O_3 mass fluxes are shown by shades (units: kg season^{-1} m^{-2}), and winds are represented by contours (units: m s^{-1}). The dotted areas are statistically significant at the 95 % level, as determined by a two-sample Student's *t*-test.