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# Projected Changes in $NO_x$ Emissions from Lightning as a Result of 2000–2050 Climate Change

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**Abstract** Lightning is one of the most important natural sources of atmospheric $NO_x$. The authors investigate the 2000–2050 changes in $NO_x$ emissions from lightning using the global three-dimensional Goddard Earth Observing System chemical transport model (GEOS-Chem) driven by meteorological fields from the Goddard Institute for Space Studies (GISS) general circulation model (GCM) 3. Projected changes in climate over 2000–2050 are based on the Intergovernmental Panel on Climate Change (IPCC) A1B scenario. The global $NO_x$ emission from lightning is simulated to be 4.8 Tg N in present day and to increase by about 16.7% over 2000–2050 as a result of the future climate change. The largest present-day emissions and climate-induced changes are found in the upper troposphere in the tropics. Regionally in eastern China (20–55°N, 98–125°E), $NO_x$ emissions from lightning is simulated to be 0.3 Tg N (6.3% of the global total emission) in present day and to increase by 26.7% over 2000–2050. The simulated changes in $NO_x$ from lightening correspond well with the projected future changes in convective precipitation.

**Keywords:** $NO_x$, lightning, climate change

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## 1 Introduction

Lightning is an important natural source of $NO_x$ (NO and $NO_2$) (Ridley et al., 1996, DeCaria et al., 2000). Although lightning accounts for only about 15% of the $NO_x$ input into the troposphere (Bradshaw et al., 2000), lightning $NO_x$ is found primarily in the upper troposphere (Pickering et al., 1998) where its lifetime is longer and its ozone producing potential is greater than $NO_x$ in the boundary layer (Liu et al., 1987, Pickering et al., 1990). Previous studies have shown that the production of tropical tropospheric ozone is primarily driven by $NO_x$ from lightning (e.g., Sauvage et al., 2007, Ziemke et al., 2009). Global estimates of present-day $NO_x$ from lightning range from 1 to 20 Tg N $yr^{-1}$, with a most probable range of 2–8 Tg N $yr^{-1}$ (Schumann and Huntrieser, 2007). Estimate of future emissions of $NO_x$ from lightning is important for understanding future changes in tropospheric ozone.

Lightning occurs mainly over land, with an average land/ocean ratio of 6–10 derived from the Lightning Imaging Sensor (LIS) satellite data over 1997–2002 and the Optical Transient Detector (OTD) satellite data over 1995–2000 (National Aeronautics and Space Administration (NASA)'s Global Hydrology and Climate Center at Marshall Space Flight Center, 2006). The LIS/OTD satellite data from the High Resolution Monthly Climatology (HRMC) v2.2 show that the maximum lightning densities are located over central Africa, South America, the Indo-China Peninsula, and Indonesia (Murray et al., 2012). Climate change is expected to influence emissions of $NO_x$ from lightning. For example, Grenfell et al. (2003) reported that global $NO_x$ from lightning increases from 4.89 Tg N $yr^{-1}$ to 6.86 Tg N $yr^{-1}$ in a doubled $CO_2$ simulation using the Goddard Institute for Space Studies (GISS) general circulation model (GCM). Brasseur et al. (2006) estimated an approximately 20% increase in $NO_x$ production from lightning over 2000–2100 in the Model for Ozone and Related Tracers (MOZART). Zeng et al. (2008) also found that lightning-produced $NO_x$ increases by about 20% in the doubled $CO_2$ climate using the chemistry-climate module of the United Kingdom Met Office's Unified Model (UM_CAM). However, few previous studies examined the spatial distributions of the changes in $NO_x$ from lightning as a result of future climate change.

We present here a study to estimate the 2000–2050 changes in $NO_x$ emissions from lightning following the Intergovernmental Panel on Climate Change (IPCC) Scenario A1B. The GISS Model 3 global meteorological fields are used to drive the global three-dimensional Goddard Earth Observing System chemical transport model (GEOS-Chem) to simulate $NO_x$ emissions from lightning for both present day (1999–2001) and years 2049–2051.

## 2 Methods

### 2.1 GEOS-Chem/GISS model description

The atmospheric chemical transport model, GEOS-Chem (v.7-4-11, http://acmg.seas.harvard.edu/geos/) is driven by the GISS Model 3 meteorological data (Rind et al., 2007). Both the GISS Model 3 and GEOS-Chem have a horizontal resolution of 4° latitude by 5° longitude with 23 vertical layers. The interface between GEOS-Chem

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and the GISS meteorological fields has been described by Wu et al. (2007), Pye et al. (2009), and Jiang et al. (2013). The GEOS-Chem model includes coupled ozone-NO$_x$-hydrocarbon and aerosol chemistry (Jiang et al., 2013). Present-day meterological fields from the NASA GISS Model 3 were simulated with greenhouse gas levels corresponding to years 1999–2001. Year 2049–2051 climate was obtained from a simulation in which CO$_2$ and other greenhouse gases follow the IPCC A1B scenario. Warming under scenario A1B is generally predicted to be more pronounced than under scenario B1 and less pronounced than under A2 since A1B represents rapid growth with balanced energy use (IPCC, 2007).

### 2.2 Parameterization of the NO$_x$ emissions from lightning

Lightning NO$_x$ emission is parameterized in the GEOS-Chem model based on convective cloud-top height that relates to flash rates (Wang et al., 1998, Price and Rind, 1992). Lightning flash rates in global atmospheric models are usually parameterized as functions of proxies of deep convection. In the version of the GEOS-Chem model we use, the emissions of NO$_x$ from lightning are calculated by Price and Rind (1992):

$$\mathrm{LNO}_x = \mathrm{RFLASH}\times(((1-R_1)\times\mathrm{CICG}\times Z_2)+(R_1\times Z_1))$$
$$\times(\mathrm{FLASHRATE}\times 60)\times\mathrm{FLASHSCALE}$$

where LNO$_x$ is the total NO$_x$ molecules released from lightning. RFLASH is the number of NO$_x$ molecules per meter released per flash, which is assumed to be $2.073\times10^{22}$ molecules m$^{-1}$. FLASHRATE is the lightning flash rate (the flashes per minute) calculated as a function of convective cloud top height in the model, and FLASHSCALE is the scaling factor with a value of 15.0. The convective cloud top height is determined by temperature and convective updraft flux that are simulated from GISS Model 3. $R_1$ is calculated as $1.0/(1.0+2.7\times\sqrt{\mathrm{FLASHRATE}})$. CICG is the ratio of inter-cloud flashes to ground-cloud flashes with an assumed value of 1.0/3.0. $Z_1$ is the height from ground to the negative charge layer in meters and $Z_2$ is the height from the negative charge layer to cloud top in meters. Lightning is caused by the buildup of negative and positive electrostatic charges in clouds. The negative charges usually occur in the bottom of the cloud and may leap to the positive side of another cloud or to the ground. The negative charge layer is determined by simulated temperatures because observations have shown that negative layers generally occur as temperatures are less than 263 K (Williams, 1985).

### 2.3 Projected changes in convective precipitation over 2000–2050

We present convective precipitation because lightning is parameterized to be dependent on convective events in the atmosphere. Figure 1 shows the projected changes in convective precipitation from present day to year 2050 by the GISS Model 3. In present day, the convective precipitation occurs mainly in the tropical regions, with the maximum precipitation found over the Bay of Bengal in June-July-August (JJA) and over Indonesia in December-January-February (DJF). These patterns of convective precipitation correspond to those of 1997–2001 precipitation in study of Adler et al. (2003). The maximum convective precipitation in China is simulated to occur in eastern China in March-April-May (MAM) and JJA. Convective precipitation is simulated to generally increase over 2000–2050, with the most significant increases in the tropics. Relative to present day, the year 2050 global total convective precipitation increases by about 5% in all seasons. Note that the projected patterns of precipitation changes (the increases in precipitation in northern China in DJF and the increases in precipitation in eastern China in JJA) from the GISS Model 3 generally agree with those from the IPCC AR4 multi-model predictions for China under the A1B scenario (IPCC, 2007).

### 2.4 Simulations

We perform simulations of NO$_x$ emissions from lightening for: (1) present-day climate (1999–2001) and (2) 2050 climate (2049–2051). Each case is integrated for three years (1999–2001 or 2049–2051) following one year of model spin-up. All results presented in this paper are three-year averages.

## 3 Projected 2000–2050 changes in NO$_x$ emissions from lightning

The simulated present-day global annual emission of NO$_x$ from lightning is 4.8 Tg N (Table 1), which agree closely with the value of 5.8 Tg N yr$^{-1}$ reported in Murray et al. (2012). The simulated horizontal distributions of the present-day seasonal mean NO$_x$ emissions from lightning are shown in Fig. 2a. Corresponding to the strong convective precipitation in present day, the present-day NO$_x$ emissions from lightning locate mainly over the tropical countries in South America, Africa, and South Asia. The present-day global and seasonal total NO$_x$ emission is the largest (1.37 Tg N) in JJA and the smallest (1.14 Tg N) in DJF. The maximum NO$_x$ emissions in South America are simulated to occur in DJF and MAM, and those in Africa and Indo-China Peninsula are found in JJA. The simulated present-day spatial distributions of NO$_x$ emissions from lightning in our study agree with those reported in Sauvage et al. (2007). To see the vertical distributions of NO$_x$ emissions from lightning, the altitude-longitude cross sections of the simulated NO$_x$ emissions averaged from 20°S to 20°N are shown in Fig. 3. The maxima of NO$_x$ emissions from lightning are found in the upper troposphere. Our simulated vertical distributions of NO$_x$ emissions are similar to those reported in Pickering et al. (1998), Ott et al. (2010), and Murray et al. (2012).

The projected year 2050 global annual emission of NO$_x$ from lightning is 5.6 Tg N (Table 1), which is a 16.7% increase relative to present day. Figure 2b shows the changes in lightening NO$_x$ emissions over 2000–2050. The global seasonal NO$_x$ emissions increase in all seasons, with the largest increases of 0.31 Tg N (or 29.0%) in September-October-November (SON) and 0.22 Tg N (or

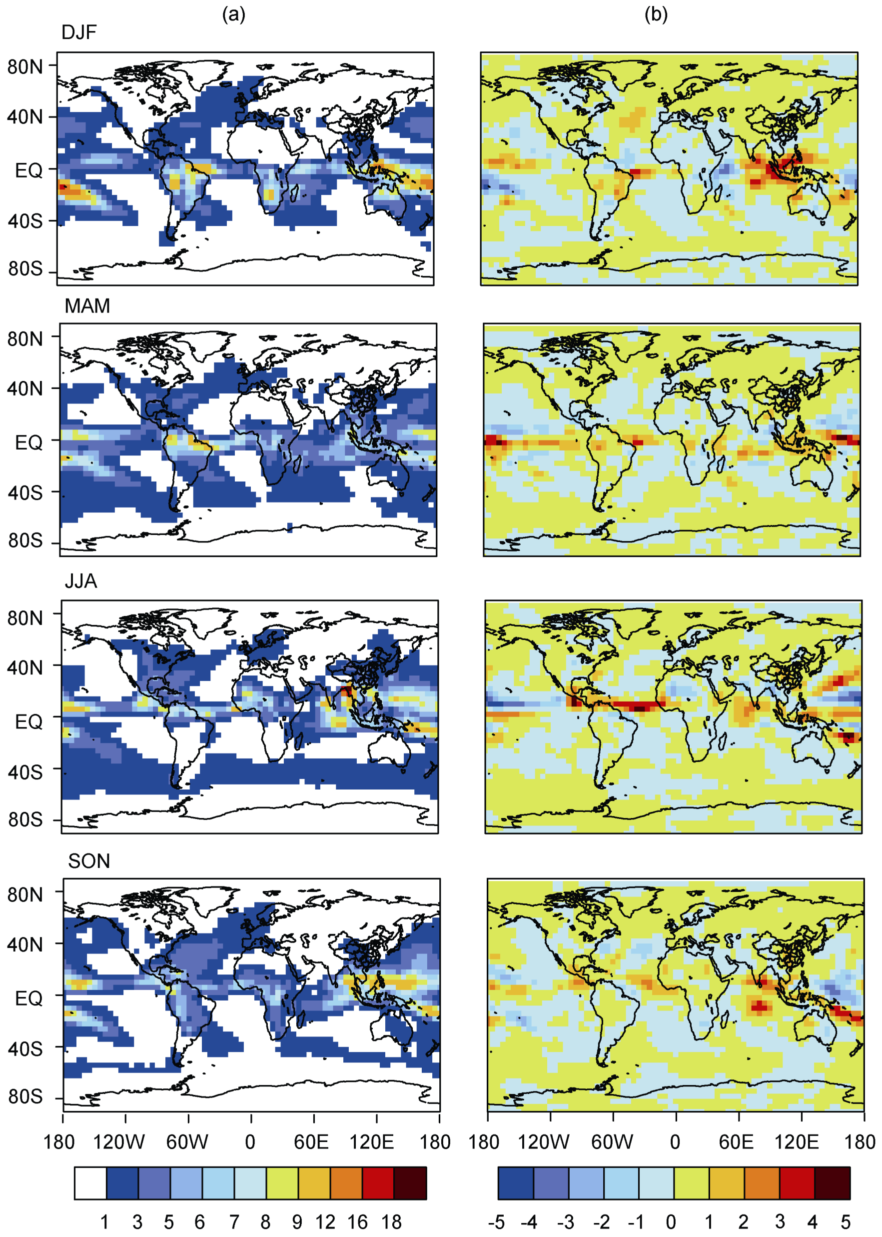

**Figure 1** Simulated convective precipitation (mm d$^{-1}$) in present day (column (a)); projected changes in convective precipitation (mm d$^{-1}$) from present day (1999–2001) to future (2049–51) under the IPCC A1B scenario (column (b)).

**Table 1** Simulated changes in emissions of NO$_x$ from lightning due to predicted climate change (IPCC A1B Scenario) in eastern China (20–55°N, 98–125°E), South America (15°N–40°S, 35–80°W), Australia (15–40°S, 110–155°E), and Africa (35°N–30°S, 15°W–40°E).

| | NO$_x$ from lightning (Tg N yr$^{-1}$) | | |
|---|---|---|---|
| | 2000 | 2050 | Change, % |
| Global | 4.8 | 5.6 | +16.7 |
| Eastern China | 0.30 | 0.38 | +26.7 |
| South America | 1.61 | 1.92 | +19.3 |
| Australia | 0.53 | 0.67 | +26.4 |
| Africa | 1.81 | 2.14 | +18.2 |

16.1%) in JJA. Regionally, relative to present day, year 2050 NO$_x$ emissions in DJF and MAM are projected to increase by 30%–60% over Indonesia, Australia, southern Africa, and South America (Fig. 1). In JJA, the significant increases of 60%–120% in NO$_x$ emissions are projected over the eastern United States, northwestern South America, central Africa, and eastern China. In SON, similar increases in NO$_x$ emissions are projected over the southeastern United States, central Africa, India, eastern China, and Australia. These changes in NO$_x$ emissions are generally consistent with the changes in convective precipitation. The largest increases in NO$_x$ emissions in the tropics over 2000–2050 are simulated to occur in the upper troposphere where lightning NO$_x$ emissions are the greatest in present day (Fig. 3).

The present-day total emission of NO$_x$ from lightning in eastern China (20–55°N, 98–125°E) is simulated to be 0.30 Tg N, which is 6.3% of the global total emission. Over 2000–2050, NO$_x$ emission from lightning in eastern

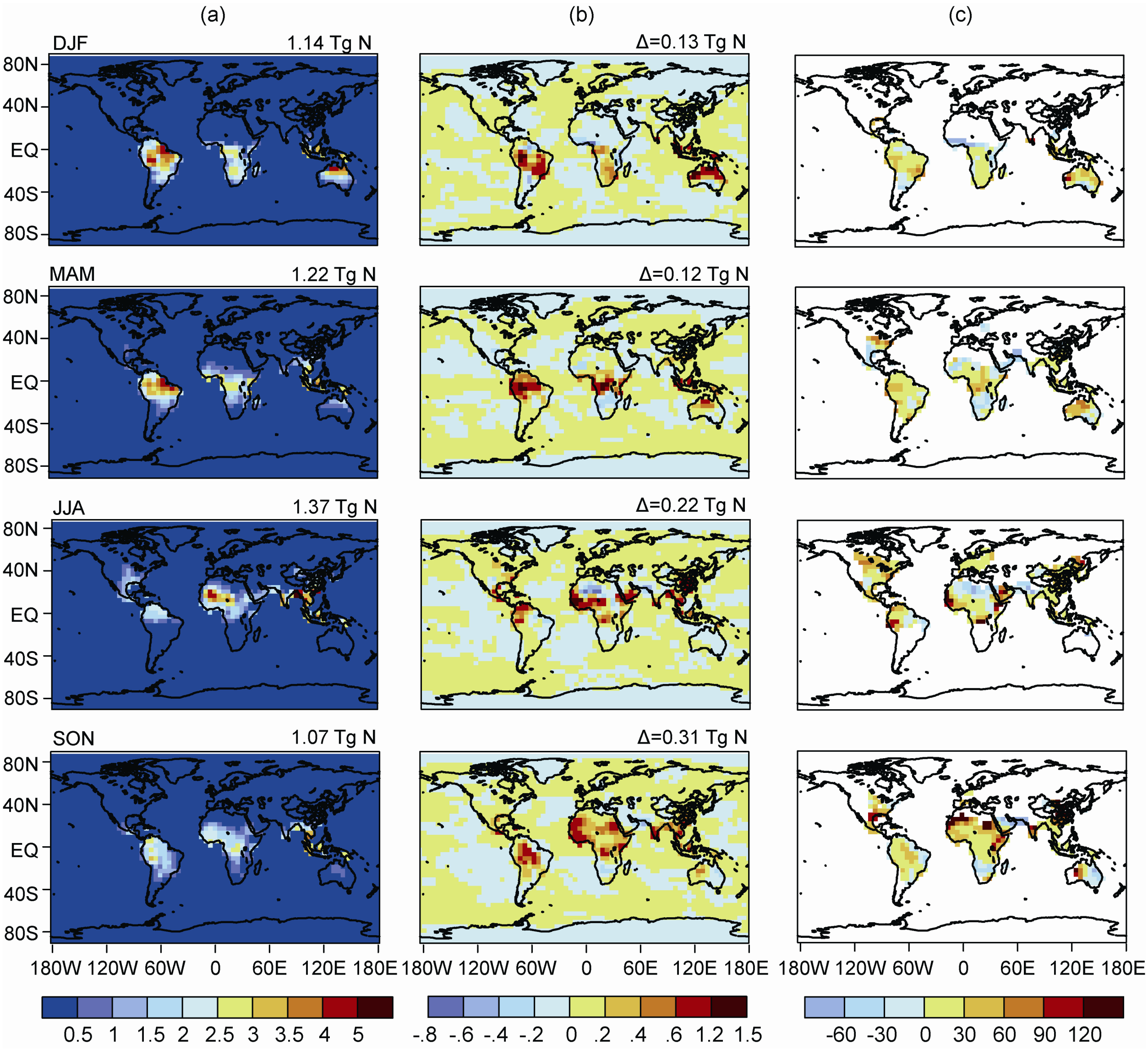

**Figure 2** Simulated present-day emissions of NO$_x$ from lightning (column (a)); projected changes in the emissions of NO$_x$ from lightning from present day (1999–2001) to future (2049–51) owing to climate change alone (units: $10^{-3}$ Tg) (column (b)); percentage changes in emissions of NO$_x$ from lightning relative to present-day values (column (c)). White areas represent those with negligible precipitation in present day.

China is estimated to increase by 26.7%, which is larger than the 16.7% increase predicted on the global scale. As mentioned above, both present-day and year 2050 NO$_x$ emissions in eastern China are the largest in MAM and JJA, corresponding well with the simulated future changes in convective precipitation in eastern China.

## 4 Conclusions and discussions

We estimate changes in NO$_x$ emissions from lightning over the period 2000–2050 by using the global chemical transport model GEOS-Chem with meteorological inputs from the GISS GCM 3. The simulated present-day annual emission of NO$_x$ from lightning is 4.8 Tg N on the global scale and 0.30 Tg N in eastern China. The present-day largest NO$_x$ emissions from lightning are simulated to occur mainly in the upper troposphere in the tropical regions, including South America, central Africa, and Indonesia. As a result of the increases in convective events over 2000–2050, the year 2050 annual emission of NO$_x$ from lightning is projected to increase by 16.7% on the global scale and by 26.7% in eastern China relative to present day, with the largest future increases occurring in JJA and SON. The 2000–2050 increases in NO$_x$ emissions from lightning are projected to occur not only in tropical regions but also in eastern United States and eastern China, which should be accounted for in simulation of future concentrations of tropospheric ozone.

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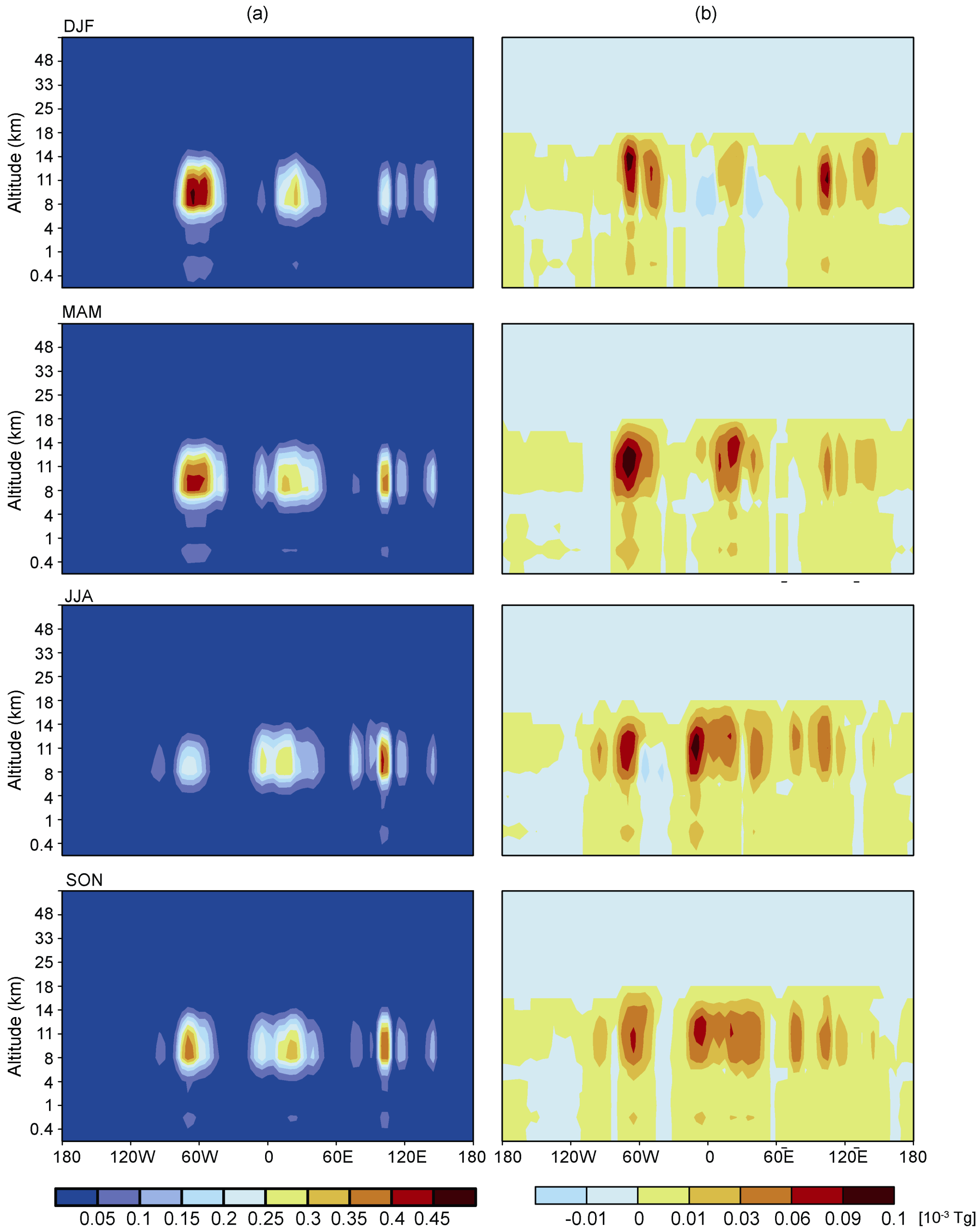

**Figure 3** Altitude-longitude cross section of $NO_x$ emissions from lightning in present day (1999–2001) (column (a)); altitude-longitude cross-section of the changes in $NO_x$ emissions from lightning from present day (1999–2001) to future (2049–51) owing to climate change alone (column (b)). Values are averaged over latitude range of 20°N–20°S.

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