

# The HNO<sub>3</sub> forming branch of the HO<sub>2</sub> + NO reaction: pre-industrial-to-present trends in atmospheric species and radiative forcings

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**Abstract.** Recent laboratory measurements have shown the existence of a HNO<sub>3</sub> forming branch of the HO<sub>2</sub> + NO reaction. This reaction is the main source of tropospheric O<sub>3</sub>, through the subsequent photolysis of NO<sub>2</sub>, as well as being a major source of OH. The branching of the reaction to HNO<sub>3</sub> reduces the formation of these species significantly, affecting O<sub>3</sub> abundances, radiative forcing and the oxidation capacity of the troposphere. The Oslo CTM2, a three-dimensional chemistry transport model, is used to calculate atmospheric composition and trends with and without the new reaction branch. Results for the present day atmosphere, when both temperature and pressure effects on the branching ratio are accounted for, show an 11 % reduction in the calculated tropospheric burden of O<sub>3</sub>, with the main contribution from the tropics. An increase of the global, annual mean methane lifetime by 10.9 %, resulting from a 14.1 % reduction in the global, annual mean OH concentration is also found. Comparisons with measurements show that including the new branch improves the modelled O<sub>3</sub> in the Oslo CTM2, but that it is not possible to conclude whether the NO<sub>y</sub> distribution improves. We model an approximately 11 % reduction in the tropical tropospheric O<sub>3</sub> increase since pre-industrial times, and a 4 % reduction of the increase in total tropospheric burden. Also, an 8 % decrease in the trend of OH concentrations is calculated, when the new branch is accounted for. The radiative forcing due to changes in O<sub>3</sub> over the industrial era was calculated as 0.33 W m<sup>-2</sup>, reducing to 0.26 W m<sup>-2</sup> with the new reaction branch. These results are significant, and it is important that this reaction branching is confirmed by other laboratory groups.

## 1 Introduction

Photochemical activity in the troposphere and lower stratosphere is strongly affected by the reaction



which is the major source of photochemically produced O<sub>3</sub> in the troposphere, through photodissociation of NO<sub>2</sub>, and a major source of OH through recycling of HO<sub>2</sub>. Changes in the concentration of OH lead to changes in methane lifetime, and the resulting change in methane concentration then amplifies the change in OH concentration, in a “feed-back cycle”.

Tropospheric O<sub>3</sub> has increased significantly since pre-industrial times, mainly due to increased emissions of NO<sub>x</sub> (i.e. NO + NO<sub>2</sub>), CH<sub>4</sub>, CO and non-methane hydrocarbons (NMHC) (IPCC, 2001). Both in situ O<sub>3</sub> production and transport from the surface play important roles in determining upper tropospheric O<sub>3</sub>. Berntsen et al. (1997), for example, found a ~35 % reduction in the tropospheric lifetime of O<sub>3</sub>, due to enhanced HO<sub>2</sub> levels, while Lamarque et al. (2005) found a reduction of ~30 %. Hauglustaine and Brasseur (2001) found increases of surface O<sub>3</sub> over industrialised areas in the northern mid-latitudes by more than a factor of 3.

Tropospheric OH is also affected by anthropogenic emissions: Increases in NO<sub>x</sub> and O<sub>3</sub> (via NO<sub>x</sub>) enhance OH, while increased levels of methane, CO, and hydrocarbons reduce OH levels. Model studies by e.g., Hauglustaine and Brasseur (2001); Shindell et al. (2003); Wong et al. (2004); Gauss et al. (2006) find a decrease of maximum 33 % in tropospheric OH levels since pre-industrial times, although other studies also find a non-decrease of OH (IPCC AR4, 2007).



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New information on the efficiency of Reaction (R1) will therefore not only have consequences for modelled distributions of O<sub>3</sub>, OH, and for the lifetime of methane, but will also influence the calculated trends in these species between pre-industrial times and the present.

Reaction (R1) is part of an efficient recycling of NO<sub>x</sub> compounds, going through a large number of cycles before the NO<sub>x</sub> is eventually converted to the less photochemically active species HNO<sub>3</sub>, and removed from the atmosphere. The efficiency of Reaction (R1) is highly dependent on altitude, latitude, and season.

The products of Reaction (R1) were examined by Butkovskaya et al. (2005), who showed that a minor fraction goes through the branch that forms HNO<sub>3</sub>:



Although they find that this branch only accounts for around 0.18–0.87 % of the products (at 298 K and 223 K, respectively), due to the large number of times NO<sub>x</sub> is recycled and passes through this reaction, the small branching ratio will still represent a significant loss. This pathway will therefore provide an important shortcut from NO to HNO<sub>3</sub>, reducing the abundance of NO<sub>2</sub>, and its contribution to O<sub>3</sub> and OH formation.

Beside the effect of temperature on the branching ratio, Butkovskaya et al. (2005) showed that the efficiency of the reaction increases in the presence of water vapour, more specifically by about 90 % at 3 Torr of H<sub>2</sub>O. Their study was extended by Butkovskaya et al. (2007), presenting the branching ratio of the HO<sub>2</sub> + NO reaction (in percent), as a function of air pressure (*P*, in Torr) and temperature (*T*, in Kelvin) below 298 K:

$$\beta(P, T) = (530 \pm 20)/T + (6.4 \pm 1.3) \times 10^{-4}P - (1.73 \pm 0.07) \quad (1)$$

The effect of water on the branching ratio was further investigated by Butkovskaya et al. (2009) at 298 K and 200 Torr. Unpublished results suggests that the pressure dependence is small while the temperature effect is uncertain at higher altitudes (Le Bras, 2011), therefore we will leave the H<sub>2</sub>O effect for later studies, and return to the topic in the conclusions.

Although to our knowledge these were the only experimental works which detected HNO<sub>3</sub> formation from Reaction (R2), a reaction modelling study by Chen et al. (2009), using the quasiclassical trajectory method, also predicts HNO<sub>3</sub> formation, and at a similar rate to that found by Butkovskaya et al. (2007).

The effects of Reaction (R2) on tropospheric and stratospheric chemistry were assessed by Cariolle et al. (2008), using a three dimensional tropospheric chemistry transport model (CTM) and a two dimensional stratosphere/troposphere CTM. They find substantial influence of the new reaction branch on tropospheric chemistry, including a 13 % mean global reduction in OH, a 5 % increase in methane lifetime and a 5–12 % decrease in tropospheric O<sub>3</sub>.

However, no radiative effects were calculated, and as only present day runs were performed, the effect on O<sub>3</sub> trends could not be investigated.

In the past, it has been shown that the Oslo CTM2, the model used in this study, has a high bias in O<sub>3</sub> concentrations, in the upper tropical troposphere (Søvde et al., 2008). A new reaction pathway by which the chemical production of O<sub>3</sub> is reduced has the potential to improve this bias, providing further motivation for this study.

The main focus of this study is on the changes in NO<sub>x</sub>, O<sub>3</sub>, OH, and the tropospheric lifetime of methane ( $\tau_{\text{CH}_4}$ ), leading to changes in the calculated trends of these species since pre-industrial times, and ultimately to changes in radiative forcing since pre-industrial times. In the next section, the Oslo CTM2 is described, and in Sect. 3 we discuss the effects of the new reaction branch on atmospheric composition. In Sect. 4 the model simulations are compared more closely to observations, whereas the radiative forcing estimates are discussed in Sect. 5. Section 6 provides a summary and conclusions.

## 2 The Oslo CTM2

The Oslo CTM2 is a three dimensional off-line chemistry transport model (Berntsen and Isaksen, 1997; Berglen et al., 2004; Isaksen et al., 2005; Søvde et al., 2008, 2011), which was run in T42 (approximately 2.8° × 2.8°) resolution for this study. Vertically, the model is divided into 60 layers between the surface and 0.1 hPa. The meteorological data used is from 3 h forecasts generated by running the Integrated Forecast System (IFS) of the European Centre for Medium Range Weather Forecasts (ECMWF), for the year 2000. Meteorological data is updated (off-line) in the CTM every 3 h, however the transport time step is determined by the Courant-Friedrichs-Lewy (CFL) criteria, with a basic operator splitting time step of 1 h. The advection of chemical species is calculated by the second-order moment method, which is able to maintain large gradients in the distribution of species (Prather, 1986). Convective transport of tracers is based on the convective upward flux from the ECMWF model, allowing for entrainment or detrainment of tracers depending on the changes in the upward flux. Turbulent mixing in the boundary layer is treated according to the Holtslag K-profile scheme (Holtslag et al., 1990). In both convective and large scale precipitation, soluble species are dissolved in available cloud water according to their solubility (Henry's law or mass limited), and transported downward, where they can evaporate or ultimately be removed at the surface.

In the configuration used here the model chemistry accounts for the most important parts of the O<sub>3</sub>-NO<sub>x</sub>-hydrocarbon chemistry cycle in the troposphere and includes a comprehensive stratospheric chemistry scheme. Stratospheric heterogeneous reactions on aerosols and polar stratospheric clouds (PSC) are accounted for, as is the removal of

**Table 1.** The model runs carried out in this study.

Model run	Description
REF_2000	Present day reference run, without Reaction (R2)
REF_1850	Pre-industrial reference run, without Reaction (R2)
R2_2000	Present day run, Reaction (R2) included
R2_1850	Pre-industrial run, Reaction (R2) included

HNO<sub>3</sub> through sedimentation of the PSC particles. For the chemistry calculations, the quasi steady state approximation (QSSA) chemistry solver (Hesstvedt et al., 1978) is used. Photochemical dissociation rates are taken from Sander et al. (2006) when available, otherwise we use data from IUPAC (Atkinson et al., 2010).

NO<sub>x</sub> emissions from lightning are coupled on-line to the convection in the model using the parameterisation proposed by Price and Rind (1993) as described by Berntsen and Isaksen (1999). Emissions of CFCs, HCFCs, N<sub>2</sub>O and other species with long tropospheric lifetimes are approximated with a constant lower boundary condition, according to WMO (2007). A list of chemical species, comprehensive model description and validation of ability of the Oslo CTM2 to reproduce the observed O<sub>3</sub> distribution is provided by Søvde et al. (2008). They also show that the model represents both the spatial and temporal variations of O<sub>3</sub> in the upper troposphere well, although the concentration is overestimated by up to 30–50%. As shown below, the inclusion of Reaction (R2) improves this bias.

The model experiments performed are listed in Table 1, and in the text below these experiments with and without Reaction (R2) are also referred to simply as R2 and REF, respectively, when the year is evident from the context. To avoid confusion, note that the new reaction is always referred to as "Reaction (R2)", and that simply "R2" refers to the model simulation. In all simulations we use meteorological data for the year 2000, so that the only differences between REF and R2 are related to the inclusion of the new reaction branch. Also the pre-industrial runs use the meteorological data from 2000, and we will discuss the uncertainty related to this later.

For the year 2000 model runs, anthropogenic emissions on a 1° × 1° grid were taken from the data base developed during the EU project POET (Precursors of Ozone and their Effects in the Troposphere) (Olivier et al., 2003; Granier et al., 2005). The methane surface mixing ratio was set to 1790 ppbv in the Northern Hemisphere, and 1700 ppbv in the Southern Hemisphere. The sum of hydrogen (H<sub>2</sub>O + 2CH<sub>4</sub> + H<sub>2</sub>) was set to 6.97 ppmv in the stratosphere, and used to calculate stratospheric H<sub>2</sub>O. The upper boundary conditions for all stratospheric species were taken from a year 2000 run of the Oslo 2-D CTM, as were the surface mixing ratios for species with long tropospheric lifetimes (i.e. those which do not need to be explicitly in-

cluded in the tropospheric chemistry scheme), as in Søvde et al. (2008).

In the pre-industrial runs, all anthropogenic emissions were switched off; only the natural emissions for the year 2000 were used (20% of biomass burning is assumed natural). The surface mixing ratio of methane was set to 791.6 ppbv, and the sum of stratospheric hydrogen was set to 5.08 ppmv. Similarly as in the year 2000 run, the upper and lower boundary conditions of stratospherically relevant species were prescribed by model output from a pre-industrial run of the Oslo 2-D model.

### 3 Results

The immediate response of Reaction (R2) is to reduce HO<sub>2</sub> available for NO<sub>2</sub> production by Reaction (R1). There are also secondary effects occurring, and in this section we present the effect of Reaction (R2) on NO<sub>2</sub>, HNO<sub>3</sub>, O<sub>3</sub>, CH<sub>4</sub>, and OH, as well as changes in trends since pre-industrial times.

#### 3.1 Effect of Reaction (R2) on NO<sub>2</sub>

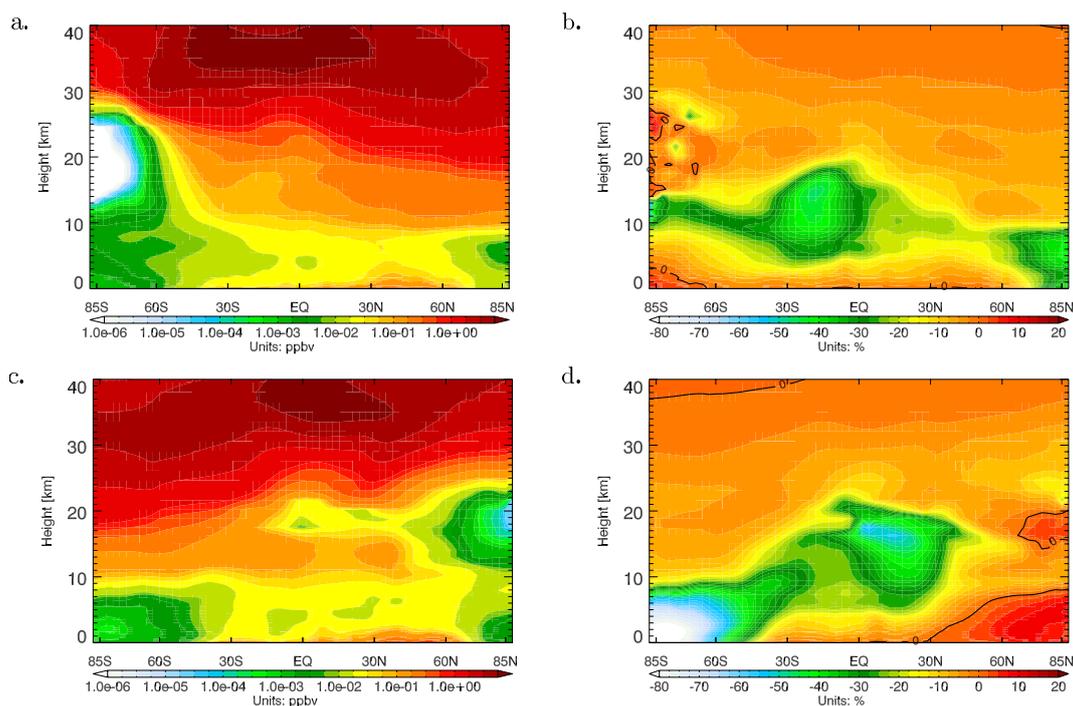
The July and December zonal monthly mean NO<sub>2</sub> mixing ratios for REF\_2000, in are shown in Fig. 1a, c, respectively. Corresponding percentage changes in NO<sub>2</sub> mixing ratio from REF\_2000 to R2\_2000 are shown in panels b and d. Mixing ratios in panels a and c are substantially higher in the stratosphere than the troposphere, and near the surface enhanced NO<sub>2</sub> values can be seen due to industrial emissions in the Northern Hemisphere. The lower values around 20 km over the Antarctic and Arctic, in July and December, respectively, are due to the formation of reservoir species such as HNO<sub>3</sub>, which are relatively stable in the low light conditions.

In panels b and d, the greatest percentage reduction in NO<sub>2</sub> mixing ratio as a result of the new reaction branch occurs between about 10 km and 20 km altitude in the tropical to mid-latitude regions. This was also predicted by Cariolle et al. (2008), however the reduction calculated here is around twice as large. Smaller effects are seen throughout the stratosphere. Below 10 km, there are also reductions of NO<sub>2</sub> of around 40% in July over the Arctic, and around 80% in December over the Antarctic. However, due to the low NO<sub>2</sub> mixing ratios in these regions, the change is not really important. The ~6% increase in NO<sub>2</sub> at high northern latitudes in December also involves small NO<sub>2</sub> mixing ratios, and comes about because the reduced OH from Reaction (R1) also leads to a reduction in the efficiency of the reaction



giving smaller NO<sub>2</sub> loss. In areas with more incident solar radiation this effect is not seen, due to higher OH abundances.

Because of the distribution of NO<sub>2</sub>, the most important effect of the new reaction branch is seen in the upper troposphere and lower stratosphere at low latitudes.



**Fig. 1.** The zonal mean NO<sub>2</sub> mixing ratio in REF\_2000, for July (a) and December (c). Panels (b) and (d) show the percent change in mixing ratio from REF\_2000 to R2\_2000, for July and December, respectively.

### 3.2 Effect of Reaction (R2) on HNO<sub>3</sub>

The July and December zonal monthly means of modelled gas phase HNO<sub>3</sub> are illustrated in Fig. 2a, c, respectively, showing well-known maximum values in the stratosphere. The low values over the Antarctic in July (panel a) are due to the sequestering of HNO<sub>3</sub> in PSC particles.

The inclusion of Reaction (R2) leads to a direct increase in HNO<sub>3</sub> mixing ratios in some areas. However, the new reaction branch also changes other processes affecting HNO<sub>3</sub>, making the effect of the reaction less intuitive.

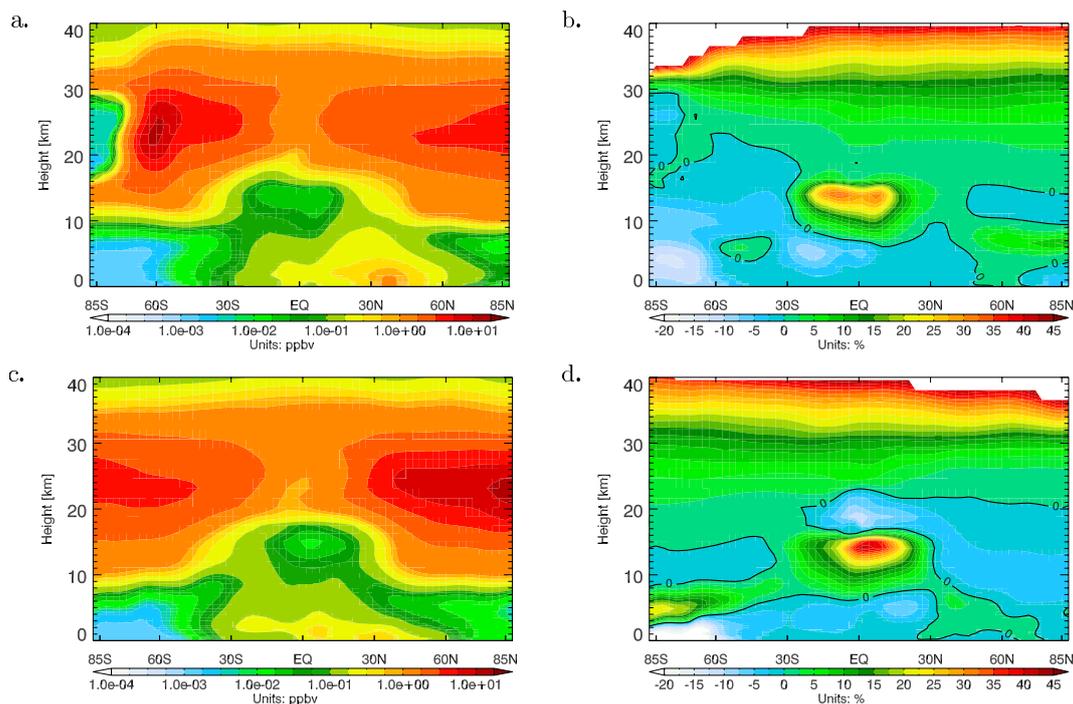
OH produced from Reaction (R1) is reduced due to Reaction (R2), in turn reducing the rate of HNO<sub>3</sub> production via Reaction (R3), giving a total reduction of HNO<sub>3</sub>. The influence of this can be seen in the troposphere at high latitudes. When more tropospheric HNO<sub>3</sub> is formed from Reaction (R1) in areas of wet deposition by rain, more HNO<sub>3</sub> will be rained out, reducing the availability of precursors for HNO<sub>3</sub> formation in other areas.

Percentage increases in HNO<sub>3</sub> are greatest in the tropics between 10 km and 20 km altitude, and in the stratosphere, above about 30 km (Fig. 2, panels b and d, respectively). In the Southern Hemisphere, in July, there is a reduction in HNO<sub>3</sub> of almost 20 % near the surface in R2\_2000 compared to REF\_2000, while there is a small increase over the Arctic (panel b). In December, there is a 15–20 % increase in HNO<sub>3</sub> at around 5 km over the Antarctic (panel d). These changes at 5–10 km over the polar regions come about as the

vertical HNO<sub>3</sub> gradient in this area is very high (see panels a and c), and in R2 the region of low HNO<sub>3</sub> is confined to slightly lower altitudes. The slight shift in the vertical position of the isolines creates a large percentage change. Also in December, the increase in HNO<sub>3</sub> above 10 km altitude in the tropics is paired with a decrease in HNO<sub>3</sub> of 10 % to 15 % at an altitude of ~20 km, again suggesting a vertical shifting of the HNO<sub>3</sub> distribution between the two runs, in addition to the extra HNO<sub>3</sub> production. This additional HNO<sub>3</sub> formed in the troposphere will be subject to wet deposition, reducing the amount of NO<sub>x</sub> and HNO<sub>3</sub> transported to higher altitudes, hence the decrease at ~20 km.

### 3.3 Effect of Reaction (R2) on OH and CH<sub>4</sub>

The tropospheric, annual mean OH concentration was calculated for the four model runs, and the results are shown in Table 2. The mean OH concentration calculated in REF\_2000 is slightly higher than the recent values listed in Wang et al. (2008), however a good agreement is reached when the new reaction branch is taken into account (R2\_2000). The reduction in the mean OH concentration, caused by Reactions (R1) and (R2), is about 13 % and 14 % for 1850 and 2000, respectively, similar to the approximately 13 % decrease calculated for the present day by Cariolle et al. (2008). From 1850 to 2000, the OH concentration declines by 12.1 % in the R2 cases, compared to 11.2 % in the REF cases.



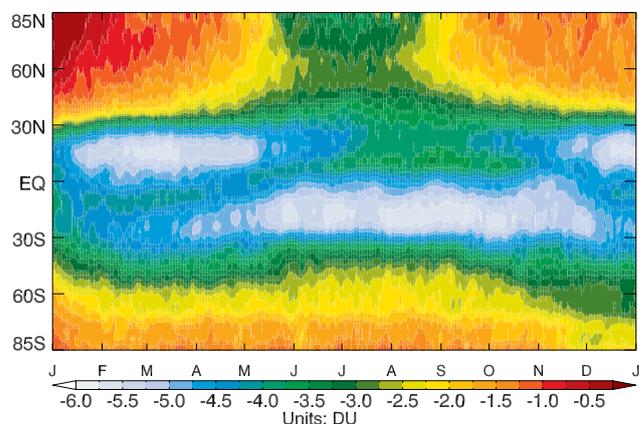
**Fig. 2.** The zonal mean HNO<sub>3</sub> mixing ratio in REF\_2000, for July (a) and December (c). Panels (b) and (d) show the percent change in mixing ratio from REF\_2000 to R2\_2000, for July and December, respectively.

The methane lifetime, being controlled predominantly by the concentration of OH, is around 10–11 % larger in the R2 cases than in the REF cases (Table 3). This is about twice the increase calculated by Cariolle et al. (2008) (ca. 5 %), however without performing a detailed model inter-comparison, it is not possible to say what the cause of this difference is. The OH reduction occurs due to several effects, the main ones being a direct effect from Reaction (R1) reducing NO<sub>x</sub> through Reaction (R2), and also a secondary effect from reduced O(<sup>1</sup>D) produced by the reduced O<sub>3</sub>. However, in this study we focus on the total change in OH and its effect on CH<sub>4</sub>.

The change in methane lifetime between REF\_1850 and REF\_2000 is 4.6 %, and the change between R2\_1850 and R2\_2000 is 4.0 %. Taking the new reaction branch into account leads to a significant decrease in the OH concentration, but also a greater decline of OH since pre-industrial times, leading to a greater calculated anthropogenic impact on the oxidising capacity of the atmosphere, and therefore the lifetime of methane.

### 3.4 Effect of Reaction (R2) on O<sub>3</sub>

The difference between the tropospheric zonal mean O<sub>3</sub> column for REF\_2000 and R2\_2000 is plotted as a function of time and latitude in Fig. 3. A zonal mean is representative due to small zonal variations between REF\_2000 and R2\_2000 (not shown). Reaction (R2) reduces this O<sub>3</sub> col-



**Fig. 3.** The change in zonal, tropospheric mean modelled O<sub>3</sub> column, between REF\_2000 and R2\_2000, as a function of time.

umn everywhere, with a maximum reduction of 5.8 DU. The main effect of the new reaction branch is seen in the tropics, with the smallest effect at polar latitudes. A reduction of up to about 3.5 DU occurs at high northern latitudes in July to August, which can be explained by the greater summer-time photodissociation leading to a more rapid removal of NO<sub>x</sub> through Reaction (R2). At high southern latitudes there is also a seasonal dependence. The smallest effect is seen at high northern latitudes in winter.

**Table 2.** The tropospheric, annual mean OH concentration (10<sup>6</sup> molec cm<sup>-3</sup>), for each of the model runs. The difference ( $\Delta$ ) between the R2 and REF runs is given in brackets. The last column shows the difference between the OH concentration in 2000 and 1850 for each run, with the effect of Reaction (R2) on this change given in brackets.

Model run	[OH], ( $\Delta$ from REF_2000)		$\Delta$
	1850	2000	
REF	1.52	1.35	-11.2 %
R2	1.32 (-13.2 %)	1.16 (-14.1 %)	-12.1 % (8.0 %)

**Table 3.** As for Table 2, except for tropospheric, annual mean CH<sub>4</sub> lifetime  $\tau_{\text{CH}_4}$ .

Model run	$\tau_{\text{CH}_4}$ (years), ( $\Delta$ from REF_2000)		$\Delta$
	1850	2000	
REF	6.71	7.02	4.6 %
R2	7.44 (10.3 %)	7.74 (10.9 %)	4.0 % (-13.0 %)

The July and December zonal monthly means of modelled O<sub>3</sub> from R2\_2000 are shown in Fig. 4 (panels a and c, respectively), with corresponding percentage changes between REF\_2000 and R2\_2000 shown in panels b and d.

The decrease in NO<sub>2</sub> between REF\_2000 and R2\_2000 leads to a reduction in O<sub>3</sub> formation, and therefore up to about 14–16 % lower O<sub>3</sub> values, predominantly in the upper tropical troposphere, although the percentage change in Fig. 4 is large throughout the troposphere. Again, the amount of O<sub>3</sub> in the middle and lower troposphere is small, as shown in panels a and c. There is a reduction in O<sub>3</sub> in the lower troposphere, at high northern and southern latitudes (panels b and d, respectively). Although the percentage change in panel d reduction is very large, O<sub>3</sub> levels in this region are low, therefore this change has a very small effect on mean tropospheric O<sub>3</sub> values. The small increase in O<sub>3</sub> at high latitudes, at an altitude of around 25 km, is due to the reduction in NO<sub>x</sub> induced O<sub>3</sub> loss.

We look more in detail on the budget and stratosphere to troposphere exchange (STE) of O<sub>3</sub> in the next section.

### 3.5 Effect on O<sub>3</sub> and NO<sub>y</sub> burden and O<sub>3</sub> STE

To quantify the change in O<sub>3</sub> and NO<sub>y</sub>, we calculate the tropospheric and stratospheric burdens (Table 4). We define the tropopause at 2.5 PVU (10<sup>-6</sup> m<sup>2</sup> s<sup>-1</sup> K kg<sup>-1</sup>) (Holton et al., 1995), with an upper limit of 380 K potential temperature and a somewhat arbitrary lower limit of 5 km (only occurs occasionally). The tropospheric O<sub>3</sub> burden for REF\_2000 is 349 Tg, close to the mean value presented by Stevenson et al. (2006), Reaction (R2) reduces the burden by 11 % (310 Tg), still within the range of Stevenson et al. (2006). For the pre-

industrial run, the corresponding values are 227 Tg and 9.9 % (204 Tg). O<sub>3</sub> burdens are also listed as global average Dobson Units.

The stratospheric O<sub>3</sub> burden is only slightly affected: in 2000 it is reduced by 0.13 %, while in the pre-industrial case it is increased by 0.26 %. The latter increase is due to Reaction (R2) reducing NO<sub>x</sub> and hence O<sub>3</sub> destruction, an effect that is overcompensated in 2000 by more efficient loss by halogens.

The amount of tropospheric NO<sub>y</sub> for 2000 is reduced by 4.5 % due to Reaction (R2), since more HNO<sub>3</sub> is available to be washed out of the atmosphere. For 1850 the reduction is 7.4 %, and the larger fraction mainly comes about because the lightning source is the same in our simulations, while surface NO<sub>x</sub> is much higher in 2000. Because the lightning source is predominantly located where Reaction (R2) is most effective, the relative change in NO<sub>y</sub> is larger in 1850.

A change in O<sub>3</sub> loading changes the stratosphere to troposphere exchange of O<sub>3</sub> (STE), however only to a small extent. In REF\_2000 the STE is 408 Tg yr<sup>-1</sup>, based on the same tropopause as described above. This value is somewhat lower than the estimate by Murphy and Fahey (1994), however, it should be noted that our methods differ and there are still uncertainties related to this number. Other model studies suggests higher STE through other methods (McLinden et al., 2000; Olsen et al., 2001; Hsu et al., 2005).

In R2\_2000, STE is 412 Tg yr<sup>-1</sup>, where the increase results from Reaction (R2) lowering the tropical upper troposphere O<sub>3</sub> and hence the upward flux to the stratosphere. STE being the net flux from the stratosphere to the troposphere, is then increased.

For the pre-industrial case, we model a higher STE, 533 Tg yr<sup>-1</sup>, increased to 534 Tg yr<sup>-1</sup> by Reaction (R2). The higher flux in 1850 is a result of a larger stratospheric O<sub>3</sub> burden due to lack of depleting halogen substances, and also due to less tropical tropospheric O<sub>3</sub> available for upwards transport.

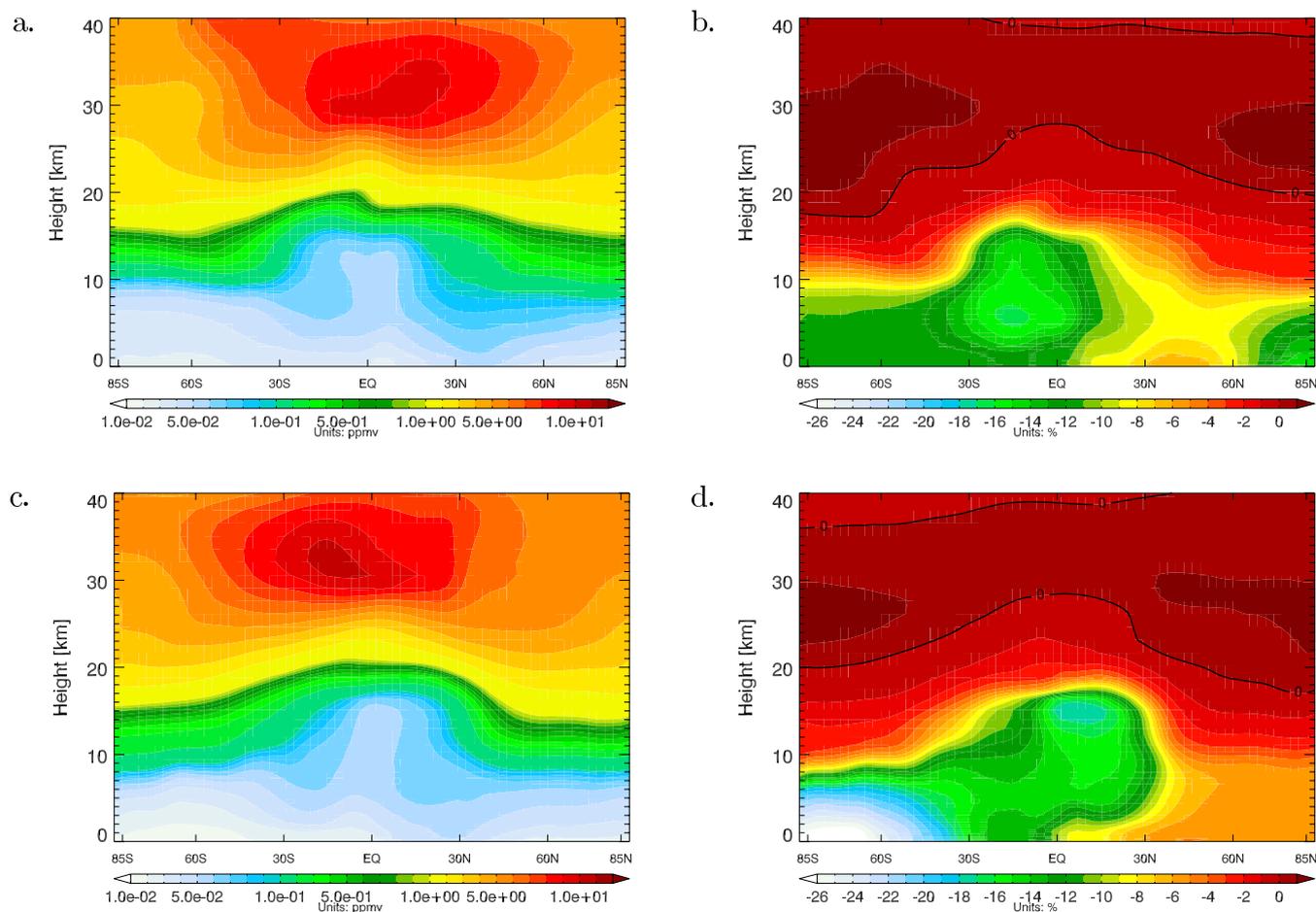
### 3.6 Effect on trends of tropical O<sub>3</sub>

Both in the pre-industrial runs and in the year 2000 runs, the O<sub>3</sub> mixing ratios were lower in R2 than in the REF case. The reduction is greater in the year 2000 runs, therefore the trend in O<sub>3</sub> mixing ratios since the pre-industrial times is also affected. From the global O<sub>3</sub> budgets in Table 4, the REF increase in O<sub>3</sub> is 54 % from pre-industrial to present, while for R2 the increase is 52 % (i.e. a 4 % reduction). In order to better quantify the effect of Reaction (R2) on O<sub>3</sub> trends since the pre-industrial times, we have calculated the changes in mixing ratios within a section of the tropical troposphere, where the greatest influence of Reaction (R2) was seen. This section extends between the approximate latitudes of 15° S to 15° N, and from approximately 5.5 km to 15 km in altitude.

Within this volume, the increase in O<sub>3</sub> between 1850 and 2000 for July was 52.7 % in the REF case, and 48.4 % in the

**Table 4.** Annual tropospheric and stratospheric budgets of O<sub>3</sub> and NO<sub>y</sub>. Units for O<sub>3</sub> are Tg(O<sub>3</sub>) and Dobson Units (DU) in parenthesis, while NO<sub>y</sub> is given as Tg(N). Note that these burdens are calculated using the model tropopause (as defined in the Sect. 3.5), while RF calculations use a slightly different tropopause (Sect. 5). As an example, the R2 tropospheric burden in RF calculations changes by 12.3 DU from 1850 to 2000, while the stratospheric burden changes by −33.3 DU.

Tropospheric burden of O <sub>3</sub> and NO <sub>y</sub>					
Model run	O <sub>3</sub> [Tg(O <sub>3</sub> )]	(O <sub>3</sub> [DU])	Δ from REF	NO <sub>y</sub>	Δ from REF
REF_2000	349	(32.1)		0.625	
R2_2000	310	(28.5)	−11.2 %	0.587	−4.5 %
REF_1850	227	(20.9)		0.267	
R2_1850	204	(18.8)	−9.9 %	0.247	−7.4 %
Stratospheric burden of O <sub>3</sub> and NO <sub>y</sub>					
Model run	O <sub>3</sub> [Tg(O <sub>3</sub> )]	(O <sub>3</sub> [DU])	Δ from REF	NO <sub>y</sub>	Δ from REF
REF_2000	2863	(263.5)		1.735	
R2_2000	2859	(263.1)	−0.13 %	1.722	−0.76 %
REF_1850	3189	(293.2)		1.538	
R2_1850	3197	(294.1)	0.26 %	1.527	−0.70 %



**Fig. 4.** The zonal mean O<sub>3</sub> mixing ratio in REF\_2000, for July (a) and December (c). Panels (b) and (d) show the percent change in mixing ratio from REF\_2000 to R2\_2000, for July and December, respectively.

R2 case, leading to a difference in O<sub>3</sub> increase of −8.1 %. Averaged over the whole year, the change in O<sub>3</sub> trend is −11.1 %.

As already mentioned, the change in tropical O<sub>3</sub> affect STE slightly, and the relative impact of Reaction (R2) is larger in 2000 than in 1850.

The 1850 study is carried out with meteorology for the year 2000, for which the stratosphere was colder than usual (Randel et al., 2004). A colder upper troposphere and lower stratosphere (UTLS) is expected to be a result of global warming, suggesting that the pre-industrial UTLS temperatures may have been higher. Since Reaction (R2) is more effective at low temperatures, it can be argued that the effect on the trend also depends on the UTLS temperature trend.

#### 4 Comparison with measurements

In Sect. 3 we have shown the effects of Reaction (R2), and these effects must be evaluated against observations. We do this by comparing model results to satellite measurements as well as in-situ measurements. First we compare O<sub>3</sub>, then nitrogen species.

##### 4.1 Modelled and measured O<sub>3</sub>

In order to confirm that the model represents the observed O<sub>3</sub> fields correctly, monthly averages of modelled total column O<sub>3</sub> (R2\_2000) are plotted in Fig. 5, along with the average total column O<sub>3</sub> measured by the Total Ozone Mapping Spectrometer (TOMS), for January, April, July and October. For most months, and over most of the globe, the agreement between the modelled and the measured values is excellent. In January, the model overestimates the column O<sub>3</sub> west of Europe, and over the Antarctic, and slightly underestimates the values over the tropics, however the main features of the column O<sub>3</sub> distribution are captured well. In April and July, there is very little difference between the modelled and measured columns, with slightly lower values in the model in the tropics and slightly higher values at mid-latitudes in the Southern Hemisphere, than in the TOMS data. In October, the column values to the west of Europe as well as over North America and Northern Africa are again slightly overestimated by the model, however, the magnitude and extent of the Antarctic O<sub>3</sub> hole is well represented. As explained in Sect. 3.4, the zonal mean effect of Reaction (R2) shown on Fig. 3 can roughly be transferred to Fig. 5, and it can be argued that both REF\_2000 and R2\_2000 compare well with TOMS.

We have also produced modelled O<sub>3</sub> profiles at the time and location of all O<sub>3</sub>-sondes at 11 stations within the framework of SHADOZ (Thompson et al., 2003). These stations are located predominantly in the tropics, where Reaction (R2) has the largest effect, and are listed in Table 5, including the number of sondes through the year. Annual av-

**Table 5.** Locations of SHADOZ stations used for the mean profile in Fig. 6. #prof is the number of profiles used in mean values.

Name	longitude (° E)	latitude (° N)	#prof.
American Samoa	189.44	−14.23	40
Ascension	345.58	−7.98	31
Fiji	178.40	−18.13	38
Irene	28.22	−25.90	40
Java, Watukosek	112.65	−7.57	44
Kuala Lumpur	101.70	2.73	25
La Réunion	55.48	−21.06	37
Nairobi	36.80	1.27	39
Natal	324.62	−5.42	34
Paramaribo	304.79	5.81	48
San Cristóbal	270.40	−0.92	56
Total			432

erages of measured and modelled O<sub>3</sub> profiles are shown in Fig. 6.

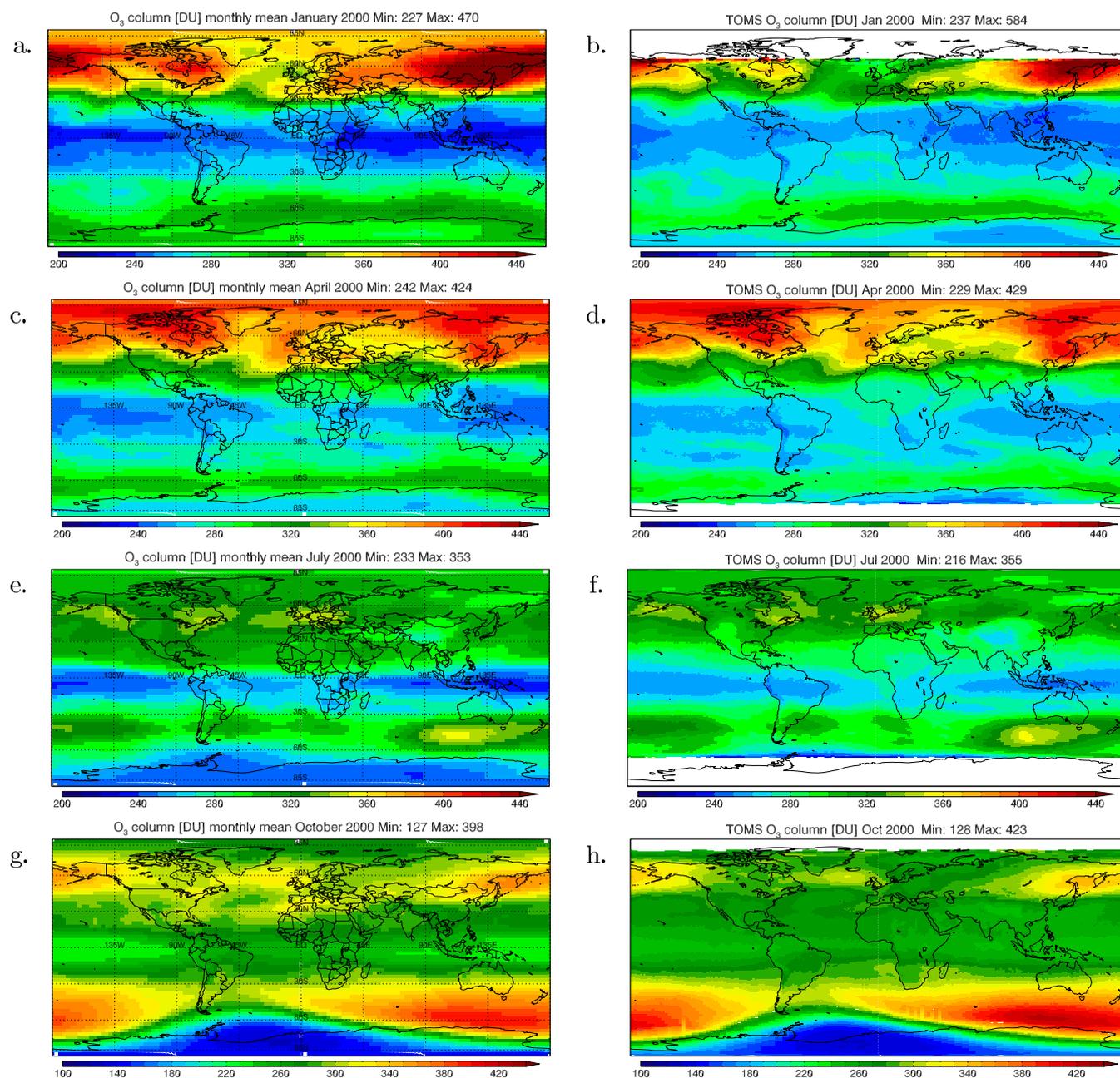
In the lower and middle troposphere, the SHADOZ sondes measure smaller O<sub>3</sub> mixing ratios than the model predicts, with REF\_2000 overestimating the measured values by 16 ppbv, or almost 33 % at about 300 hPa. In R2\_2000 however, this overestimation is reduced to only 7 ppbv, or 14 %. Above ~ 200 hPa and in the lower troposphere (below ~ 500 hPa), the R2\_2000 O<sub>3</sub> mixing ratios are very similar to the measured values. The inclusion of Reaction (R2) therefore leads to a significant improvement in the model's ability to reproduce the observed tropospheric O<sub>3</sub> values in the tropics.

##### 4.2 Modelled and measured NO, NO<sub>y</sub> and O<sub>3</sub>

Tropical tropospheric O<sub>3</sub> production is largely controlled by the amount of nitrogen species. The amount of nitrogen species is mainly controlled by emissions from the surface and from lightning, combined with rainout of HNO<sub>3</sub>, whereas chemistry and clouds are most important for the partitioning.

Comparing modelled NO, NO<sub>2</sub> and HNO<sub>3</sub> with measurements is challenging and should therefore be carried out with care. NO<sub>2</sub> is seldom measured, and the partitioning between NO and NO<sub>2</sub> depends on sunlight. Unless the modelled cloud cover very closely matches the cloud cover at the time and location of the measurement (a difficult task, given the sub-grid scale variability of clouds), such a comparison will be difficult, since NO is usually measured only during daytime.

However, an important part of the nitrogen budget is HNO<sub>3</sub>, which is washed out by rain. Precipitation and the associated wet scavenging of chemical species has a variability which cannot be resolved by large scale models, and this

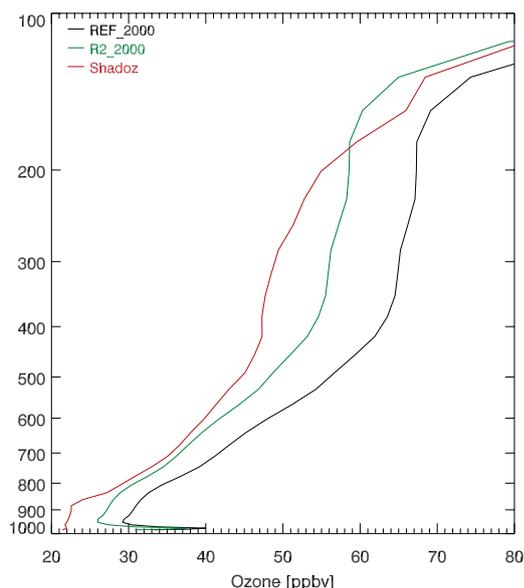


**Fig. 5.** The monthly mean total column of O<sub>3</sub> from run R2\_2000, for July 2000. Note the different scale in October.

may hamper the comparison with measured HNO<sub>3</sub>, as well as other nitrogen components.

Atmospheric measurements of upper tropospheric nitrogen species are rather limited; only a few aircraft campaigns are available. Instead of comparing the model to a climatology, we compare the model with in-situ measurements carried out by CARIBIC flights (Civil Aircraft for the Regular Investigation of the atmosphere Based on an Instrument Container, Brenninkmeijer et al., 2007, <http://www.caribic-atmospheric.com>). Measurements used in this com-

parison are O<sub>3</sub> (A. Zahn, personal communication, 2011) and NO and NO<sub>y</sub> (H. Ziereis, G. Stratmann, H. Lichtenstern, H. Schlager and U. Shumann, personal communication, 2011). In order to do this for R2 and REF, simulations are carried out with meteorological data for the year 2005, a year with frequent CARIBIC flights in the tropics. Emissions data used in these simulations were identical to those for 2000 except biomass burning which was taken from data for 2005.



**Fig. 6.** A comparison of annual mean profiles from SHADOZ, with corresponding profiles from REF\_2000 and R2\_2000.

Atmospheric species are retrieved from the Oslo CTM2 at the time and location of all CARIBIC measurements (flights 110–136, only missing flight 137 due to technicalities), allowing a one-to-one comparison. In Fig. 7 we show time series of these species at the location and times where NO was measured, at the aircraft cruise altitude around 200 hPa. Only measurements above 400 hPa are used, to limit comparison to the free troposphere. A few observations are located in the stratosphere and are shown in blue in the figure. As was the case for the SHADOZ comparison, the comparison of modelled O<sub>3</sub> with the CARIBIC measurements (upper time series) is slightly better for R2. NO<sub>y</sub> (lower time series) is close to unchanged by the inclusion of Reaction (R2), while NO (middle) is slightly reduced. It is not, however, possible to conclude whether or not Reaction (R2) improves the modelled NO. In both REF and R2 simulations, the model fails to catch high values of NO and NO<sub>y</sub>, probably due to either unresolved variation in surface emissions, or the transport of emitted species to the free troposphere, unresolved variation in lightning emissions of NO<sub>x</sub>, or the limitations in modelling wet scavenging discussed above.

For these simulations, HNO<sub>3</sub> above 100 hPa has also been compared profile-by-profile to measurements by the Earth Observing System Microwave Limb Sounder (MLS) aboard the AURA satellite, showing a slight improvement from REF to R2 (not shown). However, the effect on O<sub>3</sub>, compared for the same satellite profiles, was negligible at these altitudes.

The study here and that of Cariolle et al. (2008) both show that Reaction (R2) is most important at tropical altitudes between ~8 km and ~17 km. In contrast to the model results shown in their work, the Oslo CTM2 reproduces O<sub>3</sub> mea-

surements well also above 8–12 km, where the largest effect of the reaction is found. If O<sub>3</sub> is not well modelled in the region of interest, it is hard to reach a conclusion on whether or not NO<sub>x</sub> and HNO<sub>3</sub> are correctly represented. Cariolle et al. (2008) compared their model against a climatology of NO<sub>x</sub> and HNO<sub>3</sub> compiled from aircraft campaigns, and a climatology O<sub>3</sub> from sondes, and observed that Reaction (R2) tended to make their model results worse.

It is important to note that a worsening does not need to be applicable to all atmospheric models. There are uncertainties in the meteorological data driving the models, and therefore in their treatments of transport, convection and rainout. Whether NO<sub>x</sub> and NO<sub>y</sub> are modelled correctly depends on several factors, such as the emission sources and their vertical distributions, transport and washout of HNO<sub>3</sub>.

In fact, the lightning source in Oslo CTM2 is 5 Tg (N) yr<sup>-1</sup>, while Cariolle et al. (2008) use 4 Tg (N) yr<sup>-1</sup>. Although both are within the range 5 ± 3 Tg (N) yr<sup>-1</sup> presented by Shumann and Huntrieser (2007), lightning emissions are predominantly located in the tropical upper troposphere where Reaction (R2) has the largest impact. Also our surface NO<sub>x</sub> emissions are slightly higher than theirs, 44 Tg (N) yr<sup>-1</sup> versus 42 Tg (N) yr<sup>-1</sup>, pulling in the same direction. Important would e.g. be tropical biomass burning and its vertical distributions, which may differ from model to model.

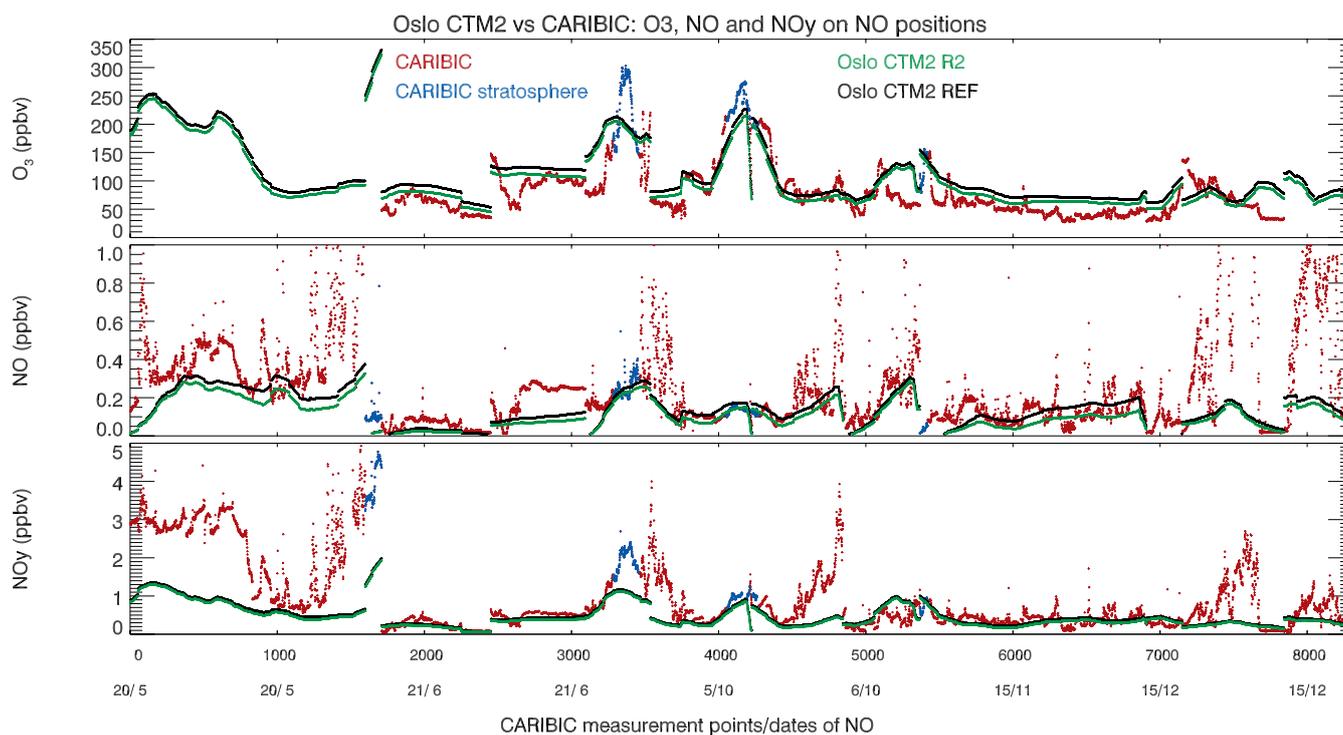
A preliminary test in the Oslo CTM2, lowering the lightning source by 20 % results in up to ~7 % reduction in the tropical upper tropospheric O<sub>3</sub>, and up to ~18 % reduction in HNO<sub>3</sub> through Reaction (R2) and Reaction (R3). Hence the different NO<sub>x</sub> sources can to some extent explain that we do not see the worsening in NO<sub>x</sub>.

From our results, and the results of Cariolle et al. (2008), we cannot conclude whether Reaction (R2) makes the model NO<sub>x</sub> and NO<sub>y</sub> results better or worse, only that the impact is important for O<sub>3</sub> and that the existence of the reaction needs to be confirmed by other measurements.

Also, a comprehensive model inter-comparison would be helpful to assess the full implications of this reaction branch, and how the model treatments of e.g. convection and washout affects the results.

## 5 Radiative forcing

The changing emissions to the atmosphere since pre-industrial times lead to a change in the O<sub>3</sub> concentration and therefore a radiative forcing (RF). In this section we investigate the magnitude of this forcing and the influence of the new reaction branch. The RF was calculated using separate radiative transfer codes for long-wave and short-wave radiation, in off-line simulations. A broad band code for long-wave (Myhre and Stordal, 1997) and a model using the discrete-ordinate method (Stamnes et al., 1988) for short-wave radiation were adopted. Meteorological data from the



**Fig. 7.** A comparison of Oslo CTM2 on CARIBIC flight routes for 2005, on all measurement locations/times where NO was measured above 400 hPa. Blue dots are measurements above the tropopause, as defined by the Oslo CTM2. Model results are produced at the same time and location as aircraft measurements.

ECMWF was used for simulations on a monthly mean time scale. A stratospheric temperature adjustment was included (Myhre et al., 2000), to follow the standard definition of radiative forcing (Forster et al., 2007).

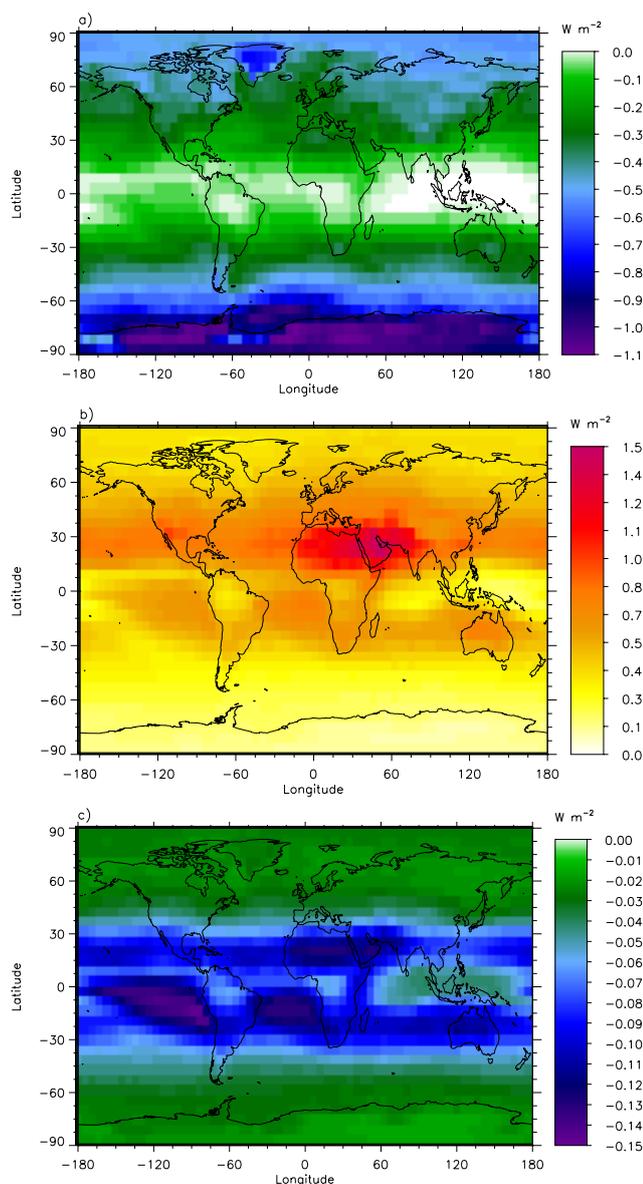
In addition to the REF and R2 runs already described, two simulations with and without Reaction (R2) for the year 2000 were performed with Cl and Br at 1850 levels, to separate out the effect of halogens. In Table 6 we show the radiative forcing from tropospheric O<sub>3</sub> precursors and Cl/Br. Values are given for the troposphere (upper), stratosphere (middle) and both (lower). The total RF due to emission changes since pre-industrial times is 0.33 W m<sup>-2</sup>, which reduces to 0.26 W m<sup>-2</sup> in R2, due to the reduced growth in tropospheric O<sub>3</sub>. The greatest contributions to the calculated RF were due to the tropospheric precursors such as NO<sub>x</sub>, CH<sub>4</sub>, CO and NMHC, which in turn also cause an increase in the stratospheric O<sub>3</sub>. Of the total of 0.52 W m<sup>-2</sup> from tropospheric O<sub>3</sub> precursors in the R2 simulations, changes in the stratosphere contributed 0.08 W m<sup>-2</sup>.

Stratospheric changes resulting from Cl and Br increases amounts to -0.20 W m<sup>-2</sup>, giving RF due to stratospheric O<sub>3</sub> change of -0.12 W m<sup>-2</sup>. The reduction in stratospheric O<sub>3</sub> due to Cl and Br leads to less O<sub>3</sub> being transported from the stratosphere into the troposphere than if Cl and Br were absent. This causes a negative contribution to the tropospheric O<sub>3</sub> development since pre-industrial times, amount-

**Table 6.** The different components of the radiative forcing due to the change in O<sub>3</sub> since the pre-industrial times.

RF due to tropospheric O <sub>3</sub> change		
Component	REF	R2
Tropospheric O <sub>3</sub> precursors	-0.50	-0.44
Cl & Br	-0.05	-0.06
Total RF, trop.	-0.45	-0.38
RF due to stratospheric O <sub>3</sub> change		
Component	REF	R2
Tropospheric O <sub>3</sub> precursors	-0.09	-0.08
Cl & Br	-0.21	-0.20
Total RF, strat.	-0.12	-0.12
RF due to tropospheric & stratospheric O <sub>3</sub> change		
Component	REF	R2
Tropospheric O <sub>3</sub> precursors	-0.59	-0.52
Cl & Br	-0.26	-0.26
Total RF, trop. & strat.	-0.33	-0.26

ing to -0.06 W m<sup>-2</sup> in the R2 simulations, hence giving a negative contribution to the RF in both the stratosphere and the troposphere.



**Fig. 8.** The radiative forcing due to changes in atmospheric O<sub>3</sub> between the pre-industrial times and the present, for the R2 simulations. **(a)** shows the RF for the change in stratospheric O<sub>3</sub>, **(b)** the RF for the change in tropospheric O<sub>3</sub>, while **(c)** shows the RF difference for changes in tropospheric O<sub>3</sub> between R2 and REF.

In other words, the total RF influence of this halogen induced O<sub>3</sub> change in the troposphere and stratosphere is  $-0.26 \text{ W m}^{-2}$ , a number that is unchanged from REF to R2.

It should be noted that the stratospheric halogen chemistry can take place to slightly lower altitudes in the CTM than the tropopause used in the RF calculations. Therefore, some of the  $-0.06 \text{ W m}^{-2}$  attributed to transport from the stratosphere could in fact be due to the direct influence of Cl and Br chemistry in the upper troposphere of the RF calculations.

The geographical distribution of the stratospheric and tropospheric RF components are shown in Fig. 8a and b, respectively, for the R2 case. The stratospheric RF is generally negative, due to halogen related O<sub>3</sub> loss since the pre-industrial times. Values are around zero at low latitudes, and the RF becomes more negative towards high latitudes, with the strongest values of  $-1.1 \text{ W m}^{-2}$  over Antarctica. Relatively large tropospheric RF values are found between about 30° S and 60° N, where substantial industrial emissions occur. The greatest RF is found over Saudi Arabia, Northern Africa and Iran, where the O<sub>3</sub> increase is coupled with high solar irradiance and high surface reflectivity, as well as temperature and cloud amount conditions for a high long-wave RF (Berntsen et al., 1997).

Figure 8c shows the difference in RF due to O<sub>3</sub> from tropospheric precursors between the R2 and REF cases. The impact of Reaction (R2) has the largest effect over oceanic sub-tropical regions in terms of RF. For the stratosphere in the R2 and REF cases, there are only minor differences in the RF due to O<sub>3</sub> changes (not shown).

## 6 Summary and conclusions

A set of model runs was performed to evaluate the chemical and climate implications of the HNO<sub>3</sub> forming branch of the HO<sub>2</sub> + NO reaction. We found that despite the small branching ratios, the atmospheric effects are important, especially in the tropical upper troposphere. NO<sub>x</sub> concentrations decrease by up to  $\sim 50\%$  in the troposphere, via conversion to HNO<sub>3</sub> and subsequent wet deposition of HNO<sub>3</sub>, making the removal permanent in some regions.

The reduction in NO<sub>x</sub> leads to a reduction in the formation rate of tropospheric O<sub>3</sub>, reducing O<sub>3</sub> by up to  $\sim 18\%$  in the tropical upper troposphere in December. The reduction in tropospheric O<sub>3</sub> is greatest in the tropics (up to 5.8 DU), and is the least at high latitudes. Consequently, the tropospheric O<sub>3</sub> burden is reduced by 11% in the year 2000, while the tropical upward flux of O<sub>3</sub> is reduced and thereby slightly increases the net flux into the troposphere from the stratosphere. The annual, global mean OH concentration decreases by 14.1%, and as a result the methane lifetime increases by 10.9%.

The increase in tropospheric O<sub>3</sub> since pre-industrial times is reduced by the inclusion of the new reaction branch, with an annual reduction in the tropics amounting to 11%. Since the effect is largest in the tropics, the corresponding increase in tropospheric O<sub>3</sub> burden is reduced by 4%.

Our model shows that OH has decreased since pre-industrial times, and the new reaction branch reduces this decrease. This means that the calculated increase in CH<sub>4</sub> lifetime since 1850 is only 4%, rather than 4.6% when the new branch is not accounted for.

We find the change in radiative forcing due to changes in O<sub>3</sub> since pre-industrial times to be  $0.26 \text{ W m}^{-2}$  with the new

branch, compared to 0.33 W m<sup>-2</sup> without. This decrease is due to changes in tropospheric O<sub>3</sub> shifting the RF from 0.45 to 0.38 W m<sup>-2</sup>, while the RF due to stratospheric O<sub>3</sub> changes is unchanged at -0.12 W m<sup>-2</sup>. Overall, we find from our results that RF due to changes in tropospheric and stratospheric O<sub>3</sub> is quite different from the RF due to O<sub>3</sub> change from tropospheric and stratospheric O<sub>3</sub> precursors.

The inclusion of the new reaction branch substantially improved the agreement of the modelled tropical upper tropospheric O<sub>3</sub> with sonde measurements, and also for the aircraft measurement comparison. The new branch also improved the agreement between modelled global mean OH concentrations and recent estimates. We find it not possible to conclude whether NO and NO<sub>y</sub> are improved or not.

It has been found by Butkovskaya et al. (2005, 2009), that water vapour may increase the branching ratio in the direction of HNO<sub>3</sub> formation. Although unpublished work suggests the pressure dependence of the H<sub>2</sub>O effect is small, there are still uncertainties when it comes to the temperature effect (Le Bras, 2011). When the H<sub>2</sub>O effect is fully documented, this study should be revisited. The H<sub>2</sub>O effect will probably increase the conversion to HNO<sub>3</sub> also at lower altitudes, as suggested by Müller (2011), and hence have a larger impact on O<sub>3</sub> than we have shown here. If there is a change in tropospheric water vapor since pre-industrial times, this should also be considered. A thorough multi-model study would be useful to better assess the effect of the new reaction branch, as well as the H<sub>2</sub>O effect.

It should also be mentioned that Mollner et al. (2010) have reported a smaller reaction rate for Reaction (R3). As explained in Sect. 2, we use the value suggested by Sander et al. (2006), which is also kept in Sander et al. (2011). Testing the value of Mollner et al. (2010) would certainly be interesting, and will be done in the near future. They found that a lower reaction rate would increase OH and thereby O<sub>3</sub> in polluted areas. Presumably, this would increase NO<sub>x</sub>, and could increase NO available for Reaction (R2).

The results of this work show that the existence of a HNO<sub>3</sub> forming branch of the HO<sub>2</sub> + NO reaction has very important implications both for the modelling of present day atmospheric composition, as well as for assessing the anthropogenic impact on the atmosphere since pre-industrial times, and therefore the branching ratios and rates of this reaction should be confirmed by other laboratory studies.

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