

This is a repository copy of *Halogen chemistry reduces tropospheric O3 radiative forcing*.

White Rose Research Online URL for this paper:

<https://eprints.whiterose.ac.uk/id/eprint/112091/>

Version: Published Version

---

## Article:

Sherwen, Tomás [orcid.org/0000-0002-3006-3876](https://orcid.org/0000-0002-3006-3876), Evans, Mathew John [orcid.org/0000-0003-4775-032X](https://orcid.org/0000-0003-4775-032X), Carpenter, Lucy Jane [orcid.org/0000-0002-6257-3950](https://orcid.org/0000-0002-6257-3950) et al. (2 more authors) (2017) Halogen chemistry reduces tropospheric O3 radiative forcing. *Atmospheric Chemistry and Physics*. pp. 1557-1569. ISSN: 1680-7324

<https://doi.org/10.5194/acp-17-1557-2017>

---

## Reuse

This article is distributed under the terms of the Creative Commons Attribution (CC BY) licence. This licence allows you to distribute, remix, tweak, and build upon the work, even commercially, as long as you credit the authors for the original work. More information and the full terms of the licence here:

<https://creativecommons.org/licenses/>

## Takedown

If you consider content in White Rose Research Online to be in breach of UK law, please notify us by emailing [eprints@whiterose.ac.uk](mailto:eprints@whiterose.ac.uk) including the URL of the record and the reason for the withdrawal request.



# Halogen chemistry reduces tropospheric O<sub>3</sub> radiative forcing

Tomás Sherwen<sup>1</sup>, Mat J. Evans<sup>1,2</sup>, Lucy J. Carpenter<sup>1</sup>, Johan A. Schmidt<sup>3</sup>, and Loretta J. Mickley<sup>4</sup>

<sup>1</sup>Wolfson Atmospheric Chemistry Laboratories, Department of Chemistry, University of York, York, YO10 5DD, UK

<sup>2</sup>National Centre for Atmospheric Science, University of York, York, YO10 5DD, UK

<sup>3</sup>Department of Chemistry, Copenhagen University, Universitetsparken, 2100 Copenhagen O, Denmark

<sup>4</sup>John A. Paulson School of Engineering and Applied Sciences, Harvard University, Cambridge, Massachusetts, USA

Correspondence to: Tomás Sherwen (tomas.sherwen@york.ac.uk)

Received: 29 July 2016 – Published in Atmos. Chem. Phys. Discuss.: 8 August 2016

Revised: 23 December 2016 – Accepted: 3 January 2017 – Published: 31 January 2017

**Abstract.** Tropospheric ozone (O<sub>3</sub>) is a global warming gas, but the lack of a firm observational record since the preindustrial period means that estimates of its radiative forcing (RF<sub>TO<sub>3</sub></sub>) rely on model calculations. Recent observational evidence shows that halogens are pervasive in the troposphere and need to be represented in chemistry-transport models for an accurate simulation of present-day O<sub>3</sub>. Using the GEOS-Chem model we show that tropospheric halogen chemistry is likely more active in the present day than in the preindustrial. This is due to increased oceanic iodine emissions driven by increased surface O<sub>3</sub>, higher anthropogenic emissions of bromo-carbons, and an increased flux of bromine from the stratosphere. We calculate preindustrial to present-day increases in the tropospheric O<sub>3</sub> burden of 113 Tg without halogens but only 90 Tg with, leading to a reduction in RF<sub>TO<sub>3</sub></sub> from 0.43 to 0.35 Wm<sup>−2</sup>. We attribute ~ 50 % of this reduction to increased bromine flux from the stratosphere, ~ 35 % to the ocean–atmosphere iodine feedback, and ~ 15 % to increased tropospheric sources of anthropogenic halogens. This reduction of tropospheric O<sub>3</sub> radiative forcing due to halogens (0.087 Wm<sup>−2</sup>) is greater than that from the radiative forcing of stratospheric O<sub>3</sub> (~ 0.05 Wm<sup>−2</sup>). Estimates of RF<sub>TO<sub>3</sub></sub> that fail to consider halogen chemistry are likely overestimates (~ 25 %).

shown that halogens play an important and pervasive role in the chemistry of the present-day troposphere (Read et al., 2008; Volkamer et al., 2015; Wang et al., 2015). Models that were used to calculate radiative forcing of tropospheric O<sub>3</sub> (RF<sub>TO<sub>3</sub></sub>) in the past do not contain this halogen chemistry (Hauglustaine et al., 1994; Levy et al., 1997; Myhre et al., 2013; Young et al., 2013), raising concerns that they may have a systematic bias in their simulation of past, present, and future tropospheric O<sub>3</sub> and more widely the composition of the troposphere. As increased observations of tropospheric halogens are made (Dix et al., 2013; Gómez Martín et al., 2013; Mahajan et al., 2010, 2012; Prados-Roman et al., 2015; Read et al., 2008; Volkamer et al., 2015; Wang et al., 2015) and models are used to understand them (Parrella et al., 2012; Saiz-Lopez et al., 2012a, 2014; Schmidt et al., 2016; Sherwen et al., 2016a, b), these concerns grow.

Tropospheric O<sub>3</sub> is a climate gas and a potent air pollutant. Understanding the change in its concentration from the “natural” preindustrial (~ 1750) atmosphere to the present day is important in defining those roles and informing policy decisions. Global tropospheric O<sub>3</sub> concentrations are thought to have increased substantially in this period (Lamarque et al., 2010; Myhre et al., 2013), but the observational record for this change is highly uncertain. Unlike carbon dioxide and methane, O<sub>3</sub> does not remain trapped in ice so modern analytical techniques cannot be applied to old air. Past observations suggest much lower concentrations of O<sub>3</sub> than are presently measured (Volz and Kley, 1988; Marenco et al., 1994; Pavelin et al., 1999). However, there are only a small number of past observations, and significant uncertainties exist in the methods used and their representativeness. Because of concerns over the validity of these observations, our

## 1 Introduction

The prevailing paradigm has been for tropospheric halogen chemistry not to be considered important for estimating the climate change due to increasing tropospheric ozone (O<sub>3</sub>) concentrations. However, recent observational studies have

assessment of the change in O<sub>3</sub> concentrations is predominantly based on computer simulations (Hauglustaine et al., 1994; Levy et al., 1997; Myhre et al., 2013; Young et al., 2013). Estimates of the emissions in the preindustrial and the present day (Lamarque et al., 2010), together with an understanding of the chemistry, transport, and physics of the atmosphere, underpin these simulations. An assessment of the change in O<sub>3</sub> concentrations between the preindustrial and the present day and a calculation of the associated radiative forcing was undertaken as part of the ACCMIP project (Lamarque et al., 2013; Stevenson et al., 2013; Young et al., 2013; Voulgarakis et al., 2013). This concluded that preindustrial tropospheric O<sub>3</sub> burdens were 98 Tg lower than the present day and estimated a RF<sub>TO<sub>3</sub></sub> of 0.41 Wm<sup>-2</sup>.

These model calculations are only as good as the emissions used to drive them and their representation of physical and chemical processes. These uncertainties are probably largest for the emissions, especially for the biomass burning source (Fry et al., 2012; Knorr et al., 2016; Murray et al., 2014; van der Werf et al., 2013). Over the last decades, improvements have been made in the organic tropospheric chemistry included in these models with a particular emphasis on the role of biogenic compounds such as isoprene and monoterpenes (Glasius and Goldstein, 2016).

The tropospheric impact of halogens in polar regions during springtime has been known for some time (Barrie et al., 1988; Jacob et al., 1992), but their significance for the global troposphere has only been evident in the last decade (Read et al., 2008; Saiz-Lopez et al., 2012a; Prados-Roman et al., 2015; Wang et al., 2015). Reviews of the appropriate processes are given elsewhere (Simpson et al., 2015). Sources of halogens include natural and anthropogenic organic halogen precursor gases (Montzka et al., 2011), heterogeneous chemistry on sea salt (McFiggans et al., 2000; Braban et al., 2007; Roberts et al., 2009; Bertram and Thornton, 2009), and chemistry involving atmospheric O<sub>3</sub> and iodide in the ocean surface (Carpenter et al., 2013; MacDonald et al., 2014). Once emitted into the atmosphere there is rapid photochemical processing of these compounds (Simpson et al., 2015). Catalytic cycles similar to those occurring in the stratosphere can lead to O<sub>3</sub> destruction (von Glasow et al., 2004; Simpson et al., 2015), changes to HO<sub>x</sub> and NO<sub>x</sub> cycling (Chameides and Davis, 1980; Long et al., 2014), and impacts on the distribution and deposition of mercury (Holmes et al., 2010; Parrella et al., 2012; Schmidt et al., 2016).

Here, we investigate the impact of tropospheric halogen chemistry on the change in O<sub>3</sub> concentrations between the preindustrial and the present day using the GEOS-Chem model of tropospheric chemistry and transport (Bey et al., 2001), which has been extended to provide a description of the chemistry of chlorine, bromine, and iodine (see Sect. 2 and Sherwen et al., 2016b). Comparisons between the model and present-day observations of halogen compounds have been shown previously (Bell et al., 2002; Eastham et al., 2014; Parrella et al., 2012; Schmidt et al., 2016; Sherwen

et al., 2016a, b). The model provides a good simulation of present-day bromine and iodine compounds but appears (given the limited observational record) to underestimate tropospheric chlorine sources (Sherwen et al., 2016b). We run simulations with preindustrial and present-day emissions, with and without halogen chemistry. From these we evaluate the changes in the tropospheric O<sub>3</sub> and hence radiative forcing.

## 2 Model description

We use the GEOS-Chem model of chemistry and transport (<http://www.geos-chem.org>, Bey et al., 2001), which includes O<sub>x</sub>, HO<sub>x</sub>, NO<sub>x</sub>, and VOC chemistry. The model is an enhancement of this with a representation of halogen chemistry (Eastham et al., 2014; Parrella et al., 2012; Schmidt et al., 2016; Sherwen et al., 2016a) described elsewhere (Sherwen et al., 2016b), with gas-phase chemistry based on JPL/IUPAC recommendations (Sander et al., 2011; Atkinson et al., 2006, 2007, 2008) and heterogeneous chemistry from previous work (Abbatt et al., 2012; Braban et al., 2007; Ammann et al., 2013; Sherwen et al., 2016a). Short-lived organohalogens (CH<sub>3</sub>I, CH<sub>2</sub>I<sub>2</sub>, CH<sub>2</sub>ICl, CH<sub>2</sub>IBr, CHBr<sub>3</sub>, CH<sub>2</sub>Br<sub>2</sub>) are emitted into the model surface level and then transported (Parrella et al., 2012; Schmidt et al., 2016; Sherwen et al., 2016a), whereas longer-lived species (CH<sub>3</sub>Br, CH<sub>3</sub>Cl, CHCl<sub>3</sub>, CH<sub>2</sub>Cl<sub>2</sub>) are given fixed boundary layer concentrations (Eastham et al., 2014; Parrella et al., 2012; Schmidt et al., 2016). Chlorine and bromine from sea salt can be released into the gas phase through heterogeneous chemistry involving iodine (HOI/INO<sub>2</sub>/INO<sub>3</sub>  $\xrightarrow{\text{seasalt}}$  IX, X = Cl, Br) and N<sub>2</sub>O<sub>5</sub> (N<sub>2</sub>O<sub>5</sub>  $\xrightarrow{\text{seasalt}}$  ClNO<sub>2</sub> + HNO<sub>3</sub>, for Cl) as described in Sherwen et al. (2016b). HOI and I<sub>2</sub> are emitted from the ocean surface dependent on the O<sub>3</sub> concentration in the model's lowest level and the calculated iodide concentration in the ocean (Carpenter et al., 2013; MacDonald et al., 2014). The combined impact of this chemistry for the present day has been summarised previously (Sherwen et al., 2016b) and the model has been evaluated against a range of halogenated compounds (Eastham et al., 2014; Parrella et al., 2012; Schmidt et al., 2016; Sherwen et al., 2016a, b).

The model is run for 2 years (2004 and 2005), discarding the first year as a “spin-up” period and using the second year (2005) for analysis. We run with and without halogen chemistry.

To simulate the preindustrial troposphere, anthropogenic NO<sub>x</sub>, VOC, and SO<sub>2</sub> emissions are removed, biomass burning emissions are reduced to 10 % of their present-day values, and the methane concentration is reduced to 700 nmol mol<sup>-1</sup> (Wang and Jacob, 1998). A summary of changes to base emissions from present day are given in Table 4 and the base emissions described in detail on the GEOS-Chem website ([www.geos-chem.org](http://www.geos-chem.org)). Uncertain-

**Table 1.** Emission of halogen source gases for the preindustrial (PI) and present day (PD). Long-lived sources which have fixed concentrations in the model for Cl (CH<sub>3</sub>Cl, CH<sub>2</sub>Cl<sub>2</sub>, CHCl<sub>3</sub>) and Br (CHBr<sub>3</sub>) are shown in terms of chemical release (e.g. reaction with +OH, +hν, +Cl) and are in bold. I<sub>2</sub> and HOI are the inorganic ocean source from O<sub>3</sub> reacting with oceanic iodide (Carpenter et al., 2013), IX is from the uptake of iodine gases onto sea salt to release IBr or ICl, and ClNO<sub>2</sub> is the source from the uptake of N<sub>2</sub>O<sub>5</sub> on sea salt.

	I (Tg I yr <sup>-1</sup> )		Br (Tg Br yr <sup>-1</sup> )		Cl (Tg Cl yr <sup>-1</sup> )	
Sources	PI	PD	PI	PD	PI	PD
CH <sub>3</sub> X	0.26	0.26	<b>0.04</b>	<b>0.06</b>	<b>2.28</b>	<b>2.10</b>
CH <sub>2</sub> X <sub>2</sub>	0.33	0.33	0.09	0.09	<b>0.11</b>	<b>0.57</b>
CHX <sub>3</sub>	–	–	0.41	0.41	<b>0.21</b>	<b>0.25</b>
HOI	1.09	1.97	–	–	–	–
I <sub>2</sub>	0.08	0.14	–	–	–	–
IX	–	–	0.19	0.30	0.46	0.73
ClNO <sub>2</sub>	–	–	–	–	0.02	0.65
Stratosphere	0.00	0.00	0.00	0.06	0.44	0.43
Total source	1.76	2.70	0.74	0.91	3.52	4.9

ties in preindustrial emissions are large, especially for the biomass burning. We make a very large reduction here (90 %). Other estimates give smaller changes (20 %, Lamarque et al., 2010). Using a smaller change will likely reduce the overall tropospheric O<sub>3</sub> radiative forcing that we calculate, but our objective here is not primarily to calculate the tropospheric O<sub>3</sub> radiative forcing but to investigate the change that halogen chemistry makes to this value. Emissions of iodocarbons are unchanged between the preindustrial and the present day. For bromocarbons we follow a previous methodology (Parrella et al., 2012) of not changing CHBr<sub>3</sub> and CH<sub>2</sub>Br<sub>2</sub> from their present-day values, but reducing the CH<sub>3</sub>Br concentration assumed from 6–9 pmol mol<sup>-1</sup> in the present day to 5 pmol mol<sup>-1</sup> to match ice core records (Saltzman et al., 2004). Preindustrial concentrations of CH<sub>3</sub>Cl, CHCl<sub>3</sub>, and CH<sub>2</sub>Cl<sub>2</sub> are scaled from their present-day values using the estimated natural contributions to their sources (92.5, 75, and 10 %, respectively; Montzka et al., 2011; Reimann et al., 2014).

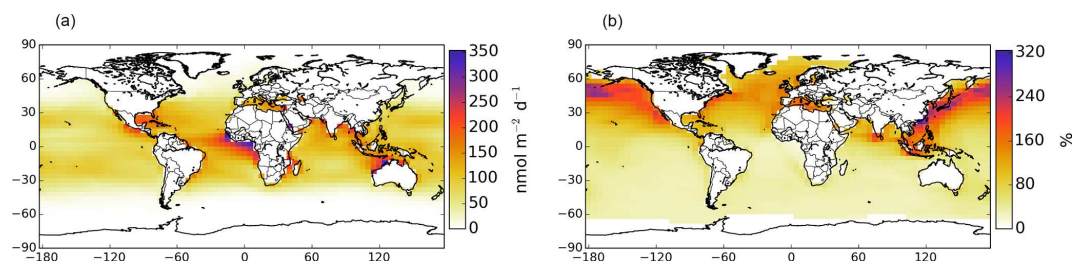
We do not explicitly treat the chemistry of the stratosphere. The model uses the same linearised stratospheric chemistry (Murray et al., 2012) in the preindustrial and the present day except we set the concentration of anthropogenic halogen species (CFCs, halons, etc.) to be zero. We scale the concentration of stratospheric Br<sub>y</sub> in the preindustrial by 0.56 to reflect the anthropogenically driven increase in bromine (Liang et al., 2010; Montzka et al., 2011). We make no similar changes to Cl<sub>y</sub> as chlorine's impact on tropospheric O<sub>3</sub> in this model has previously been shown to be insignificantly small (Sherwen et al., 2016b). The tropopause is defined here as the altitude where the lapse rate of temperature falls below 2 K km<sup>-1</sup>.

## 2.1 Results and discussion

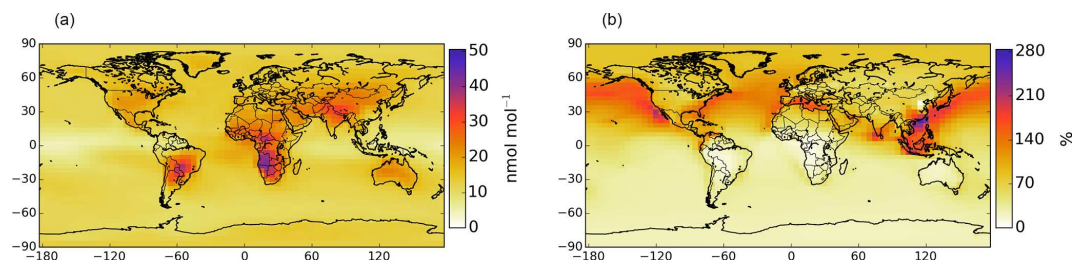
### 2.1.1 Changes from preindustrial to present

Table 1 shows our estimate of halogen emissions for the preindustrial and the present day. Iodine, bromine, and chlorine sources increase by 50, 28, and 41 % over this period. The enhanced iodine emission is due to the increases in the surface ocean inorganic (HOI, I<sub>2</sub>) source (Fig. 1) driven by anthropogenically enhanced surface O<sub>3</sub> (Fig. 2). Bromine emissions increase mainly because of increased anthropogenic precursor emissions but also due to increased iodine-driven sea-salt cycling of bromine (Sherwen et al., 2016b) and an increased stratospheric flux. Chlorine emissions increase due to enhanced NO<sub>x</sub> concentration leading to more heterogeneous uptake of N<sub>2</sub>O<sub>5</sub> on sea-salt liberating ClNO<sub>2</sub>, together with increased anthropogenic emissions of chlorinated halocarbons and faster iodine-driven sea-salt release of ICl.

These increased sources lead to increased concentrations of halogens in the present day compared to the preindustrial with global burdens of reactive inorganic halogen species increasing by 18, 39, and 20 % for I<sub>y</sub>, Br<sub>y</sub>, and Cl<sub>y</sub>, respectively (shown vertically in Fig. 3 and spatially in Fig. 4). Iodine concentrations increase less than emissions do due to a shortening of its lifetime from 3.0 days in the preindustrial to 2.3 days in the present day. This is mainly due to higher NO<sub>x</sub> concentrations, which enhance iodine nitrate hydrolysis (Ammann et al., 2013; Schmidt et al., 2016). Bromine lifetimes lengthen from 16.4 days in the preindustrial to 18.2 days in the present day. This is predominantly due to the increase in Br<sub>y</sub> source from the stratosphere, which is a region of low depositional loss. Inorganic chlorine lifetimes shorten from 6.1 days in the preindustrial to 5.2 in the present day due to the increase in methane concentrations which push Cl<sub>y</sub> into HCl, which is then readily deposited.



**Figure 1.** Inorganic emission flux (HOI, I<sub>2</sub>) in the preindustrial (a) and percent change from the preindustrial to present day ((PD – PI)/PI · 100) (b).



**Figure 2.** (a) O<sub>3</sub> surface concentration in the preindustrial and (b) percent change from the preindustrial to present day ((PD – PI)/PI · 100).

The inclusion of halogens reduces the concentration of O<sub>3</sub> in both the present-day and the preindustrial simulations. The O<sub>3</sub> simulated in the present day (see Fig. 12 in Sherwen et al., 2016b) appears to be more consistent with observations when halogen chemistry is included than without (other than for the Southern Ocean) and captures the observed diurnal cycle (Sherwen et al., 2016a). Figure 5 shows a comparison between the limited number of O<sub>3</sub> observations for preindustrial locations (Marengo et al., 1994; Pavelin et al., 1999; Volz and Kley, 1988) and the model. Both with and without halogen chemistry the model simulates significantly lower O<sub>3</sub> concentrations in the preindustrial but the addition of halogens reduces globally averaged surface O<sub>3</sub> concentrations by 8.8 nmol mol<sup>-1</sup> (39 %) (Fig. 2), making the model more consistent with observations. This reduction is largest over the oceans. Confidence in the preindustrial observation datasets is, however, low (Marengo et al., 1994; Mickley et al., 2001; Pavelin et al., 1999) and so interpreting the model overestimate is difficult. Globally, halogens reduce the tropospheric O<sub>3</sub> burden by 77 Tg in the present day and 54 Tg in the preindustrial (Table 3).

We consider halogens impacts on O<sub>3</sub> through changes to the family of odd oxygen species (O<sub>x</sub>, defined in Table 2) to account for their rapid interchange. The O<sub>x</sub> budgets for the four simulations are shown in Table 3. In both the present day and the preindustrial the halogens are responsible for around 20 % of the O<sub>3</sub> destruction, with iodine dominating (57 % : 49 % : 4 % I : Br : Cl for the present day and 61 % : 36 % : 4 % I : Br : Cl for the preindustrial). Although chlorine concentrations have increased almost as much as iodine between the preindustrial and the present, it plays little

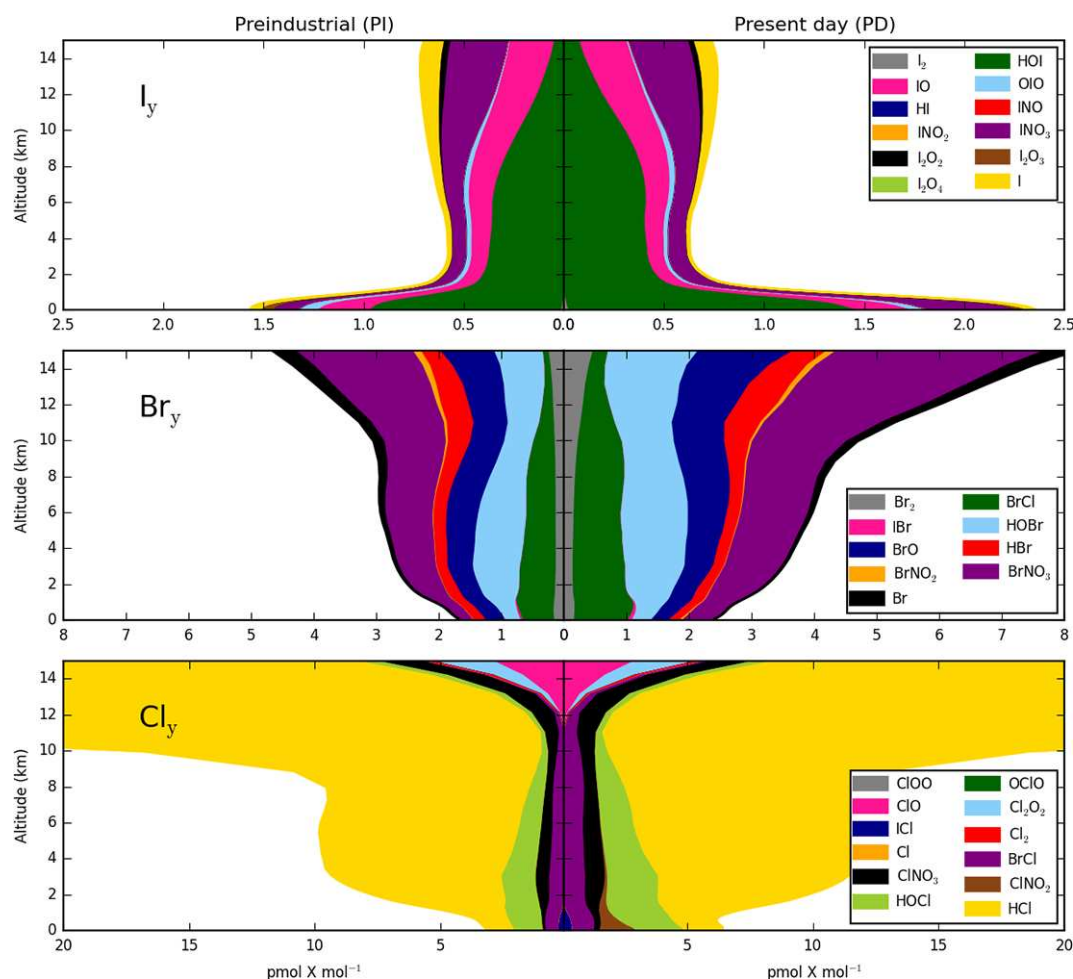
role in determining O<sub>3</sub> loss (Schmidt et al., 2016; Sherwen et al., 2016a, b). Tropospheric O<sub>3</sub> lifetimes drop from 26 to 22 days in the present day with the inclusion of halogens and from 28 to 24 days in the preindustrial.

Tropospheric chemistry is a highly coupled system with significant interplay between the NO<sub>x</sub>, HO<sub>x</sub>, and RO<sub>x</sub> systems (Monks et al., 2015). Changes in the individual production and loss terms are relatively small, but halogens reduce net O<sub>3</sub> production by 194 Tg yr<sup>-1</sup> in the present day and 145 Tg yr<sup>-1</sup> in the preindustrial. In our preindustrial simulation with halogens, the troposphere is close to being a net chemical sink for O<sub>3</sub>. Thus the impact of halogen chemistry on the overall O<sub>3</sub> burden of the troposphere is more important for the present day than it was in the preindustrial.

### 3 Implications

Figure 6 shows the change in tropospheric O<sub>3</sub> column between the preindustrial and the present day, with and without halogens. Consistent with previous work, the largest increases occur in the northern midlatitudes notably over eastern North America and Asia (Lamarque et al., 2005). Halogens reduce the column change by an average of 2.0 DU. The largest halogen-driven reductions (up to 3.5 DU) are seen over the northern Pacific and Atlantic oceans. This is where surface O<sub>3</sub> concentrations increase the most over the oceans, leading to increases in oceanic inorganic iodine emissions and in turn giving more active O<sub>3</sub> destruction by iodine chemistry.

Various studies have calculated a normalised radiative forcing (NRF), which is the radiative forcing response to per



**Figure 3.** Global mean vertical distribution of iodine, bromine, and chlorine inorganic gases ( $X_y$ ,  $X = \text{Cl, Br, I}$ ) for the preindustrial (left) and present day (right) in terms of mixing ratios of halogen. Increased halogen concentrations in the present day are predominantly at the surface for iodine but are throughout the column for bromine and chlorine.

**Table 2.** Odd oxygen ( $O_x$ ) family definition used here.

Abbreviation	Detail
$O_x$	$O_3 + \text{NO}_2 + 2\text{NO}_3 + \text{PAN} + \text{PMN} + \text{PPN} + \text{HNO}_4 + 3\text{N}_2\text{O}_5 + \text{HNO}_3 + \text{MPN} + \text{XO} + \text{HOX} + \text{XNO}_2 + 2\text{XNO}_3 + 2\text{OIO} + 2\text{I}_2\text{O}_2 + 3\text{I}_2\text{O}_3 + 4\text{I}_2\text{O}_4 + 2\text{Cl}_2\text{O}_2 + 2\text{OCIO}$ (where $X = \text{Cl, Br, I}$ )

unit O<sub>3</sub> column within a range of models (Stevenson et al., 2013; Fry et al., 2012; Gauss et al., 2003), and they calculate values of NRF in the range of 36–42 mW m<sup>−2</sup> DU<sup>−1</sup>. Here we use the most recent NRF value calculated by Stevenson et al. (2013) (42 mW m<sup>−2</sup> DU<sup>−1</sup>) and used by the IPCC (Myhre et al., 2013) to consider the implications of tropospheric halogens on O<sub>3</sub>. We acknowledge that this approach does not allow consideration of sensitivities to vertical or latitudinal changes in O<sub>3</sub>, and this offers an uncertainty on our calculation, as discussed further elsewhere (e.g. Myhre et al., 2013). Furthermore, as greatest percentage changes in O<sub>3</sub> burden on inclusions of halogens are seen closest to the

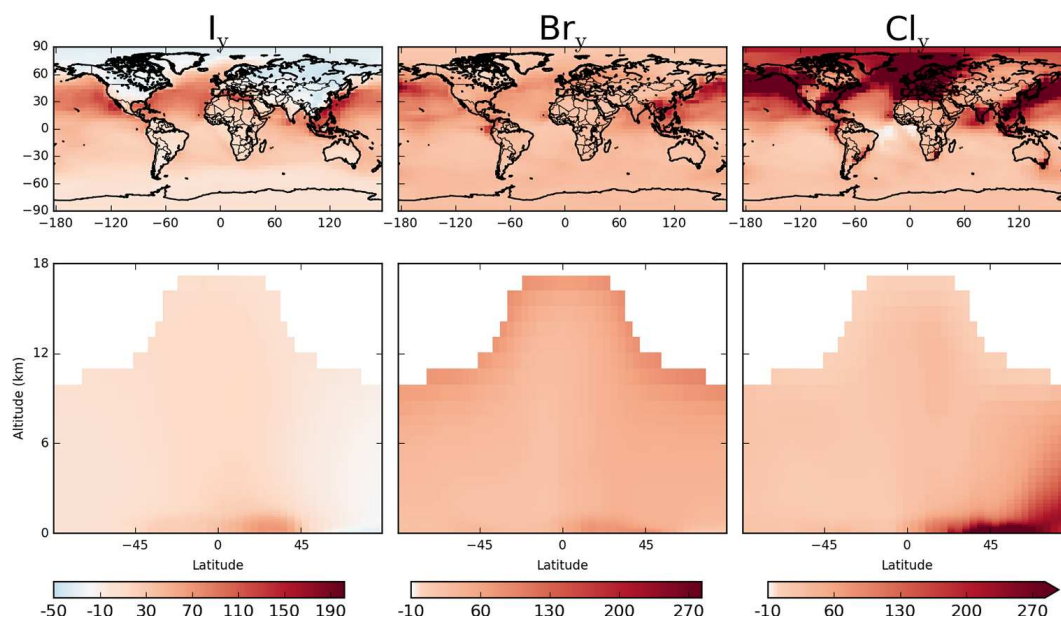
surface (Sherwen et al., 2016b), this could possibly lead to overestimating changes in radiative forcing due to increased sensitivity seen in colder and higher altitudes (Myhre et al., 2013).

For our simulations without halogens we calculate a tropospheric O<sub>3</sub> radiative forcing of 0.432 Wm<sup>−2</sup>, close to the 0.410 Wm<sup>−2</sup> found from the ACCMIP intercomparison (Stevenson et al., 2013) and within the range reported by IPCC (+0.40 (±0.2) Wm<sup>−2</sup>; Myhre et al., 2013). Our simulations with halogens, however, give a significantly lower radiative forcing of 0.345 Wm<sup>−2</sup>. Thus, the increases in halogen chemistry associated with human activity are act-



**Table 3.** Global tropospheric O<sub>x</sub> (defined in Table 2) budgets for preindustrial and present day, with and without halogens. For the X'O + X''O halogen crossover reactions where X' ≠ X'' we split the O<sub>x</sub> loss equally between the two routes. Values are rounded to the nearest integer value.

	Preindustrial	Preindustrial	Present day	Present day
	With halogens	Without	With halogens	Without
O <sub>3</sub> burden (Tg)	249	303	339	416
O <sub>x</sub> chemical sources (Tg yr <sup>-1</sup> )				
NO + HO <sub>2</sub>	2218	2357	3436	3607
NO + CH <sub>3</sub> O <sub>2</sub>	652	668	1288	1316
NO + RO <sub>2</sub>	388	375	525	508
Total chemical O <sub>x</sub> sources (PO <sub>x</sub> )	3341	3401	5249	5431
O <sub>x</sub> chemical sinks (Tg yr <sup>-1</sup> )				
O <sub>3</sub> + H <sub>2</sub> O $\xrightarrow{h\nu}$ 2OH + O <sub>2</sub>	1350	1711	1997	2489
O <sub>3</sub> + HO <sub>2</sub> → OH + O <sub>2</sub>	600	822	1061	1432
O <sub>3</sub> + OH → HO <sub>2</sub> + O <sub>2</sub>	459	601	562	737
HOBr $\xrightarrow{h\nu}$ Br + OH	188	–	285	–
HOBr + HCl → BrCl	27	–	54	–
HOBr + HBr → Br <sub>2</sub> + H <sub>2</sub> O (aq. aerosol)	12	–	22	–
BrO + BrO → 2Br + O <sub>2</sub>	8	–	13	–
BrO + BrO → Br <sub>2</sub> + O <sub>2</sub>	3	–	4	–
BrO + OH → Br + HO <sub>2</sub>	11	–	12	–
IO + BrO → Br + I + O <sub>2</sub>	9	–	11	–
ClO + BrO → Br + ClOO/OCIO	3	–	4	–
Other bromine O <sub>x</sub> sinks	0	–	0	–
Total bromine O <sub>x</sub> sinks	261	–	405	–
HOI $\xrightarrow{h\nu}$ I + OH	322	–	438	–
OIO $\xrightarrow{h\nu}$ I + O <sub>2</sub>	112	–	140	–
IO + BrO → Br + I + O <sub>2</sub>	9	–	11	–
IO + ClO → I + Cl + O <sub>2</sub> /ICl + O <sub>2</sub>	1	–	1	–
Other iodine O <sub>x</sub> sinks	1	–	2	–
Total iodine O <sub>x</sub> sinks	443	–	591	–
HOCl $\xrightarrow{h\nu}$ Cl + OH	18	–	27	–
CH <sub>3</sub> O <sub>2</sub> + ClO → ClOO	4	–	6	–
ClO + BrO → Br + ClOO/OCIO	3	–	4	–
ClNO <sub>3</sub> + HBr → BrCl	0	–	2	–
IO + ClO → I + Cl + O <sub>2</sub> /ICl + O <sub>2</sub>	1	–	1	–
Other chlorine O <sub>x</sub> sinks	1	–	1	–
Total chlorine O <sub>x</sub> sinks	28	–	40	–
Other O <sub>x</sub> sinks	101	151	184	172
Total chemical O <sub>x</sub> sinks (LO <sub>x</sub> )	3259	3240	4841	4829
O <sub>3</sub> PO <sub>x</sub> -LO <sub>x</sub> (Tg yr <sup>-1</sup> )	16	161	408	602
O <sub>3</sub> Dry deposition (Tg yr <sup>-1</sup> )	520	659	799	980
O <sub>3</sub> Lifetime (days)	24	28	22	26
O <sub>3</sub> STE (PO <sub>x</sub> -LO <sub>x</sub> -Dry dep.) (Tg yr <sup>-1</sup> )	503	498	391	378



**Figure 4.** Percentage change from preindustrial to present day in tropospheric distribution of I<sub>y</sub>, Cl<sub>y</sub>, and Br<sub>y</sub> ((PD–PI)/PI · 100). Upper plots show surface and lower plots show zonal values. Reductions in I<sub>y</sub> concentration over land are due to a shortening of the I<sub>y</sub> lifetime due to enhanced IONO<sub>2</sub> hydrolysis due to increase NO<sub>x</sub> emissions in the present day. Increases in surface Cl<sub>y</sub> are due to increased release of ClNO<sub>2</sub> attributable to higher N<sub>2</sub>O<sub>5</sub> concentrations in present day.

**Table 4.** Summary of base emissions changed between for present day and preindustrial. Full documentation of emissions implemented in the model (version 10) is documented on the GEOS-Chem website ([www.geos-chem.org](http://www.geos-chem.org)).

General descriptor	Species	Reference	Included?	
			Present day	Preindustrial
GEIA – global anthropogenic	NH <sub>3</sub>	Benkovitz et al. (1996)	✓	×
EDGAR – global anthropogenic	NO, CO, SO <sub>2</sub> , SO <sub>4</sub> , NH <sub>3</sub>	JRC/NEAA (2011)	✓	×
Global anthropogenic	C <sub>2</sub> H <sub>6</sub>	Xiao et al. (2008)	✓	×
EMEP – European anthropogenic	NO, CO, SO <sub>2</sub> , SO <sub>4</sub> , NH <sub>3</sub> , VOCs	Vestreng et al. (2009)	✓	×
BRAVO – Mexican anthropogenic	NO, CO, SO <sub>2</sub> , SO <sub>4</sub>	Kuhns et al. (2003)	✓	×
CAC – Canadian anthropogenic	NO, CO, SO <sub>2</sub> , SO <sub>4</sub>	Environment Canada (2013)	✓	×
GFED – global biomass burning	NO, CO, NH <sub>3</sub> , SO <sub>2</sub> , SO <sub>4</sub> , VOCs, Organic and black carbon aerosols	van der Werf et al. (2010)	✓	Scaled to 10 % of present day
RETRO – global anthropogenic	VOCs	Benkovitz et al. (1996)	✓	×
NEI – USA anthropogenic	NO, NO <sub>2</sub> , VOCs	EPA (2015)	✓	×
BOND – global carbon aerosol	Organic and black carbon aerosols	Bond et al. (2007)	✓	Anthropogenic removed and biomass burning scaled to 10 %
AEIC – global aircraft	NO, NO <sub>2</sub> , VOCs, aerosols	Stettler et al. (2011)	✓	×
MIX – Asian anthropogenic	NO, NO <sub>2</sub> , CO, SO <sub>2</sub> , SO <sub>4</sub> , NH <sub>3</sub> , VOCs	Li et al. (2015)	✓	×
Global soil NO <sub>x</sub>	NO	Hudman et al. (2012)	✓	No fertiliser emissions
Global ship NO <sub>x</sub>	NO	Wang et al. (2008)	✓	×

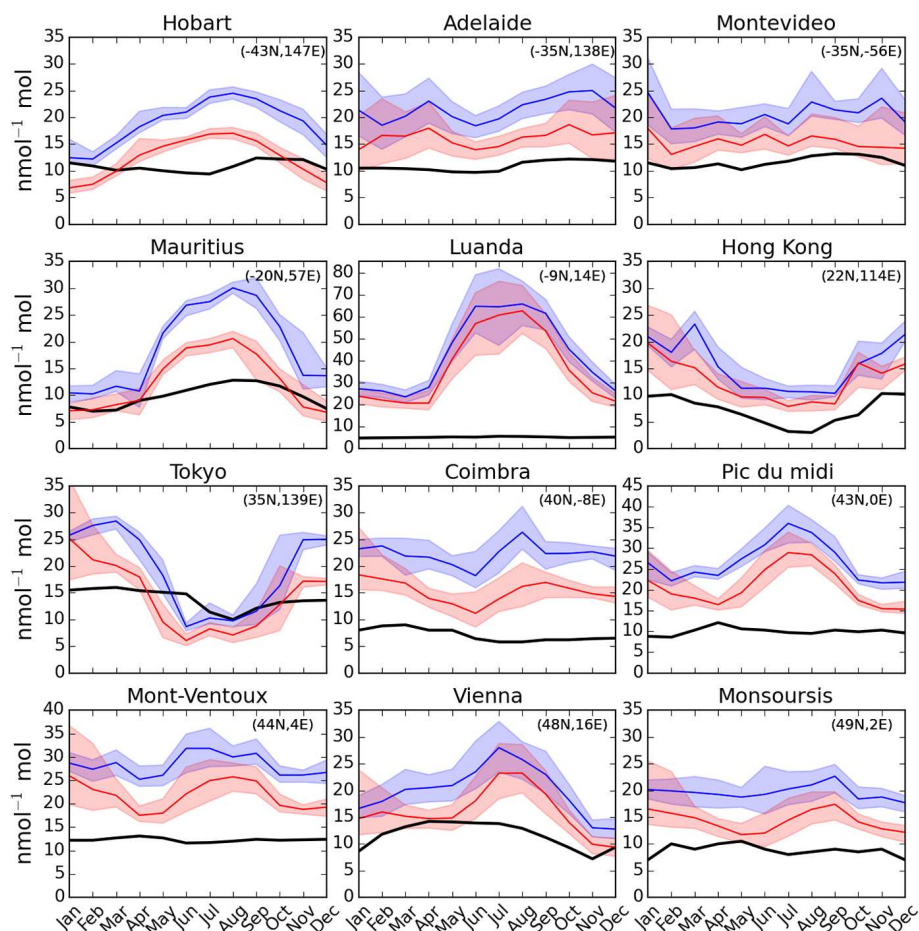
VOC is volatile organic carbon; see reference for details.

ing to dampen the anthropogenic radiative forcing of O<sub>3</sub> by 0.087 Wm<sup>−2</sup>. Given that none of the models which participated in the last IPCC assessment incorporate tropospheric halogen chemistry, it would appear that they may overestimate tropospheric O<sub>3</sub> radiative forcing by ~25 %. Our estimate for the reduction in tropospheric O<sub>3</sub> radiative forcing due to halogens is larger than the −0.05 Wm<sup>−2</sup> (−0.15 to +0.05 Wm<sup>−2</sup>) estimate of the radiative forcing of strato-

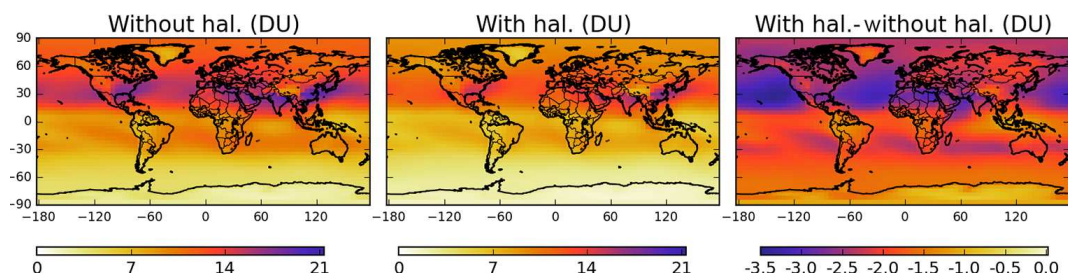
spheric O<sub>3</sub>, which is predominantly due to halogens (Myhre et al., 2013).

This halogen-induced reduction in the RF<sub>TO3</sub> is due to a combination of the increased oceanic iodine source from the increased O<sub>3</sub>, the increase in tropospheric organohalogens, and the increase in stratospheric halogen flux between the preindustrial and the present day. Removing the oceanic inorganic iodine source from the model but keeping the increase





**Figure 5.** Comparison between observed and modelled preindustrial monthly mean O<sub>3</sub>. Observations are shown in black; preindustrial model simulation with halogens are in red and without halogens are in blue. The shaded areas for the model simulation shows the first and third quartiles in the hourly values. The O<sub>3</sub> data are reproduced (Mickley et al., 2001) from previously reported observations: Mont Ventoux, Hong Kong, Tokyo, Adelaide, Coimbra, Hobart, Luanda, Mauritius, Vienna, and Montevideo (Marenco et al., 1994); Pic du Midi (Pavelin et al., 1999); Montsouris (Volz and Kley, 1988).



**Figure 6.** Increases in tropospheric O<sub>3</sub> column between the preindustrial and present day without and with halogens. Left and centre panels show the difference in annually averaged column O<sub>3</sub> (DU) between preindustrial and the present day without (left) and with halogens (centre). Right panel shows the difference.

in tropospheric halocarbons and stratospheric halogen flux gives a  $\text{RF}_{\text{TO}_3}$  of  $0.374 \text{ Wm}^{-2}$ . In addition to that change, using a present-day stratosphere for the preindustrial gives a  $\text{RF}_{\text{TO}_3}$  of  $0.389 \text{ Wm}^{-2}$ . Although the system is non-linear we thus attribute  $\sim 50\%$  to the increase in the flux of inorganic

halogens from the stratosphere,  $\sim 35\%$  of the halogen-driven reduction in O<sub>3</sub> radiative forcing to the ocean–atmosphere O<sub>3</sub>–iodine feedback, and  $\sim 15\%$  to the increase in the tropospheric halocarbons.

## 4 Conclusions

There are significant uncertainties in the chemistry of tropospheric halogens. Although the basic gas-phase chemistry of Cl and Br is well known there are larger uncertainties to the chemistry of I (Saiz-Lopez et al., 2012b). The largest uncertainties though likely lie in our understanding of the heterogeneous processing of halogens (Abbatt et al., 2012; Saiz-Lopez et al., 2012b; Sherwen et al., 2016a; Simpson et al., 2015), which affords a coupling between iodine, bromine, and chlorine and between the different emission species and sea salt. Relatively small changes to parameters here can make substantial changes to the O<sub>3</sub> radiative forcing. For example, the partitioning between ICl and IBr emissions following uptake of condensable iodine compounds to sea-salt aerosol is not well known. Changing the ICl to IBr ratio from 0.85 : 0.15 (as used here and in Sherwen et al., 2016b) to a the IBr yield (0.5 : 0.5), as used in other studies (McFiggans et al., 2000; Saiz-Lopez et al., 2014), increases the reduction in the O<sub>3</sub> radiative from the 25 % found here to 34 %. There is also a question as to whether models have some aspects of this halogen chemistry “tuned” into them through enhanced O<sub>3</sub> deposition to the ocean surface, or other mechanisms for the present day. This needs to be explored through a more detailed understanding of the deposition of O<sub>3</sub> to the ocean, but it seems unlikely that the parameterisation would slow the loss of O<sub>3</sub> in the preindustrial in the manner described here and so have the same impact on radiative forcing.

Uncertainties in the role of halogens in determining tropospheric O<sub>3</sub> radiative forcing may be reduced by more observations of halogen compounds in the present day (in the atmosphere and oceans) and by reducing uncertainties in the kinetics of the gas- and aerosol-phase chemistry. However, it would appear that model estimates of O<sub>3</sub> radiative forcing that do not consider tropospheric halogen chemistry are likely ~ 25 % too large.

## 5 Data availability

The model code used here will be made available to the community through the standard GEOS-Chem repository (<http://www.geos-chem.org>). Requests for materials should be addressed to Mat Evans ([mat.evans@york.ac.uk](mailto:mat.evans@york.ac.uk))

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

**Acknowledgements.** This work was funded by NERC quota studentship NE/K500987/1 with support from the NERC BACCHUS and CAST projects NE/L01291X/1, NE/J006165/1. J. A. Schmidt acknowledges funding through a Carlsberg Foundation post-doctoral fellowship (CF14-0519). T. Sherwen would like to acknowledge constructive comments and input from GEOS-Chem

Support Team and Daniel Jacob of Harvard University. We also acknowledge constructive input from Qianjie Chen and Becky Alexander of the University of Washington.

Edited by: J. West

Reviewed by: three anonymous referees

## References

- Abbatt, J. P. D., Lee, A. K. Y., and Thornton, J. A.: Quantifying trace gas uptake to tropospheric aerosol: recent advances and remaining challenges, *Chem. Soc. Rev.*, 41, 6555–6581, doi:10.1039/c2cs35052a, 2012.
- Ammann, M., Cox, R. A., Crowley, J. N., Jenkin, M. E., Mellouki, A., Rossi, M. J., Troe, J., and Wallington, T. J.: Evaluated kinetic and photochemical data for atmospheric chemistry: Volume VI – heterogeneous reactions with liquid substrates, *Atmos. Chem. Phys.*, 13, 8045–8228, doi:10.5194/acp-13-8045-2013, 2013.
- Atkinson, R., Baulch, D. L., Cox, R. A., Crowley, J. N., Hampson, R. F., Hynes, R. G., Jenkin, M. E., Rossi, M. J., Troe, J., and IUPAC Subcommittee: Evaluated kinetic and photochemical data for atmospheric chemistry: Volume II – gas phase reactions of organic species, *Atmos. Chem. Phys.*, 6, 3625–4055, doi:10.5194/acp-6-3625-2006, 2006.
- Atkinson, R., Baulch, D. L., Cox, R. A., Crowley, J. N., Hampson, R. F., Hynes, R. G., Jenkin, M. E., Rossi, M. J., and Troe, J.: Evaluated kinetic and photochemical data for atmospheric chemistry: Volume III – gas phase reactions of inorganic halogens, *Atmos. Chem. Phys.*, 7, 981–1191, doi:10.5194/acp-7-981-2007, 2007.
- Atkinson, R., Baulch, D. L., Cox, R. A., Crowley, J. N., Hampson, R. F., Hynes, R. G., Jenkin, M. E., Rossi, M. J., Troe, J., and Wallington, T. J.: Evaluated kinetic and photochemical data for atmospheric chemistry: Volume IV – gas phase reactions of organic halogen species, *J. Phys. Chem. Ref. Data*, 8, 4141–4496, 2008.
- Barrie, L. A., Bottenheim, J. W., Schnell, R. C., Crutzen, P. J., and Rasmussen, R. A.: Ozone destruction and photochemical reactions at polar sunrise in the lower Arctic atmosphere, *Nature*, 334, 138–141, 1988.
- Bell, N., Hsu, L., Jacob, D. J., Schultz, M. G., Blake, D. R., Butler, J. H., King, D. B., Lobert, J. M., and Maier-Reimer, E.: Methyl iodide: Atmospheric budget and use as a tracer of marine convection in global models, *J. Geophys. Res.-Atmos.*, 107, ACH 8-1–ACH 8-12, doi:10.1029/2001jd001151, 2002.
- Benkovitz, C. M., Scholtz, M. T., Pacyna, J., Tarrasón, L., Dignon, J., Voldner, E. C., Spiro, P. A., Logan, J. A., and Graedel, T. E.: Global gridded inventories of anthropogenic emissions of sulfur and nitrogen, *J. Geophys. Res.-Atmos.*, 101, 29239–29253, doi:10.1029/96JD00126, 1996.
- Bertram, T. H. and Thornton, J. A.: Toward a general parameterization of N<sub>2</sub>O<sub>5</sub> reactivity on aqueous particles: the competing effects of particle liquid water, nitrate and chloride, *Atmos. Chem. Phys.*, 9, 8351–8363, doi:10.5194/acp-9-8351-2009, 2009.
- Bey, I., Jacob, D. J., Yantosca, R. M., Logan, J. A., Field, B. D., Fiore, A. M., Li, Q., Liu, H. Y., Mickley, L. J., and Schultz, M. G.: Global modeling of tropospheric chemistry with assimilated meteorology: Model description and evaluation, *J.*

- Geophys. Res., 106, 23073–23095, doi:10.1029/2001JD000807, 2001.
- Bond, T. C., Bhardwaj, E., Dong, R., Jogani, R., Jung, S., Roden, C., Streets, D. G., and Trautmann, N. M.: Historical emissions of black and organic carbon aerosol from energy-related combustion, 1850–2000, *Global Biogeochem. Cy.*, 21, GB2018, doi:10.1029/2006GB002840, 2007.
- Braban, C. F., Adams, J. W., Rodriguez, D., Cox, R. A., Crowley, J. N., and Schuster, G.: Heterogeneous reactions of HOI, ICl and IBr on sea salt and sea salt proxies, *Phys. Chem. Chem. Phys.*, 9, 3136–3148, doi:10.1039/b700829e, 2007.
- Carpenter, L. J., MacDonald, S. M., Shaw, M. D., Kumar, R., Saunders, R. W., Parthipan, R., Wilson, J., and Plane, J. M. C.: Atmospheric iodine levels influenced by sea surface emissions of inorganic iodine, *Nat. Geosci.*, 6, 108–111, doi:10.1038/ngeo1687, 2013.
- Chameides, W. L. and Davis, D. D.: Iodine: Its possible role in tropospheric photochemistry, *J. Geophys. Res.-Oceans*, 85, 7383–7398, doi:10.1029/JC085iC12p07383, 1980.
- Dix, B., Baidar, S., Bresch, J., Hall, S., Schmidt, K., Wang, S.-Y., and Volkamer, R.: Detection of iodine monoxide in the tropical free troposphere, *P. Natl. Acad. Sci. USA*, 110, 2035–2040, doi:10.1073/pnas.1212386110, 2013.
- Eastham, S. D., Weisenstein, D. K., and Barrett, S. R. H.: Development and evaluation of the unified tropospheric-stratospheric chemistry extension (UCX) for the global chemistry-transport model GEOS-Chem, *Atmos. Environ.*, 89, 52–63, doi:10.1016/j.atmosenv.2014.02.001, 2014.
- Environment Canada: Criteria Air Contaminants (CAC) inventory, [http://www.ec.gc.ca/pdb/cac/cac\\_home\\_e.cfm](http://www.ec.gc.ca/pdb/cac/cac_home_e.cfm) (last access: 31 October 2013), 2013.
- EPA: 2011 National Emissions Inventory (NEI), version 2 Technical Support Document, Tech. rep., Environmental Protection Agency (EPA), 2015.
- Fry, M. M., Naik, V., West, J. J., Schwarzkopf, M. D., Fiore, A. M., Collins, W. J., Dentener, F. J., Shindell, D. T., Ather-ton, C., Bergmann, D., Duncan, B. N., Hess, P., MacKenzie, I. A., Marmer, E., Schultz, M. G., Szopa, S., Wild, O., and Zeng, G.: The influence of ozone precursor emissions from four world regions on tropospheric composition and radiative climate forcing, *J. Geophys. Res.-Atmos.*, 117, D07306, doi:10.1029/2011JD017134, 2012.
- Gauss, M., Myhre, G., Pitari, G., Prather, M. J., Isaksen, I. S. A., Bernsten, T. K., Brasseur, G. P., Dentener, F. J., Derwent, R. G., Hauglustaine, D. A., Horowitz, L. W., Jacob, D. J., Johnson, M., Law, K. S., Mickley, L. J., Müller, J.-F., Plantevin, P.-H., Pyle, J. A., Rogers, H. L., Stevenson, D. S., Sundet, J. K., van Weele, M., and Wild, O.: Radiative forcing in the 21st century due to ozone changes in the troposphere and the lower stratosphere, *J. Geophys. Res.-Atmos.*, 108, 4292, doi:10.1029/2002JD002624, 2003.
- Glasius, M. and Goldstein, A. H.: Recent Discoveries and Future Challenges in Atmospheric Organic Chemistry, *Environ. Sci. Technol.*, 50, 2754–2764, doi:10.1021/acs.est.5b05105, 2016.
- Gómez Martín, J. C., Mahajan, A. S., Hay, T. D., Prados-Roman, C., Ordonez, C., MacDonald, S. M., Plane, J. M. C., Sorribas, M., Gil, M., Mora, J. F. P., Reyes, M. V. A., Oram, D. E., Leedham, E., and Saiz-Lopez, A.: Iodine chemistry in the eastern Pacific marine boundary layer, *J. Geophys. Res.-Atmos.*, 118, 887–904, doi:10.1002/jgrd.50132, 2013.
- Hauglustaine, D. A., Granier, C., Brasseur, G. P., and Mégie, G.: The importance of atmospheric chemistry in the calculation of radiative forcing on the climate system, *J. Geophys. Res.-Atmos.*, 99, 1173–1186, doi:10.1029/93JD02987, 1994.
- Holmes, C. D., Jacob, D. J., Corbitt, E. S., Mao, J., Yang, X., Talbot, R., and Slemr, F.: Global atmospheric model for mercury including oxidation by bromine atoms, *Atmos. Chem. Phys.*, 10, 12037–12057, doi:10.5194/acp-10-12037-2010, 2010.
- Hudman, R. C., Moore, N. E., Mebust, A. K., Martin, R. V., Russell, A. R., Valin, L. C., and Cohen, R. C.: Steps towards a mechanistic model of global soil nitric oxide emissions: implementation and space based-constraints, *Atmos. Chem. Phys.*, 12, 7779–7795, doi:10.5194/acp-12-7779-2012, 2012.
- Jacob, D. J., Wofsy, S. C., Bakwin, P. S., Fan, S.-M., Harriss, R. C., Talbot, R. W., Bradshaw, J. D., Sandholm, S. T., Singh, H. B., Browell, E. V., Gregory, G. L., Sachse, G. W., Shipham, M. C., Blake, D. R., and Fitzjarrald, D. R.: Summertime photochemistry of the troposphere at high northern latitudes, *J. Geophys. Res.-Atmos.*, 97, 16421–16431, doi:10.1029/91JD01968, 1992.
- JRC/NEAA: Emission Database for Global Atmospheric Research (EDGAR) – Emission Database for Global Atmospheric Research version 4.2, <http://edgar.jrc.ec.europa.eu> (28 March 2014), 2011.
- Knorr, W., Jiang, L., and Arneth, A.: Climate, CO<sub>2</sub> and human population impacts on global wildfire emissions, *Biogeosciences*, 13, 267–282, doi:10.5194/bg-13-267-2016, 2016.
- Kuhns, H., Green, M., and Etyemezian, V.: Big Bend Regional Aerosol and Visibility Observational (BRAVO) Study Emissions Inventory, tech. rep., 2003.
- Lamarque, J. F., Hess, P., Emmons, L., Buja, L., Washington, W., and Granier, C.: Tropospheric ozone evolution between 1890 and 1990, *J. Geophys. Res.-Atmos.*, 110, D08304, doi:10.1029/2004JD005537, 2005.
- Lamarque, J.-F., Bond, T. C., Eyring, V., Granier, C., Heil, A., Klimont, Z., Lee, D., Liousse, C., Mieville, A., Owen, B., Schultz, M. G., Shindell, D., Smith, S. J., Stehfest, E., Van Aardenne, J., Cooper, O. R., Kainuma, M., Mahowald, N., McConnell, J. R., Naik, V., Riahi, K., and van Vuuren, D. P.: Historical (1850–2000) gridded anthropogenic and biomass burning emissions of reactive gases and aerosols: methodology and application, *Atmos. Chem. Phys.*, 10, 7017–7039, doi:10.5194/acp-10-7017-2010, 2010.
- Lamarque, J.-F., Shindell, D. T., Josse, B., Young, P. J., Cionni, I., Eyring, V., Bergmann, D., Cameron-Smith, P., Collins, W. J., Doherty, R., Dalsoren, S., Faluvegi, G., Folberth, G., Ghan, S. J., Horowitz, L. W., Lee, Y. H., MacKenzie, I. A., Nagashima, T., Naik, V., Plummer, D., Righi, M., Rumbold, S. T., Schulz, M., Skeie, R. B., Stevenson, D. S., Strode, S., Sudo, K., Szopa, S., Voulgarakis, A., and Zeng, G.: The Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP): overview and description of models, simulations and climate diagnostics, *Geosci. Model Dev.*, 6, 179–206, doi:10.5194/gmd-6-179-2013, 2013.
- Levy, H., Kasibhatla, P. S., Moxim, W. J., Klonecki, A. A., Hirsch, A. I., Oltmans, S. J., and Chameides, W. L.: The global impact of human activity on tropospheric ozone, *Geophys. Res. Lett.*, 24, 791–794, doi:10.1029/97GL00599, 1997.

- Li, M., Zhang, Q., Kurokawa, J., Woo, J.-H., He, K. B., Lu, Z., Ohara, T., Song, Y., Streets, D. G., Carmichael, G. R., Cheng, Y. F., Hong, C. P., Huo, H., Jiang, X. J., Kang, S. C., Liu, F., Su, H., and Zheng, B.: MIX: a mosaic Asian anthropogenic emission inventory for the MICS-Asia and the HTAP projects, *Atmos. Chem. Phys. Discuss.*, 15, 34813–34869, doi:10.5194/acpd-15-34813-2015, 2015.
- Liang, Q., Stolarski, R. S., Kawa, S. R., Nielsen, J. E., Douglass, A. R., Rodriguez, J. M., Blake, D. R., Atlas, E. L., and Ott, L. E.: Finding the missing stratospheric Br<sub>y</sub>: a global modeling study of CHBr<sub>3</sub> and CH<sub>2</sub>Br<sub>2</sub>, *Atmos. Chem. Phys.*, 10, 2269–2286, doi:10.5194/acp-10-2269-2010, 2010.
- Long, M. S., Keene, W. C., Easter, R. C., Sander, R., Liu, X., Kerkweg, A., and Erickson, D.: Sensitivity of tropospheric chemical composition to halogen-radical chemistry using a fully coupled size-resolved multiphase chemistry–global climate system: halogen distributions, aerosol composition, and sensitivity of climate-relevant gases, *Atmos. Chem. Phys.*, 14, 3397–3425, doi:10.5194/acp-14-3397-2014, 2014.
- MacDonald, S. M., Gómez Martín, J. C., Chance, R., Warriner, S., Saiz-Lopez, A., Carpenter, L. J., and Plane, J. M. C.: A laboratory characterisation of inorganic iodine emissions from the sea surface: dependence on oceanic variables and parameterisation for global modelling, *Atmos. Chem. Phys.*, 14, 5841–5852, doi:10.5194/acp-14-5841-2014, 2014.
- Mahajan, A. S., Plane, J. M. C., Oetjen, H., Mendes, L., Saunders, R. W., Saiz-Lopez, A., Jones, C. E., Carpenter, L. J., and McFiggans, G. B.: Measurement and modelling of tropospheric reactive halogen species over the tropical Atlantic Ocean, *Atmos. Chem. Phys.*, 10, 4611–4624, doi:10.5194/acp-10-4611-2010, 2010.
- Mahajan, A. S., Gómez Martín, J. C., Hay, T. D., Royer, S.-J., Yvon-Lewis, S., Liu, Y., Hu, L., Prados-Roman, C., Ordóñez, C., Plane, J. M. C., and Saiz-Lopez, A.: Latitudinal distribution of reactive iodine in the Eastern Pacific and its link to open ocean sources, *Atmos. Chem. Phys.*, 12, 11609–11617, doi:10.5194/acp-12-11609-2012, 2012.
- Marengo, A., Gouget, H., Nédélec, P., Pagés, J.-P., and Karcher, F.: Evidence of a long-term increase in tropospheric ozone from Pic du Midi data series: Consequences: Positive radiative forcing, *J. Geophys. Res.-Atmos.*, 99, 16617–16632, doi:10.1029/94JD00021, 1994.
- McFiggans, G., Plane, J. M. C., Allan, B. J., Carpenter, L. J., Coe, H., and O'Dowd, C.: A modeling study of iodine chemistry in the marine boundary layer, *J. Geophys. Res.-Atmos.*, 105, 14371–14385, doi:10.1029/1999JD901187, 2000.
- Mickley, L. J., Jacob, D. J., and Rind, D.: Uncertainty in preindustrial abundance of tropospheric ozone: Implications for radiative forcing calculations, *J. Geophys. Res.-Atmos.*, 106, 3389–3399, doi:10.1029/2000JD900594, 2001.
- Monks, P. S., Archibald, A. T., Colette, A., Cooper, O., Coyle, M., Derwent, R., Fowler, D., Granier, C., Law, K. S., Mills, G. E., Stevenson, D. S., Tarasova, O., Thouret, V., von Schneidmesser, E., Sommariva, R., Wild, O., and Williams, M. L.: Tropospheric ozone and its precursors from the urban to the global scale from air quality to short-lived climate forcer, *Atmos. Chem. Phys.*, 15, 8889–8973, doi:10.5194/acp-15-8889-2015, 2015.
- Montzka, S. A., Reimann, S., Engel, A., Krueger, K., O'Doherty, S., Sturges, W. T., Blake, D., Dorf, M., Fraser, P., Froidevaux, L., Jucks, K., Kreher, K., Kurylo, M. J., Mellouki, A., Miller, J., Nielsen, O.-J., Orkin, V. L., Prinn, R. G., Rhew, R., Santee, M. L., and Verdonik, D.: Ozone-Depleting Substances (ODSs) and Related Chemicals. Chapter 1 in Scientific Assessment of Ozone Depletion: 2010, Global Ozone Research and Monitoring Project, Report No. 52, 516 pp., World Meteorological Organization, Geneva, Switzerland, Tech. rep., World Health Organisation, Geneva, Switzerland, 2011.
- Murray, L. T., Jacob, D. J., Logan, J. A., Hudman, R. C., and Koshak, W. J.: Optimized regional and interannual variability of lightning in a global chemical transport model constrained by LIS/OTD satellite data, *J. Geophys. Res.-Atmos.*, 117, D20307, doi:10.1029/2012JD017934, 2012.
- Murray, L. T., Mickley, L. J., Kaplan, J. O., Sofen, E. D., Pfeiffer, M., and Alexander, B.: Factors controlling variability in the oxidative capacity of the troposphere since the Last Glacial Maximum, *Atmos. Chem. Phys.*, 14, 3589–3622, doi:10.5194/acp-14-3589-2014, 2014.
- Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestad, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and Zhang, H.: Anthropogenic and Natural Radiative Forcing, in: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, tech. rep., IPCC, 2013.
- Parrella, J. P., Jacob, D. J., Liang, Q., Zhang, Y., Mickley, L. J., Miller, B., Evans, M. J., Yang, X., Pyle, J. A., Theys, N., and Van Roozendael, M.: Tropospheric bromine chemistry: implications for present and pre-industrial ozone and mercury, *Atmos. Chem. Phys.*, 12, 6723–6740, doi:10.5194/acp-12-6723-2012, 2012.
- Pavelin, E. G., Johnson, C. E., Rughooputh, S., and Toumi, R.: Evaluation of pre-industrial surface ozone measurements made using Schönbein's method, *Atmos. Environ.*, 33, 919–929, doi:10.1016/S1352-2310(98)00257-X, 1999.
- Prados-Roman, C., Cuevas, C. A., Hay, T., Fernandez, R. P., Mahajan, A. S., Royer, S.-J., Galí, M., Simó, R., Dachs, J., Großmann, K., Kinnison, D. E., Lamarque, J.-F., and Saiz-Lopez, A.: Iodine oxide in the global marine boundary layer, *Atmos. Chem. Phys.*, 15, 583–593, doi:10.5194/acp-15-583-2015, 2015.
- Read, K. A., Mahajan, A. S., Carpenter, L. J., Evans, M. J., Faria, B. V. E., Heard, D. E., Hopkins, J. R., Lee, J. D., Moller, S. J., Lewis, A. C., Mendes, L., McQuaid, J. B., Oetjen, H., Saiz-Lopez, A., Pilling, M. J., and Plane, J. M. C.: Extensive halogen-mediated ozone destruction over the tropical Atlantic Ocean, *Nature*, 453, 1232–1235, doi:10.1038/nature07035, 2008.
- Reimann, S., Carpenter, L. J., Lead, A., Burkholder, J., Clerbaux, C., Hall, B. D., Hossaini, R., Laube, J., and Yvon-Lewis, S. A.: Ozone-Depleting Substances (ODSs) and Other Gases of Interest to the Montreal Protocol Chapter 1 in Scientific Assessment of Ozone Depletion: 2014, Global Ozone Research and Monitoring Project – Report No. 55, tech. rep., World Meteorological Organization, Geneva, Switzerland, 2014.
- Roberts, J. M., Osthoff, H. D., Brown, S. S., Ravishankara, A. R., Coffman, D., Quinn, P., and Bates, T.: Laboratory studies of products of N<sub>2</sub>O<sub>5</sub> uptake on Cl containing substrates, *Geophys. Res. Lett.*, 36, L20808, doi:10.1029/2009GL040448, 2009.
- Saiz-Lopez, A., Lamarque, J. F., Kinnison, D. E., Tilmes, S., Ordonez, C., Orlando, J. J., Conley, A. J., Plane, J. M. C., Mahajan, A. S., Santos, G. S., Atlas, E. L., Blake, D. R., Sander, S. P., Schauffler, S., Thompson, A. M., and Brasseur, G.: Estimating

- the climate significance of halogen-driven ozone loss in the tropical marine troposphere, *Atmos. Chem. Phys.*, 12, 3939–3949, doi:10.5194/acp-12-3939-2012, 2012a.
- Saiz-Lopez, A., Plane, J. M. C., Baker, A. R., Carpenter, L. J., von Glasow, R., Martin, J. C. G., McFiggans, G., and Saunders, R. W.: Atmospheric Chemistry of Iodine, *Chem. Rev.*, 112, 1773–1804, doi:10.1021/cr200029u, 2012b.
- Saiz-Lopez, A., Fernandez, R. P., Ordóñez, C., Kinnison, D. E., Gómez Martín, J. C., Lamarque, J.-F., and Tilmes, S.: Iodine chemistry in the troposphere and its effect on ozone, *Atmos. Chem. Phys.*, 14, 13119–13143, doi:10.5194/acp-14-13119-2014, 2014.
- Saltzman, E. S., Aydin, M., De Bruyn, W. J., King, D. B., and Yvon-Lewis, S. A.: Methyl bromide in preindustrial air: Measurements from an Antarctic ice core, *J. Geophys. Res.-Atmos.*, 109, D05301, doi:10.1029/2003JD004157, 2004.
- Sander, S. P., Friedl, R. R., Abbatt, J. P. D., Barker, J. R., Burkholder, J. B., Golden, D. M., Kolb, C. E., Kurylo, M. J., Moortgat, G. K., Wine, P. H., Huie, R. E., and Orkin, V. L.: Chemical kinetics and photochemical data for use in atmospheric studies, Evaluation Number 17, Tech. rep., NASA Jet Propulsion Laboratory, Pasadena, 2011.
- Schmidt, J. A., Jacob, D. J., Horowitz, H. M., Hu, L., Sherwen, T., Evans, M. J., Liang, Q., Suleiman, R. M., Oram, D. E., Breton, M. L., Percival, C. J., Wang, S., Dix, B., and Volkamer, R.: Modeling the observed tropospheric BrO background: Importance of multiphase chemistry and implications for ozone, OH, and mercury, *J. Geophys. Res.-Atmos.*, 2169–8996, doi:10.1002/2015JD024229, 2016.
- Sherwen, T., Evans, M. J., Carpenter, L. J., Andrews, S. J., Lidster, R. T., Dix, B., Koenig, T. K., Sinreich, R., Ortega, I., Volkamer, R., Saiz-Lopez, A., Prados-Roman, C., Mahajan, A. S., and Ordóñez, C.: Iodine's impact on tropospheric oxidants: a global model study in GEOS-Chem, *Atmos. Chem. Phys.*, 16, 1161–1186, doi:10.5194/acp-16-1161-2016, 2016a.
- Sherwen, T., Schmidt, J. A., Evans, M. J., Carpenter, L. J., Großmann, K., Eastham, S. D., Jacob, D. J., Dix, B., Koenig, T. K., Sinreich, R., Ortega, I., Volkamer, R., Saiz-Lopez, A., Prados-Roman, C., Mahajan, A. S., and Ordóñez, C.: Global impacts of tropospheric halogens (Cl, Br, I) on oxidants and composition in GEOS-Chem, *Atmos. Chem. Phys.*, 16, 12239–12271, doi:10.5194/acp-16-12239-2016, 2016b.
- Simpson, W. R., Brown, S. S., Saiz-Lopez, A., Thornton, J. A., and von Glasow, R.: Tropospheric Halogen Chemistry: Sources, Cycling, and Impacts, *Chem. Rev.*, 115, 4035–4062, doi:10.1021/cr5006638, 2015.
- Stettler, M., Eastham, S., and Barrett, S.: Air quality and public health impacts of UK airports. Part I: Emissions, *Atmos. Environ.*, 45, 5415–5424, doi:10.1016/j.atmosenv.2011.07.012, 2011.
- Stevenson, D. S., Young, P. J., Naik, V., Lamarque, J.-F., Shindell, D. T., Voulgarakis, A., Skeie, R. B., Dalsoren, S. B., Myhre, G., Bernsten, T. K., Folberth, G. A., Rumbold, S. T., Collins, W. J., MacKenzie, I. A., Doherty, R. M., Zeng, G., van Noije, T. P. C., Strunk, A., Bergmann, D., Cameron-Smith, P., Plummer, D. A., Strode, S. A., Horowitz, L., Lee, Y. H., Szopa, S., Sudo, K., Nagashima, T., Josse, B., Cionni, I., Righi, M., Eyring, V., Conley, A., Bowman, K. W., Wild, O., and Archibald, A.: Tropospheric ozone changes, radiative forcing and attribution to emissions in the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), *Atmos. Chem. Phys.*, 13, 3063–3085, doi:10.5194/acp-13-3063-2013, 2013.
- van der Werf, G. R., Randerson, J. T., Giglio, L., Collatz, G. J., Mu, M., Kasibhatla, P. S., Morton, D. C., DeFries, R. S., Jin, Y., and van Leeuwen, T. T.: Global fire emissions and the contribution of deforestation, savanna, forest, agricultural, and peat fires (1997–2009), *Atmos. Chem. Phys.*, 10, 11707–11735, doi:10.5194/acp-10-11707-2010, 2010.
- van der Werf, G. R., Peters, W., van Leeuwen, T. T., and Giglio, L.: What could have caused pre-industrial biomass burning emissions to exceed current rates?, *Clim. Past*, 9, 289–306, doi:10.5194/cp-9-289-2013, 2013.
- Vestreng, V., Ntziachristos, L., Semb, A., Reis, S., Isaksen, I. S. A., and Tarrasón, L.: Evolution of NO<sub>x</sub> emissions in Europe with focus on road transport control measures, *Atmos. Chem. Phys.*, 9, 1503–1520, doi:10.5194/acp-9-1503-2009, 2009.
- Volkamer, R., Baidar, S., Campos, T., Coburn, S., DiGangi, J., Dix, B., Eloranta, E., Koenig, T., Moley, B., Ortega, I., Pierce, B., Reeves, M., Sinreich, R., Wang, S.-Y., Zondlo, M., and Romashkin, P.: Aircraft measurements of BrO, IO, glyoxal, NO<sub>2</sub>, H<sub>2</sub>O, O<sub>2</sub>–O<sub>2</sub> and aerosol extinction profiles in the tropics: Comparison with aircraft-/ship-based in situ and lidar measurements, *Atmos. Meas. Tech.*, 8, 623–687, doi:10.5194/amt-8-2121-2015, 2015.
- Volz, A. and Kley, D.: Evaluation of the Montsouris series of ozone measurements made in the nineteenth century, *Nature*, 332, 240–242, doi:10.1038/332240a0, 1988.
- von Glasow, R., von Kuhlmann, R., Lawrence, M. G., Platt, U., and Crutzen, P. J.: Impact of reactive bromine chemistry in the troposphere, *Atmos. Chem. Phys.*, 4, 2481–2497, doi:10.5194/acp-4-2481-2004, 2004.
- Voulgarakis, A., Naik, V., Lamarque, J.-F., Shindell, D. T., Young, P. J., Prather, M. J., Wild, O., Field, R. D., Bergmann, D., Cameron-Smith, P., Cionni, I., Collins, W. J., Dalsøren, S. B., Doherty, R. M., Eyring, V., Faluvegi, G., Folberth, G. A., Horowitz, L. W., Josse, B., MacKenzie, I. A., Nagashima, T., Plummer, D. A., Righi, M., Rumbold, S. T., Stevenson, D. S., Strode, S. A., Sudo, K., Szopa, S., and Zeng, G.: Analysis of present day and future OH and methane lifetime in the ACCMIP simulations, *Atmos. Chem. Phys.*, 13, 2563–2587, doi:10.5194/acp-13-2563-2013, 2013.
- Wang, C., Corbett, J. J., and Firestone, J.: Improving Spatial Representation of Global Ship Emissions Inventories, *Environ. Sci. Technol.*, 42, 193–199, doi:10.1021/es0700799, 2008.
- Wang, S.-Y., Schmidtd, J., Baidar, S., Coburn, S., Dix, B., Koenig, T., Apel, E., Bowdalo, D., Campos, T., Eloranta, E., Evans, M., DiGangii, J., Zondlo, M., Gao, R.-S., Haggerty, J., Hall, S., Hornbrook, R., Jacob, D., Morley, B., Pierce, B., Reeves, M., Romashkin, P., ter Schure, A., and Volkamer, R.: Active and widespread halogen chemistry in the tropical and subtropical free troposphere, *P. Natl. Acad. Sci. USA*, 112, 9281–9286, doi:10.1073/pnas.1505142112, 2015.
- Wang, Y. and Jacob, D. J.: Anthropogenic forcing on tropospheric ozone and OH since preindustrial times, *J. Geophys. Res.-Atmos.*, 103, 31123–31135, doi:10.1029/1998JD100004, 1998.
- Xiao, Y., Logan, J. A., Jacob, D. J., Hudman, R. C., Yantosca, R., and Blake, D. R.: Global budget of ethane and regional constraints on U.S. sources, *J. Geophys. Res.*, 113, D21306, doi:10.1029/2007JD009415, 2008.

Young, P. J., Archibald, A. T., Bowman, K. W., Lamarque, J. F., Naik, V., Stevenson, D. S., Tilmes, S., Voulgarakis, A., Wild, O., Bergmann, D., Cameron-Smith, P., Cionni, I., Collins, W. J., Dalsøren, S. B., Doherty, R. M., Eyring, V., Faluvegi, G., Horowitz, L. W., Josse, B., Lee, Y. H., MacKenzie, I. A., Nagashima, T., Plummer, D. A., Righi, M., Rumbold, S. T., Skeie, R. B., Shindell, D. T., Strode, S. A., Sudo, K., Szopa, S., and Zeng, G.: Pre-industrial to end 21st century projections of tropospheric ozone from the Atmospheric Chemistry and Climate Model Intercomparison Project (ACCMIP), *Atmos. Chem. Phys.*, 13, 2063–2090, doi:10.5194/acp-13-2063-2013, 2013.