

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/103497/>

Version: Accepted Version

Article:

Sherwen, Tomás orcid.org/0000-0002-3006-3876, Evans, Mathew John orcid.org/0000-0003-4775-032X, Carpenter, Lucy Jane orcid.org/0000-0002-6257-3950 et al. (2 more authors) (2016) Halogen chemistry reduces tropospheric O3 radiative forcing. Atmospheric Chemistry and Physics Discussions. ISSN 1680-7367

<https://doi.org/10.5194/acp-2016-688>

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 including the URL of the record and the reason for the withdrawal request.



Halogen chemistry reduces tropospheric O₃ radiative forcing

T. Sherwen¹, M. J. Evans^{1,2}, L. J. Carpenter¹, J. A. Schmidt³, and L. J. Mickely⁴

¹Wolfson Atmospheric Chemistry Laboratories, Department of Chemistry, University of York, York, YO10 5DD, UK

²National Centre for Atmospheric Science, University of York, York, YO10 5DD, UK

³Department of Chemistry, Copenhagen University, Universitetsparken, DK-2100 Copenhagen O, Denmark

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

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

Abstract. Tropospheric ozone (O₃) is a global warming gas, however the lack of a firm observational record since the pre-industrial period means that estimates of its radiative forcing (RF_{TO3}) 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 O₃. Using the GEOS-Chem model we show that tropospheric halogen chemistry is more active in the present-day than in the pre-industrial. This is due to increased oceanic iodine emissions driven by increased surface O₃, higher anthropogenic emissions of bromo-carbons and an increased flux of bromine from the stratosphere. We calculate pre-industrial to present-day increases in the tropospheric O₃ burden of 113 Tg without halogens but only 95 Tg with, leading to a reduction in RF_{TO3} from 0.432 to 0.366 Wm⁻². We attribute ~40% of this reduction to the ocean-atmosphere iodine feedback, ~30% to increased anthropogenic halogens in the troposphere and ~30% to increased bromine flux from the stratosphere. This reduction of RF_{TO3} (0.066 Wm⁻²) is greater than that from stratospheric ozone (~0.05 Wm⁻²). Estimates of RF_{TO3} that fail to consider halogen chemistry are likely overestimates (~20%).

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 (O₃) concentrations. However recent studies have shown that halogens play an important and pervasive role in the chemistry of the present-day troposphere (Parrella et al., 2012; Saiz-Lopez et al., 2012a, 2014; Schmidt et al., 2016; Sherwen et al., 2016a, b). The fact that the models that are used to calculate radiative forcing of tropospheric O₃ (RF_{TO3}) do not contain this chemistry (Hauglustaine et al., 1994; Levy et al., 1997; Myhre et al., 2013; Young et al., 2013) raises questions over their ability to reproduce tropospheric composition as more and more 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).

Tropospheric O₃ is a climate gas and a potent air pollutant. Understanding the change in its concentration from the “natural” pre-industrial (~1750) atmosphere to the present-day, is important in defining those roles and informing policy decisions. Global tropospheric O₃ concentrations are thought to have increased substantially in this period (Lamarque et al., 2010; Myhre et al., 2013), however, the observational record for this change is highly uncertain. Unlike carbon dioxide and methane, O₃



does not remain trapped in ice so modern analytical techniques cannot be applied to old air. Past observations suggest much lower concentrations of O₃ 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 assessment of the change in O₃ 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 pre-industrial 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 concentrations between the pre-industrial 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), which concluded that pre-industrial tropospheric O₃ burdens were 98 Tg lower than the present-day and estimated a RF_{TO_3} of 0.410 W m⁻².

These model calculations are only as good as the emissions used to drive them and their representation of physical and chemical processes. Over the last decades, the emphasis for tropospheric chemistry has been on improving the representation of organic chemistry with particular emphasis on the role of biogenic compounds such as isoprene and monoterpenes (Glasius and Goldstein, 2016). This has contrasted with the stratosphere where the emphasis has been on halogen (predominantly Br and Cl) chemistry (Morgenstern et al., 2010).

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 O₃ 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 O₃ destruction (von Glasow et al., 2004; Simpson et al., 2015), changes to HO_x and NO_x 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 O₃ concentrations between the pre-industrial 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 (Eastham et al., 2014; 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 pre-industrial and present-day emissions, with and without halogen chemistry. From these we evaluate the changes in the tropospheric O₃ and hence radiative forcing.



2 Model description

We use the GEOS-Chem model of chemistry and transport (www.geos-chem.org, Bey et al. 2001), which includes O_x, HO_x, NO_x, and VOC chemistry. The model is an enhancement of this with a representation of halogen chemistry (Eastham et al., 2014; 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 organo-halogens (CH₃I, CH₂I₂, CH₂ICl, CH₂IBr, CHBr₃, CH₂Br₂) 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 (CH₃Br, CH₃Cl, CHCl₃, CH₂Cl₂) 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/INO₂/INO₃ $\xrightarrow{\text{sea-salt}}$ IX, X=Cl, Br) and N₂O₅ (N₂O₅ $\xrightarrow{\text{sea-salt}}$ ClNO₂ + HNO₃, for Cl) as described in Sherwen et al. (2016b). HOI and I₂ are emitted from the ocean surface dependent on the O₃ concentration in the model's lowest level and the iodide concentration of 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 two 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 pre-industrial troposphere, anthropogenic NO_x, VOC and SO₂ emissions are removed, biomass burning emissions are reduced to 10 % of their present-day values and the methane concentration is reduced to 700 pmol mol⁻¹ (Wang and Jacob, 1998). Emission of iodocarbons are unchanged between the pre-industrial and the present-day. For bromocarbons we follow a previous methodology (Parrella et al., 2012) of not changing CHBr₃ and CH₂Br₂ from their present-day values, but reducing the CH₃Br concentration assumed from 6-9 pmol mol⁻¹ in the present-day to 5 pmol mol⁻¹ to match ice core records (Saltzman et al., 2004). Pre-industrial emissions of CH₃Cl, CHCl₃, and CH₂Cl₂ 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 pre-industrial 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_y in the pre-industrial 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_y as chlorine's impact on tropospheric O₃ has previously been shown to be insignificantly small (Sherwen et al., 2016b).



2.1 Results and Discussion

2.1.1 Changes from pre-industrial to present

Table 1 shows our estimate of halogen emissions for the pre-industrial and the present-day. Iodine, bromine and chlorine emissions increase by 50 %, 25 % and 40 %. The enhanced iodine emission is due to the increases in the surface ocean inorganic (HOI, I₂) source (Fig. 1) driven by anthropogenically-enhanced surface O₃ (Fig. 2). Bromine emissions increase mainly because of increased anthropogenic precursor emissions but also due to increased iodine driven sea-salt cycling (Sherwen et al., 2016b) and an increased stratospheric flux. Chlorine emissions increase due to enhanced NO_x concentration leading to more heterogeneous uptake of N₂O₅ on sea-salt liberating ClNO₂, together with increased anthropogenic emissions of chlorinated halocarbons and faster iodine driven sea-salt release of ICl.

These increased emissions lead to increased concentrations of halogens in the present-day compared to the pre-industrial with global burdens of reactive inorganic halogen species increasing by 19, 42 and 18 % for I_y, Br_y, and Cl_y, 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 2.9 days in the pre-industrial to 2.3 days in the present-day. This is mainly due to higher NO_x concentrations which enhance iodine nitrate hydrolysis (Ammann et al., 2013; Schmidt et al., 2016). Bromine lifetimes lengthen from 13.4 days in the pre-industrial to 15.2 in the present-day. This is predominantly due to the increase in Br_y flux from the stratosphere which is a region of low depositional loss. Inorganic chlorine lifetimes shortens from 5.3 days in the pre-industrial to 4.5 in the present-day due to the increase in methane concentrations which push Cl_y into HCl, which is then readily deposited.

The inclusion of halogens reduces the concentration of O₃ in both the present-day and the pre-industrial simulations. The O₃ 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 O₃ observations for pre-industrial locations (Marengo et al., 1994; Pavelin et al., 1999; Volz and Kley, 1988) and the model. Globally surface O₃ concentrations are reduced by 9.2 nmol mol⁻¹ (37%) in the pre-industrial on inclusion of halogens (Fig. 2), making the model more consistent with observations. This reduction is largest over the oceans. Confidence in the pre-industrial 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 O₃ burden by 61 Tg in the present-day and 43 Tg in the pre-industrial (Table 2).

The O₃ budgets for the four simulations are shown in Table 2. In both the present-day and the pre-industrial the halogens are responsible for around 20 % of the O₃ destruction, with iodine dominating (66 %: 32 %: 3 % I:Br:Cl for the present-day and 69 %: 28 %: 2 % I:Br:Cl for the pre-industrial). Although chlorine concentrations have increased almost as much as iodine between the pre-industrial and the present, it plays little role in determining O₃ loss (Schmidt et al., 2016; Sherwen et al., 2016a, b). Tropospheric O₃ lifetimes drop from 26 days to 22 days in the present-day with the inclusion of halogens and from 28 days to 25 days in the pre-industrial.

Tropospheric chemistry is a highly coupled system with significant interplay between the NO_x, HO_x and RO_x systems (Monks et al., 2015). Changes in the individual production and loss terms are relatively small but halogens reduce net O₃



production by 159 Tg yr^{-1} in the present-day and only 119 Tg yr^{-1} in the pre-industrial. In our pre-industrial simulation with halogens, the troposphere is close to being a net chemical sink for O_3 . Thus the impact of halogen chemistry on the overall O_3 burden of the troposphere is more important for the present-day than it was in the pre-industrial. This is mainly due to the higher O_3 concentrations in the present-day leading to higher oceanic iodine emissions.

5 3 Implications

Figure 6 shows the change in tropospheric O_3 column between the pre-industrial and the present-day, with and without halogens. Consistent with previous work, the largest increases occur in the northern mid-latitudes notably over eastern North America and Asia (Lamarque et al., 2005). Halogens reduce the column change by an average of 1.6 DU. The largest halogen-driven reductions (up to 3 DU) are seen over the northern Pacific and Atlantic oceans. This is where surface O_3 concentration increase the most over the oceans leading to increases in oceanic inorganic iodine emissions, in turn giving more active O_3 destruction by iodine chemistry.

We calculate the radiative forcing caused by these changes based on previous work (Myhre et al., 2013) using a linear relationship between radiative forcing and O_3 column change ($0.042 \text{ Wm}^{-2} \text{ DU}^{-1}$). For our simulations without halogens we calculate a tropospheric ozone radiative forcing of 0.432 Wm^{-2} , close to the 0.410 Wm^{-2} found from the ACCMIP inter-comparison (Stevenson et al., 2013). Our simulations with halogens though give a radiative forcing of 0.366 Wm^{-2} . Thus, the increases in halogen chemistry associated with human activity are acting to dampen the anthropogenic radiative forcing of O_3 by 0.066 Wm^{-2} . Given that none of the models which participated in the last IPCC assessment incorporate tropospheric halogen chemistry, it would appear that they may over-estimate tropospheric O_3 radiative forcing by $\sim 20\%$. Our estimate for the reduction in tropospheric O_3 radiative forcing due to halogens is larger than the -0.05 Wm^{-2} estimate of the radiative forcing of stratospheric O_3 which is predominantly due to halogens (Myhre et al., 2013).

This halogen-induced reduction in the RF_{TO_3} is due to a combination of the increased oceanic iodine source from the increased O_3 , the increase in tropospheric organo-halogens, and the increase in stratospheric halogen flux between the pre-industrial and the present-day. Removing the oceanic inorganic iodine source from the model but keeping the increase in tropospheric halocarbons and stratospheric halogen flux, gives a RF_{TO_3} of 0.391 Wm^{-2} . In addition to that change, using a present-day stratosphere for the preindustrial gives a RF_{TO_3} of 0.411 Wm^{-2} . Although the system is non-linear we thus attribute $\sim 40\%$ of the halogen-driven reduction in O_3 radiative forcing to the ocean-atmosphere O_3 -iodine feedback, $\sim 30\%$ to the increase in the tropospheric halocarbons and $\sim 30\%$ to the increase in the flux of inorganic halogens from the stratosphere.

4 Discussion

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, chlorine and between the different emission types and sea-salt. Relatively small changes to parameters here can make substantial changes to the O₃ 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 (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 O₃ radiative from the 18 % found here to 23 %.

Uncertainties in the role of halogens in determining tropospheric O₃ 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 O₃ radiative forcing that do not consider tropospheric halogen chemistry are likely ~20% too large.

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.



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, 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.
- Bertram, T. H. and Thornton, J. A.: Toward a general parameterization of N₂O₅ 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, 23 073–23 095, doi:10.1029/2001JD000807, 2001.
- 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, *Nature 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, *Proc. Natl. Acad. Sci. U.S.A.*, 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:http://dx.doi.org/10.1016/j.atmosenv.2014.02.001, 2014.
- Glasius, M. and Goldstein, A. H.: Recent Discoveries and Future Challenges in Atmospheric Organic Chemistry, *Environmental Science & Technology*, 50, 2754–2764, doi:10.1021/acs.est.5b05105, 2016.



- Gómez Martín, J. C., Mahajan, A. S., Hay, T. D., Prados-Roman, C., Ordóñez, 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, 12 037–12 057, doi:10.5194/acp-10-12037-2010, 2010.
- 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, *Journal of Geophysical Research: Atmospheres*, 97, 16 421–16 431, doi:10.1029/91JD01968, 1992.
- 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, D08 304, 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, *Geoscientific Model Development*, 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, *Geophysical Research Letters*, 24, 791–794, doi:10.1029/97GL00599, 1997.
- 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 Br₂: a global modeling study of CHBr₃ and CH₂Br₂, *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, 11 609–11 617, 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, *Journal of Geophysical Research: Atmospheres*, 99, 16 617–16 632, 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, 14 371–14 385, 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, *Journal of Geophysical Research: Atmospheres*, 106, 3389–3399, doi:10.1029/2000JD900594, <http://dx.doi.org/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 Schneidemesser, 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.
- Morgenstern, O., Giorgetta, M. A., Shibata, K., Eyring, V., Waugh, D. W., Shepherd, T. G., Akiyoshi, H., Austin, J., Baumgaertner, A. J. G., Bekki, S., Braesicke, P., Brühl, C., Chipperfield, M. P., Cugnet, D., Dameris, M., Dhomse, S., Frith, S. M., Garny, H., Gettelman, A., Hardiman, S. C., Hegglin, M. I., Jöckel, P., Kinnison, D. E., Lamarque, J.-F., Mancini, E., Manzini, E., Marchand, M., Michou, M., Nakamura, T., Nielsen, J. E., Olivé, D., Pitari, G., Plummer, D. A., Rozanov, E., Scinocca, J. F., Smale, D., Teyssède, H., Toohey, M., Tian, W., and Yamashita, Y.: Review of the formulation of present-generation stratospheric chemistry-climate models and associated external forcings, doi:10.1029/2009JD013728, 2010.
- 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.
- Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestedt, J., Huang, J., Koch, D., Lamarque, J.-F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T., and H. Zhang, .: 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., 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, *Atmospheric Environment*, 33, 919–929, doi:[http://dx.doi.org/10.1016/S1352-2310\(98\)00257-X](http://dx.doi.org/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.



- Ravishankara, A. R., Daniel, J. S., and Portmann, R. W.: Nitrous Oxide (N₂O): The Dominant Ozone-Depleting Substance Emitted in the 21st Century, *Science*, 326, 123–125, <http://science.sciencemag.org/content/326/5949/123.abstract>, 2009.
- 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., B.D., Hall, Hossaini, R., Laube, J., Yvon-Lewis, and 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 N₂O₅ uptake on Cl containing substrates, *Geophys. Res. Lett.*, 36, 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, 19985–20044, doi:10.5194/acpd-14-19985-2014, 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, *Journal of Geophysical Research: Atmospheres*, 109, n/a—n/a, 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, 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.*, 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., J., D. J., Dix, B., Koenig, T. K., Sinreich, R., Ortega, I., Volkamer, R., Saiz-Lopez, A., Prados-Roman, C., Mahajan, A. S., and C. Ordóñez: Global impacts of tropospheric halogens (Cl, Br, I) on oxidants and composition in GEOS-Chem, *Atmos. Chem. Phys. Discuss.*, 2016b.
- Simpson, W. R., Brown, S. S., Saiz-Lopez, A., Thornton, J. A., and von Glasow, R.: Tropospheric Halogen Chemistry: Sources, Cycling, and Impacts, *Chemical Reviews*, 115, 4035–4062, doi:10.1021/cr5006638, 2015.
- Stevenson, D. S., Young, P. J., Naik, V., Lamarque, J.-F., Shindell, D. T., Voulgarakis, A., Skeie, R. B., Dalsoren, S. B., Myhre, G., Berntsen, 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), *Atmospheric Chemistry and Physics*, 13, 3063–3085, doi:10.5194/acp-13-3063-2013, 2013.
- Volkamer, R., Baidar, S., Campos, T., Coburn, S., DiGangi, J., Dix, B., Eloranta, E., Koenig, T., Moley, B., Ortega, I., Pierce, B., Reeves, M.,
5 Sinreich, R., Wang, S.-Y., Zondlo, M., and Romashkin, P.: Aircraft measurements of BrO, IO, glyoxal, NO₂, H₂O, O₂-O₂ 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, <http://dx.doi.org/10.1038/332240a0>, 1988.
- 10 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
15 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, 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, *Proc. Natl. Acad. Sci. U.S.A.*, 112, 9281–9286, doi:10.1073/pnas.1505142112, 2015.
- 20 Wang, Y. and Jacob, D. J.: Anthropogenic forcing on tropospheric ozone and OH since preindustrial times, *J Geophys. Res-Atmos.*, 103, 31 123–31 135, doi:10.1029/1998JD100004, 1998.
- 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.,
25 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.

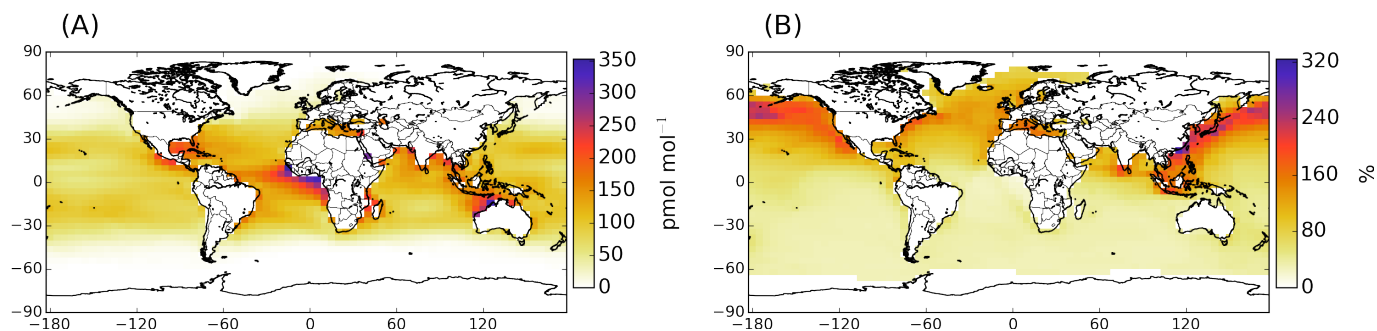


Figure 1. Inorganic emission flux (HOI, I₂) in the pre-industrial (A) and % change from the pre-industrial to present-day ((PD-PI)/PI*100) (B).

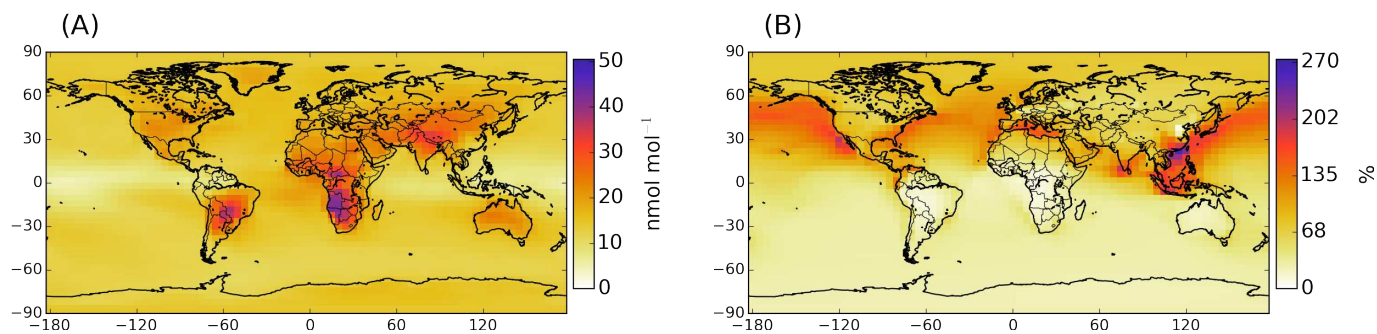


Figure 2. (A) O₃ surface concentration in the pre-industrial and (B) % change from the pre-industrial to present-day ((PD-PI)/PI*100).

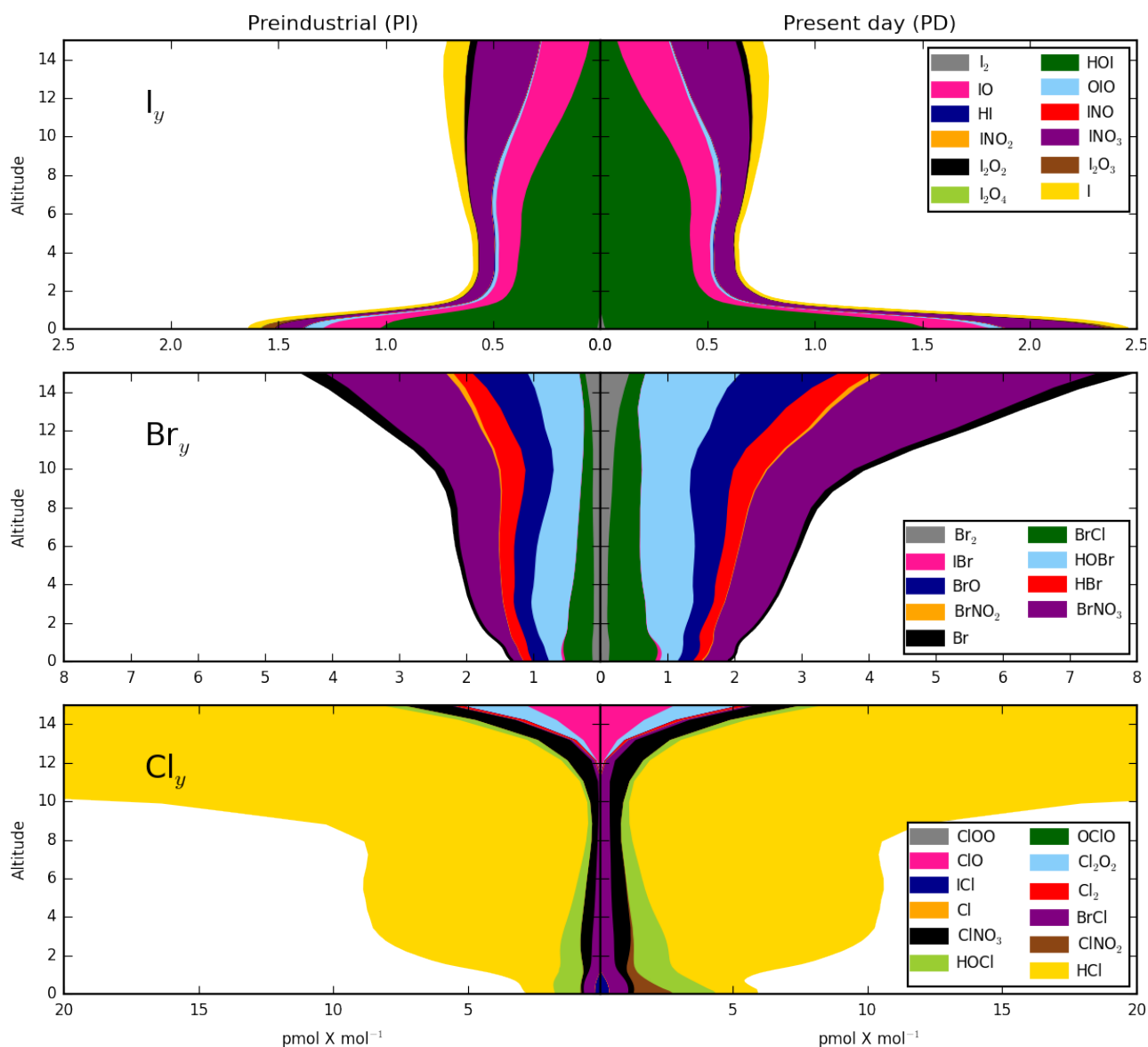


Figure 3. Global mean vertical distribution of iodine, bromine and chlorine inorganic gases (X_y , $X=Cl, Br, I$) for the pre-industrial (left) and present-day (right) in terms of mixing ratios of halogen. Increased halogen concentrations in the present-day are predominantly at the surface for iodine,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

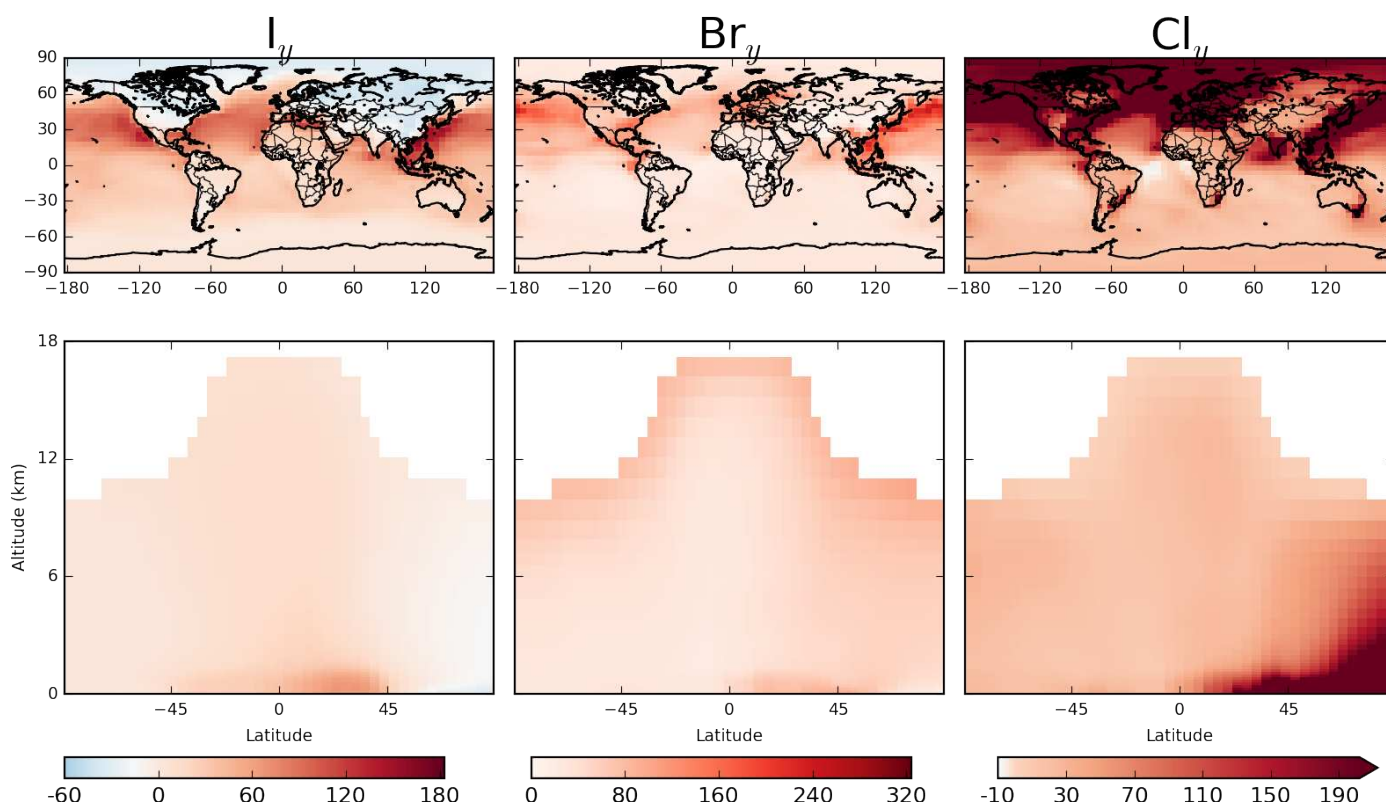


Figure 4. Percentage change from pre-industrial to present-day in tropospheric distribution of I_y , Cl_y , and Br_y ($(PD-PI)/PI \cdot 100$). Upper plots show surface and lower plots show zonal values. Reductions in I_y concentration over land are due to a shortening of the I_y lifetime due to enhanced IO_2 hydrolysis due to increase NO_x emissions in the present-day. Increases in surface Cl_y are due to increased release of $ClNO_2$ due to higher N_2O_5 concentrations in present-day

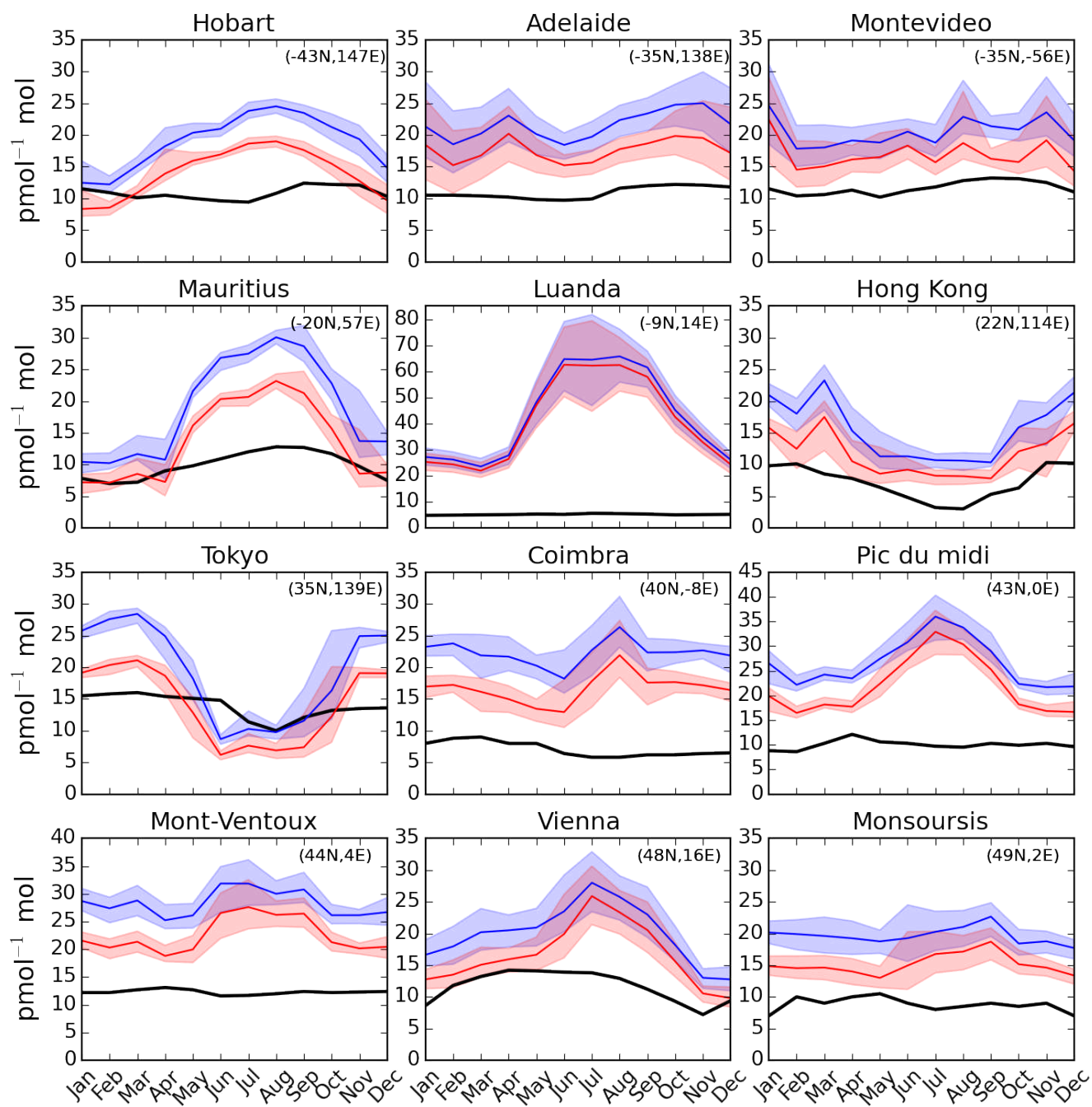


Figure 5. Comparison between observed and modelled pre-industrial monthly mean O_3 . Observations are shown in black, pre-industrial model simulation with halogens in red and without halogens in blue. The shaded areas for the model simulation shows the 1st and 3rd quartiles in the hourly values. The O_3 data is reproduced (Mickley et al., 2001) from previously reported observations: Mont Ventoux, Hong Kong, Tokyo, Adelaide, Coimbra, Hobart, Luanda, Mauritius, Vienna, and Montevideo (Marengo et al., 1994); Pic du Midi (Pavelin et al., 1999); Montsouris (Volz and Kley, 1988).

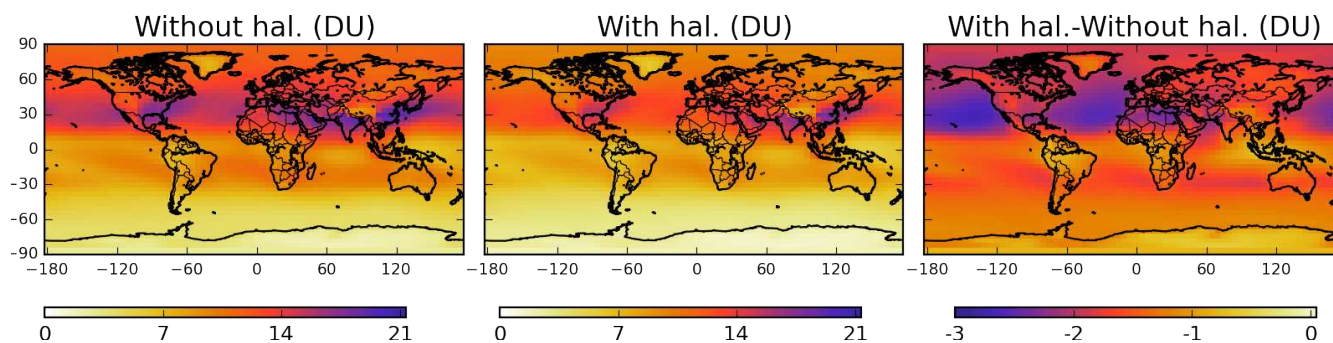


Figure 6. Increases in tropospheric O₃ column between the pre-industrial and present-day without and with halogens. Left and centre panels show the difference in annually averaged column O₃ (DU) between pre-industrial and the present-day without (left) and with halogens (centre). Right panel shows the difference.



Table 1. Emission of halogen source gases for the pre-industrial (PI) and present-day (PD). Long lived sources which have fixed concentrations in the model for Cl (CH_3Cl , CH_2Cl_2 , CHCl_3) and Br (CHBr_3) are shown in terms of chemical release (e.g. reaction with $+\text{OH}$, $+h\nu$, $+\text{Cl}$) and are in bold. I_2 and HOI are the inorganic ocean source from O_3 reacting with oceanic iodide (Carpenter et al., 2013), IX is from the uptake of iodine gases onto sea salt to release IBr or ICl, ClNO_2 is the source from the uptake of N_2O_5 on sea-salt.

Sources	I (Tg I yr ⁻¹)		Br (Tg Br yr ⁻¹)		Cl (Tg Cl yr ⁻¹)	
	PI	PD	PI	PD	PI	PD
CH_3X	0.26	0.26	0.04	0.06	2.28	2.19
CH_2X_2	0.33	0.33	0.09	0.09	0.11	0.59
CHX_3	-	-	0.41	0.41	0.21	0.26
HOI	1.17	2.02	-	-	-	-
I_2	0.08	0.14	-	-	-	-
IX	-	-	0.19	0.31	0.46	0.78
ClNO_2	-	-	-	-	0.02	0.66
Stratosphere	0.00	0.00	0.02	0.06	0.44	0.43
Total source	1.84	2.75	0.74	0.92	3.52	4.9



Table 2. Global tropospheric O_x budgets for pre-industrial and present-day, with and without halogens. For the X'^o+X''^o halogen crossover reactions where X' ≠ X'' we split the O_x loss equally between the two routes. Values are rounded to the nearest integer value.

	Pre-industrial With halogens	Pre-industrial Without	present-day With halogens	present-day Without
O ₃ burden (Tg)	260	303	355	416
O _x chemical sources (Tg yr ⁻¹)				
NO + HO ₂	2,256	2,357	3,526	3,607
NO + CH ₃ O ₂	662	668	1,327	1,316
NO + RO ₂	423	375	524	508
Total chemical O _x sources (PO _x)	3,341	3,401	5,376	5,431
O _x chemical sinks (Tg yr ⁻¹)				
O ₃ + H ₂ O $\xrightarrow{h\nu}$ 2OH + O ₂	1,421	1,711	2,102	2,489
O ₃ + HO ₂ → OH + O ₂	641	822	1,136	1,432
O ₃ + OH → HO ₂ + O ₂	497	601	611	737
Bromine sinks				
HOBr $\xrightarrow{h\nu}$ Br + OH	139	-	214	-
HOBr + HCl → BrCl	13	-	28	-
HOBr + HBr → Br ₂ + H ₂ O (aq. aerosol)	7	-	13	-
BrO + BrO → 2Br + O ₂	4	-	8	-
BrO + BrO → Br ₂ + O ₂	1	-	3	-
BrO + OH → Br + HO ₂	8	-	9	-
IO + BrO → Br + I + O ₂	7	-	9	-
ClO + BrO → Br + ClOO/OCIO	1	-	2	-
Other bromine O _x sinks	0	-	0	-
Total bromine O _x sinks	180	-	284	-
Iodine sinks				
HOI $\xrightarrow{h\nu}$ I + OH	336	-	457	-
OIO $\xrightarrow{h\nu}$ I + O ₂	99	-	125	-
IO + BrO → Br + I + O ₂	7	-	9	-
IO + ClO → I + Cl + O ₂ / ICl + O ₂	0	-	0	-
Other iodine O _x sinks	1	-	2	-
Total iodine O _x sinks	443	-	593	-
Chlorine sinks				
HOCl $\xrightarrow{h\nu}$ Cl + OH	10	-	15	-
CH ₃ O ₂ + ClO → ClOO	3	-	4	-
ClO + BrO → Br + ClOO/OCIO	1	-	2	-
ClNO ₃ + HBr → BrCl	0	-	1	-
IO + ClO → I + Cl + O ₂ / ICl + O ₂	0	-	0	-
Other chlorine O _x sinks	1	-	1	-
Total chlorine O _x sinks	15	-	23	-
Other O _x sinks	101	151	184	172
Total chem. O _x sinks (LO _x)	3299	3240	4933	4829
O ₃ PO _x -LO _x (Tg yr ⁻¹)	42	161	443	602
O ₃ Dry deposition (Tg yr ⁻¹)	545	659	832	980
O ₃ Lifetime (days)	25	28	22	26
O ₃ STE (PO _x -LO _x -Dry dep.) (Tg yr ⁻¹)	503	498	389	378