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RESEARCH LETTER
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Key Points:
- Model of iodine aerosol shows skill in reproducing observations
- Highest iodine mass is in the tropical marine boundary layer, up to 101% of DMS sulfate aerosol
- Regionally iodine aerosol is up to 11% of total sulfate and higher (21%) in the preindustrial

Supporting Information:
- Supporting Information S1

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Global modeling of tropospheric iodine aerosol

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Abstract Natural aerosols play a central role in the Earth system. The conversion of dimethyl sulfide to sulfuric acid is the dominant source of oceanic secondary aerosol. Ocean emitted iodine can also produce aerosol. Using a GEOS-Chem model, we present a simulation of iodine aerosol. The simulation compares well with the limited observational data set. Iodine aerosol concentrations are highest in the tropical marine boundary layer (MBL) averaging 5.2 ng (I) m^{-3} with monthly maximum concentrations of 90 ng (I) m^{-3}. These masses are small compared to sulfate (0.75% of MBL burden, up to 11% regionally) but are more significant compared to dimethyl sulfide sourced sulfate (3% of the MBL burden, up to 101% regionally). In the preindustrial, iodine aerosol makes up 0.88% of the MBL burden sulfate mass and regionally up to 21%. Iodine aerosol may be an important regional mechanism for ocean-atmosphere interaction.

1. Introduction

Atmospheric aerosols are important for climate as they scatter solar radiation and change cloud properties, with secondary aerosols playing a significant role [*Stocker et al.*, 2000]. Anthropogenic activities have changed their global distribution and abundance, but to understand the impact of these aerosols, both natural and anthropogenic sources need to be well understood [*Carslaw et al.*, 2013]. The oceans cover most of the planet, and for the last four decades the most important oceanic secondary source of aerosols has been thought to be the emission of dimethyl sulfide (DMS) and its oxidation to H_2SO_4 [*Lovelock et al.*, 1972; *Fitzgerald*, 1991]. Recent evidence for significant emissions of iodine from the ocean [*Carpenter et al.*, 2013; *MacDonald et al.*, 2014], coupled to previous coastal studies of iodine aerosol production [*O'Dowd et al.*, 2002], suggests the potential for an additional ocean aerosol source from iodine.

The presence of iodine in both the gas and aerosol phase in the marine boundary layer (MBL) has been established over the last few decades [*Saiz-Lopez et al.*, 2012a]. Oceanic emissions of methyl iodide were considered the dominant source for many years, but studies have shown that emission of other iodinated hydrocarbons from the open and coastal ocean play an important role [*Jones et al.*, 2010; *Saiz-Lopez et al.*, 2012a]. More recently, inorganic iodine compounds (I_2, HOI) produced in the ocean surface layer from the reaction of O_3 with iodide are thought to be the dominant global source of iodine [*Carpenter et al.*, 2013]. Observations, box modeling, and global model studies [*Saiz-Lopez and von Glasow*, 2012; *Saiz-Lopez et al.*, 2014; *Sherwen et al.*, 2016a, 2016b] in coastal and remote sites have shown the ability of iodine to impact the concentration of O_3 and oxidants. Similar studies in coastal and polar sites have shown that gas-phase iodine compounds can form low volatile gas-phase products which can both condense onto preexisting aerosol and nucleate to form new particles [*O'Dowd et al.*, 2002; *Allan et al.*, 2015; *Roscoe et al.*, 2015; *Sellegri et al.*, 2016]. Open-ocean observations are sparse but suggest iodine aerosol concentrations in the range of 0.1–17 ng (I) m^{-3} [*Baker*, 2004, 2005; *Gilfedder et al.*, 2010; *Lai et al.*, 2008; *Rancher and Kritz*, 1980]. Aerosol iodine is composed of both inorganic and organic forms [*Baker*, 2005] with a complex aerosol phase chemistry [*Pechtl et al.*, 2007]. It is believed that iodine higher oxides (I_xO_y), formed through the self-reaction of iodine oxides (IO and OIO), and hydroiodic acid (HI) are the gas-phase condensables predominantly responsible for production of the iodine aerosol [*Saiz-Lopez et al.*, 2012a].

Recent advances in the representation of iodine in global chemical-transport models [*Saiz-Lopez et al.*, 2012b, 2014; *Sherwen et al.*, 2016a, 2016b] allow us, for the first time, to simulate the global distribution of iodine aerosol. Here we describe simulations of tropospheric iodine aerosol within the GEOS-Chem chemical transport model, compare the calculated iodine masses against observations, and evaluate its impact as a source of secondary aerosol for the present day and preindustrial.

2. Model Setup

This work uses GEOS-Chem (www.geos-chem.org) version v10 at 4° × 5° resolution with a coupled halogen chemistry scheme as described and evaluated for present day [*Sherwen et al.*, 2016b] and for the preindustrial [*Sherwen et al.*, 2016c]. This incorporates previous halogen development in GEOS-Chem [*Bell et al.*, 2002; *Eastham et al.*, 2014; *Parrella et al.*, 2012; *Sherwen et al.*, 2016a; *Schmidt et al.*, 2016], with gas-phase chemistry based on Jet Propulsion Laboratory/International Union of Pure and Applied Chemistry 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 iodocarbons (CH_3I, CH_2I_2, CH_2ICl, and CH_2IBr) are emitted using the inventory of *Ordóñez et al.* [2012]. HOI and I_2 are emitted from the ocean surface, using the parameterization of *Carpenter et al.* [2013] which uses surface O_3 concentration and oceanic iodide concentration [*MacDonald et al.*, 2014]. We run the model for two years (2004 and 2005) ignoring the first year as "spin-up" and using the final year for analysis.

We consider three iodine aerosol tracers based on the uptake of gas-phase iodine species onto coarse and accumulation mode sea-salt aerosol and onto sulfate aerosol. The uptake of iodine species (HI, HOI, INO_2, INO_3, I_2O_2, I_2O_3, and I_2O_4) to these aerosols can lead to the iodine being permanently deposited onto that aerosol depending upon species, the aerosol type, and its pH (see Table S1 in the supporting information and *Sherwen et al.* [2016b] for details). The physical properties of the iodine aerosol tracers are assumed to be the same as its parent aerosol as previously described [*Alexander et al.*, 2012; *Jaeglé et al.*, 2011]. We do not consider uptake of iodine species onto aerosol types where these processes lack experimental constraint (e.g., black carbon and dust) [*Sherwen et al.*, 2016a, 2016b], and this probably causes an underestimate in the iodine aerosol in some regions which are subject to dust or biomass burning emissions. Significant uncertainty exists as to the chemical speciation of the iodine in aerosol, with iodide, iodate, and organic iodine compounds all being present [*Baker*, 2005]. The speciation of iodine in aerosol is not considered here, only total aerosol iodine concentrations (in units of ng (I) m^{-3}).

Oceanic noniodine secondary aerosol processes in the model are described elsewhere [*Park et al.*, 2004; *Alexander*, 2005]. In the GEOS-Chem version used here (v10), DMS emissions are calculated from an ocean-water climatology [*Kettle et al.*, 1999] and a transfer velocity [*Liss and Merlivat*, 1986]. They amount to 16.6 Tg (S) yr^{-1} (21% of the global sulfur emission of 78.8 Tg (S) yr^{-1} in the model). This is ~6 times the oceanic iodine emission of 2.75 Tg (I) yr^{-1} [*Sherwen et al.*, 2016b]. Iodine and DMS emissions are essentially uncorrelated due to their differing sources (see supporting information Figure S1). Relative spatial contributions are considered further in section 3. DMS contribution to total aerosol sulfate is estimated through a perturbation experiment. Assuming a linear model response, this allows the fraction of the sulfate that is due to DMS within the simulation to be determined. Globally, a 10% increase in DMS emissions leads to a 2.17% increase in sulfate deposition to 15.2 Tg (S) yr^{-1}. From this we conclude that 21.7% of the global burden of sulfate comes from DMS, consistent with previous work [*Rap et al.*, 2013], and a DMS to sulfate conversion efficiency of 19.5%.

To probe the possible changes of iodine aerosol between preindustrial and the present day, the model was also run with preindustrial emissions as described previously [*Parrella et al.*, 2012; *Sherwen et al.*, 2016c]. Anthropogenic emissions of O_3 precursors are switched off and natural emissions maintained at their present day values. Biomass burning emissions are scaled to 10% of the present day. Natural sources of sulfur from DMS and volcanos are unchanged, but anthropogenic sources are switch off. Emissions of iodinated hydrocarbons are unchanged (they are presumed entirely natural). Ocean iodide concentrations are unchanged, but the O_3 dependence of the emissions parameterization allows inorganic iodine emissions to change.

3. Results

3.1. Present Day Iodine Aerosol

We calculate a global iodine emission of 2.75 Tg (I) yr^{-1} (2.2 Tg (I) yr^{-1} from inorganic species (I_2, HOI) and 0.6 Tg (I) yr^{-1} from organic species) as described in *Sherwen et al.* [2016b] and consistent with previous studies [*Saiz-Lopez et al.*, 2014; *Sherwen et al.*, 2016a]. Although iodine emissions are, on a per area basis, highest in coastal waters, the tropical open ocean is so large it dominates the total global emission (supporting information Figure S1). These emissions rapidly photolyze, leading to a complex gas-phase chemistry [*Saiz-Lopez et al.*, 2012a], deposition, or the production of iodine aerosol.

The model's ability to simulate surface and vertical iodine oxide (IO) concentrations has previously been assessed against observations by *Sherwen et al.* [2016b]. The self-reactions of IO and OIO lead to the production of iodine higher oxides [*Saiz-Lopez et al.*, 2012a], which together with uptake of HI (see section 2) and other iodine compounds cause increases in iodine aerosol mass [*O'Dowd et al.*, 2002]. The surface concentrations of key gas-phase iodine species are shown in the supporting information Figure S2, with iodine aerosol mass concentrations at the surface calculated in the range 0.01 to 90 ng (I) m^{-3} in the monthly means with annual means of 0.01–31 ng (I) m^{-3} (Figure 1). The global modeled surface iodine aerosol concentrations are plotted on a monthly basis in the supporting information (Figure S6).

Iodine aerosol is primarily located in the tropics, where the emission sources are largest [see *Sherwen et al.*, 2016b, Figures 1 and 3], with tropical marine-boundary-layer concentrations of at least 2.6 ng (I) m^{-3} in the annual mean. Highest concentrations are found within the Arabian Sea, the Bay of Bengal, and off the Atlantic coast of central Africa. Concentrations fall off rapidly with altitude (supporting information Figure S3). Modeled iodine aerosol concentrations in polar regions are small (supporting information Figures S3 and S4), compared to observations [*Alicke et al.*, 1999; *McElroy et al.*, 1999; *Hausmann and Platt*, 1994; *Saiz-Lopez et al.*, 2007; *Tuckermann et al.*, 1997]. This probably highlights the missing snow/ice-related processes in the model. We find a global annual mean iodine aerosol burden of 2.5 Gg (I), with 2.0 Gg (I) in the marine boundary layer, and a globally averaged conversion efficiency of iodine emission into aerosol of 15.3%. We calculate this as the ratio between the global emission of iodine (Tg (I) yr^{-1}) and the global deposition of aerosol tracers (Tg (I) yr^{-1}). This efficiency is uncertain, and it is controlled by the chemistry scheme and notably by the fate of higher oxide chemistry for which our understanding is poor [*Sommariva et al.*, 2012; *Simpson et al.*, 2015; *Sherwen et al.*, 2016a].

3.2. Observational Comparisons

Iodine aerosol observations are sparse; however, comparisons to the available observations of nonpolar open-ocean iodine aerosol are shown in Figure 1 and in the supporting information (Table S1). The model-calculated iodine aerosol mass concentrations are extracted from the model for the month and region of the observation (Figure 1 (top)). Due to the scarcity of marine aerosol iodine observations, data for total soluble iodine from cruises "M55" and "AMT13" [*Baker*, 2005] is included alongside other total iodine concentrations in the comparison (see Table S1). Unpublished iodine aerosol data from cruises "D325," "D357," and "D361" are also included (Table S1), with a description of their processing as discussed previously [*Baker et al.*, 2001; *Chance et al.*, 2015; *Powell et al.*, 2015] and raw data (Table S3) given in the supporting information.

Although there is a degree of scatter, the model appears broadly consistent with the observations with some indication of a model overestimate. The observations are not in the regions where the model predicts its highest concentrations and further observations in these regions would be very useful. We therefore conclude that given the current observational data set, and the significant uncertainties in the modeled chemistry and aerosol processes [*Sherwen et al.*, 2016a; *Sommariva et al.*, 2012] the model provides a useful simulation of iodine aerosol.

3.3. Comparisons With Other Secondary Aerosol Sources

In order to place the calculated iodine aerosol mass into a wider secondary-aerosol context, we compare it to the calculated sulfate aerosol. For consistency we consider sulfate aerosol in the same elemental terms as we use for iodine aerosol (ng (S) m^{-3}). Figure 2 shows the annual mean surface concentrations of the sulfate (total and from DMS) and their mass (I/S) ratio (as a percent) compared to the iodine aerosol (zonal comparison in the supporting information Figure S5). The highest total sulfate aerosol is found over SE Asia, Europe, and North America where the anthropogenic source is highest. These concentrations rapidly decay away from the sources. Over the ocean, total sulfate concentrations become much smaller (29–452 ng (S) m^{-3} 5th to

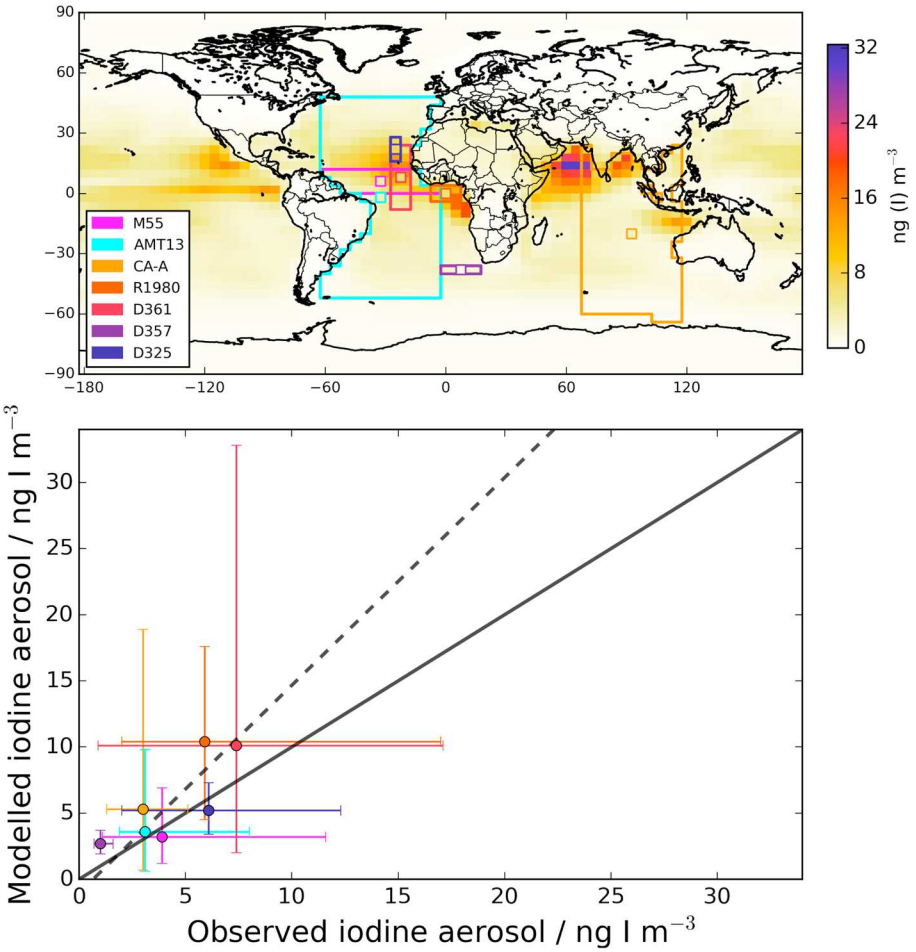

Figure 1. Simulated and observed surface iodine aerosol. (top) The modeled annual mean surface aerosol mass concentrations (ng (I) m^{-3}). Observations (small colored squares) indicate the average value reported by individual studies [*Baker*, 2004, 2005; *Gilfedder et al.*, 2010; *Lai et al.*, 2008; *Rancher and Kritz*, 1980] and data sets "D325," "D357," and "D361" are described in the supporting information. The small colored square is located at the center of the domain (large colored region). (bottom) The observed mean values with the error bar representing the reported maximum and minimum. Each modeled point represents the mean value in the region shown in Figure 1 (top) with the error bar representing the 5th and 95th percentiles of the distribution in that region. The colors of the points are the same as the areas on the map. The continuous black line is the 1:1 line, and the dashed line is the orthogonal linear regression best fit.

95th percentiles of annual mean). Highest DMS sulfate (up to 204 ng (S) m^{-3}) occurs where the DMS emissions are highest over the northern extratropical oceans (supporting information Figure S1), but generally, concentrations are in the range 14–78 ng (S) m^{-3} (5th to 95th percentiles of annual mean).

Compared to the total sulfate on an annual basis, iodine aerosol mass is small. Within the marine boundary layer, the annually averaged iodine aerosol burden is 2.0 Gg (I) which can be compared to 270 Gg (S) for sulfate. Regionally, this ratio (I/S as a percent) typically lies between 0.3–5.6% (5th to 95th percentiles) with a maximum of 11% (Figure 2 and zonally in supporting information Figure S5). Regions of the tropical marine boundary layer far from local anthropogenic or volcanic influences and with relatively low DMS emission ratio show the highest significance. This fraction can become as high as 35% on a monthly basis in these regions. Outside the marine boundary layer (supporting information Figure S3) iodine aerosol contributes negligible mass.

Sulfate from DMS is the primary oceanic secondary aerosol source in the model. Compared to the DMS sulfate source, iodine plays a more significant role than to total sulfate aerosol (Figure 2 and zonally in the supporting information Figure S5). Again, the iodine aerosol burden of 2.0 Gg (I) in the marine boundary layer can be compared to the 67 Gg (S) due to DMS emissions. Annually, this ratio (I/S DMS as a percent) lies in the range of

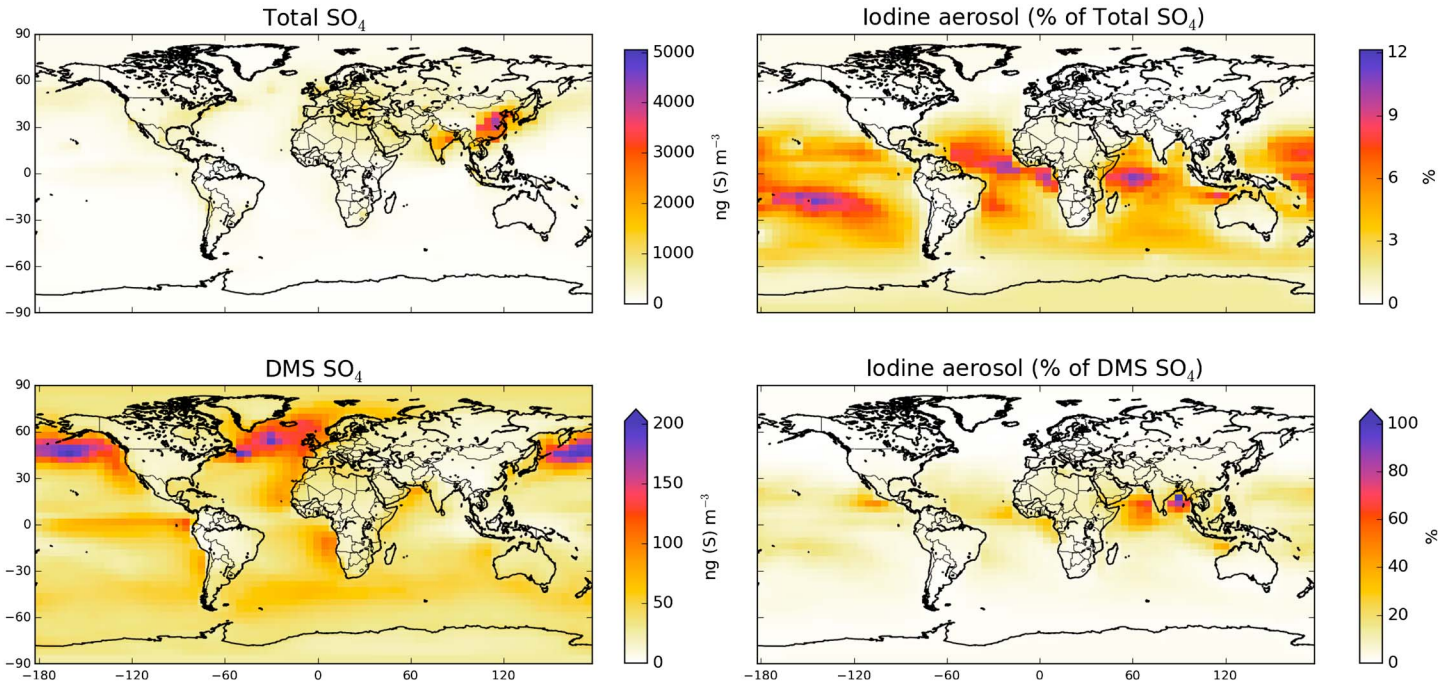

Figure 2. Annual average present day modeled surface mass concentrations of (top left) total and (bottom left) DMS sourced SO_4^{2-} aerosol in (left column) ng S m^{-3}. (right column) Iodine mass fraction (ng (I) m^{-3}) as percent of sulfate species.

0.75 to 15% (5th to 95th percentiles) over the tropical oceans with a maximum of 101%. On a monthly basis, this can increase by in excess of a factor of 4. The iodine to DMS sourced sulfate mass fraction is highest in regions of the tropical marine boundary layer where the iodine emissions are high and DMS emissions low (Indian ocean and the Pacific coast of Mexico). From an ocean-atmosphere perspective iodine thus appears to play a regionally important role in determining the secondary aerosol load of the marine boundary layer.

3.4. Preindustrial Concentrations

Understanding the aerosol distribution before human perturbation helps define the direct and indirect effects of aerosol. Our simulation of the preindustrial is described in section 2 and previously in *Sherwen et al.* [2016c]. We find lower O_3 concentrations (globally averaged 28% and 38% in the marine boundary layer) in the preindustrial, consistent with previous studies [*Lamarque et al.*, 2010; *Parrella et al.*, 2012]. This lower O_3 leads to a reduction in the inorganic ocean iodine source of 42% to 1.25 Tg (I) yr^{-1}. This is higher than the reduction in marine boundary layer O_3 as the largest reduction in O_3 occurs in the tropics where most of the inorganic iodine emissions occur. Total iodine emissions are thus reduced 33% to 1.84 Tg (I) yr^{-1}. The iodine processing in the atmosphere changes significantly in the preindustrial, with the lower NO_x concentrations lengthening the I_y lifetime due to reduced $IONO_2$ hydrolysis. Thus, the iodine aerosol burdens only reduced by 23% from the present day. Figure 3 shows the preindustrial iodine mass concentrations as a fraction of the preindustrial

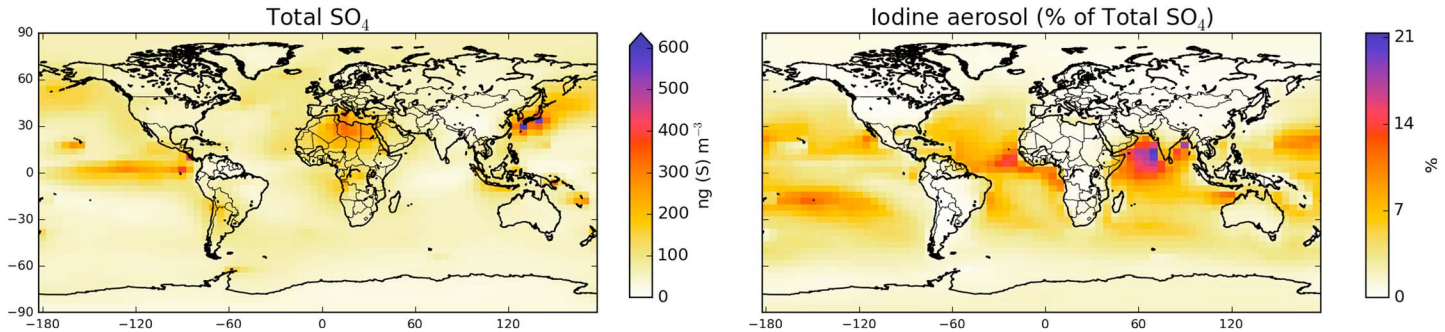

Figure 3. Annual average preindustrial modeled surface mass concentrations of (left) total sulfate (ng S m^{-3}) and the mass of (right) iodine aerosol (ng (I) m^{-3}) as a fraction of this.

total sulfate mass concentration. The reduction in the anthropogenic sulfur emissions leads to iodine aerosol being a larger fraction of the total sulfate in the preindustrial. The global iodine burden of 1.6 Gg (I) in the marine boundary layer compares to a total sulfate burden of 181 Gg (S). Spatially, iodine aerosol within the atmosphere above the tropical ocean surface can be up to 21% (0.2–6.8%, 5th to 95th percentiles) of the total sulfate mass on an annual basis with some locations showing iodine aerosol mass being ~50% of the sulfate mass in some months. Thus, iodine aerosol may have played an important regional role in determining the preindustrial marine-boundary-layer aerosol load.

4. Implications and Conclusions

The size distribution, optical, and cloud condensation properties of iodine aerosol are unknown or uncertain, which makes investigating the aerosol radiative impacts of iodine difficult. However, studies of aerosol optical depth have identified model underprediction compared to satellite observations in marine locations such as the Indian Ocean, Oceania, and the Gulf of Guinea where we predict the highest iodine aerosol mass concentrations [*Lapina et al.*, 2011]. An additional source of aerosol in those regions may make a contribution to reconcile observations with models. There is also strong evidence to support the nucleation of new particles from iodine [*O'Dowd et al.*, 2002; *Allan et al.*, 2015; *Roscoe et al.*, 2015; *Sellegri et al.*, 2016]. For regions where nucleation due to sulfur compounds is slow, iodine may be an important source of new particles.

There are still significant uncertainties in the magnitude and impacts of the ocean-atmosphere cycling of iodine. However, it would appear from these calculations that iodine aerosol may play an important regional role in determining the aerosol load of the remote tropical ocean both in the present and in the preindustrial. Further observations in these regions would help us to constrain the magnitude of this role.

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