

**Simulated perturbation in the sea-to-air flux of dimethylsulfide
and the impact on polar climate**

Author

Qu, Bo, Gabric, Albert J, Jackson, Rebecca

Published

2021

Journal Title

Journal of Oceanology and Limnology

Version

Accepted Manuscript (AM)

DOI

[10.1007/s00343-020-0007-8](https://doi.org/10.1007/s00343-020-0007-8)

Rights statement

© 2021 Springer Nature Switzerland AG. This is an electronic version of an article published in Journal of Oceanology and Limnology, 2021, 39 (1), pp. 110-121. Journal of Oceanology and Limnology is available online at: <http://link.springer.com/> with the open URL of your article.

Downloaded from

<http://hdl.handle.net/10072/405112>

Griffith Research Online

<https://research-repository.griffith.edu.au>

Simulated Perturbation in the Sea-to-Air Flux of Dimethylsulfide and the Impact on Polar Climate

Bo QU^{1*}, Albert J. Gabric², Rebecca Jackson²

QU: Perturbation of DMS Flux in Polar Regions

¹ School of Science, Nantong University, Nantong, Jiangsu Province, China

² School of Environment and Science, Griffith University, Brisbane, QLD, Australia

Abstract Marine biogenic emission of dimethylsulfide (DMS) is well recognized as the main natural source of reduced sulfur to the remote marine atmosphere and has the potential to affect climate, especially in polar regions. Here we use a global climate model (GCM) to investigate the impact on atmospheric chemistry from a change to the contemporary DMS flux to that which has been projected for the late 21stC. The perturbed simulation corresponds to conditions that pertain to a tripling of equivalent CO₂, which is estimated to occur by 2090 based on current worst-case greenhouse gas emission scenarios. The changes in zonal mean DMS flux are applied to 50°S-70°S (ANT) and 50°N-80°N (ARC) regions. The results indicate that there are clearly different impacts after perturbation in the southern and northern polar regions. Most quantities related to the sulfur cycle show a higher increase in ANT. However, most sulfur compounds have higher peaks in ARC. The perturbation in DMS flux leads to an increase of atmospheric DMS of around 45% in ANT and 33.6% in ARC. The sulfur dioxide vertical integral (SO₂) increases around 43% in ANT and 7.5% in ARC. Sulfate vertical integral (SO₄) increases 17% in ANT and increases around 6% in ARC. Sulfur emissions increase 21% in ANT and increases 9.7% in ARC. However, oxidation of DMS by OH increases by 38.2% in ARC and by 15.17% in ANT. Aerosol Optical Depth (AOD) increased by 4% in the ARC and 17.5% in the ANT, and increased 22.8% in austral summer. The importance of the perturbation of the biogenic source to future aerosol burden in polar regions leads to a cooling in surface temperature of 1K in the ANT and 0.8K in the ARC. Generally, polar regions in the Antarctic Ocean will have a higher offsetting effect on warming after DMS flux perturbation.

Keyword: Dimethylsulfide (DMS), Sulfur dioxide, DMS sea-to-air flux, perturbation, Global Climate Model (GCM), Polar regions

1. INTRODUCTION

Dimethylsulfide (DMS) has long been recognized as a key compound in the global sulfur cycle (Lovell et al., 1972). Charlson et al. (1987) proposed the “CLAW hypothesis” suggested that a warming-induced increase of marine DMS emissions, could affect cloud microphysics through a change in cloud condensation nuclei (CCN), increasing global albedo and reducing the amount of solar radiation reaching the Earth’s surface, and hence cooling the climate. DMS derives from the enzymatic cleavage of the precursor compound dimethylsulfoniopropionate (DMSP), which was originally

identified in marine phytoplankton (Karl et al., 2007).

DMS is synthesized by phytoplankton, and is the most abundant marine source of reduced sulfur to the atmosphere. After ventilation its oxidation products can increase the back scatter of sunlight and form CCN affecting the brightness and lifetime of low-level stratiform clouds over the ocean. In the atmosphere DMS undergoes photochemical reactions, producing a large variety of sulfur-containing compounds, including sulfur dioxide (SO_2), sulfuric acid (H_2SO_4), dimethylsulfoxide (DMSO), and methanesulfonic acid (MSA). The processes are depicted in Figure 1 (adapted from Nunes-Neto et al. (2011))... H_2SO_4 is formed from SO_2 , can be further oxidized in the atmosphere by OH radical to form sulfuric acid (H_2SO_4) and plays a key role in particle formation and particle growth. The importance of biogenic DMS emissions in the global CCN budget is emphasized by Sanchez et al. (2018) and Ghahremaninezhad et al. (2019). DMS can play a significant climatic role especially in remote oceans especially during the biologically productive summer season (Ghahremaninezhad et al., 2016; Quinn et al., 2017).

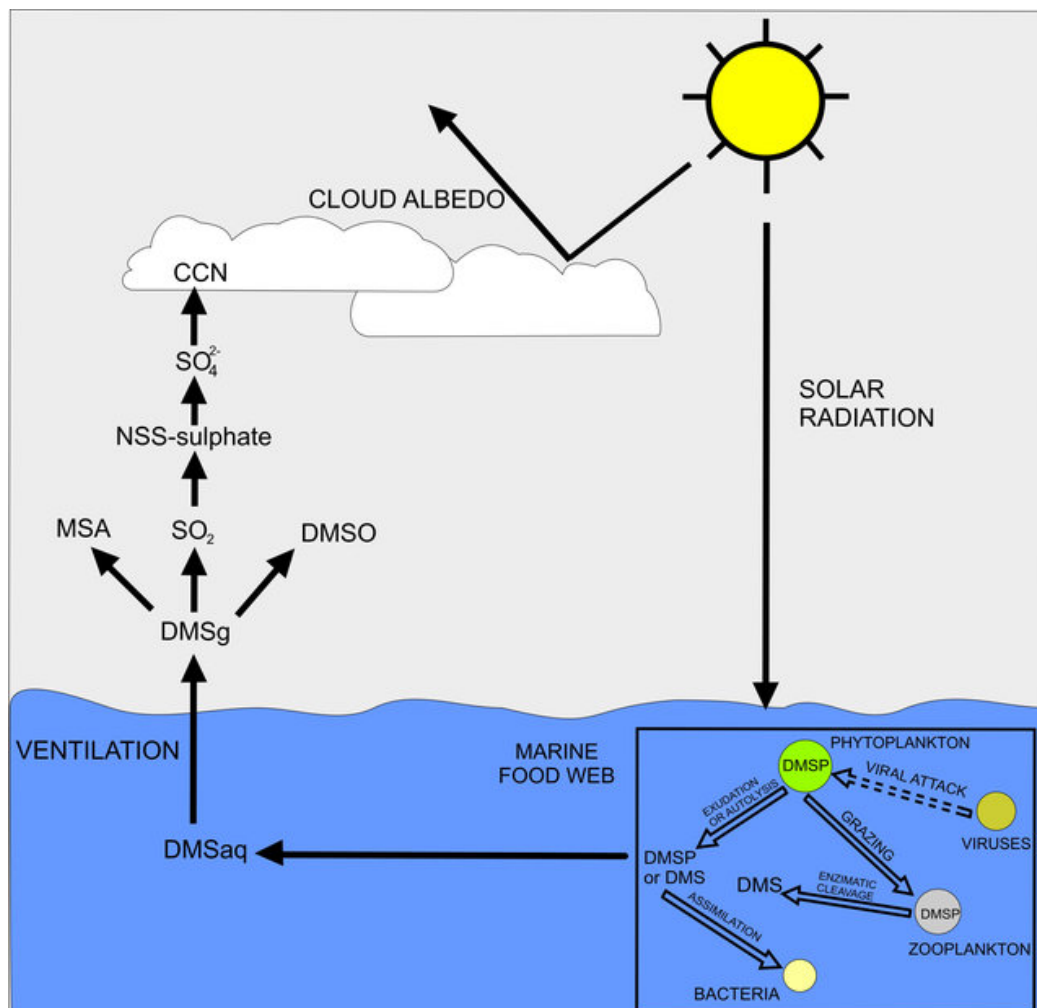


Fig.1: Schematic representation of the main mechanisms from marine algae to formation of CCN. In the figure, DMS in the ocean is denoted by DMS_{aq}; DMS in the atmosphere is denoted by DMS_g; dimethyl sulfoxide is denoted by DMSO; methane sulfonic acid is denoted by MSA; sulfate ion is denoted by SO₄²⁻, non-sea-salt sulfate is denoted by NSS-sulfate (from Nunes-Neto et al. (2011)).

There is some debate on the importance of DMS flux in climate change (Bates et al., 1992; Malin, 1997; Vallina et al., 2007), however it is generally agreed that DMS emissions make a significant contribution to global marine CCN concentrations, especially in the Southern Ocean (SO) (Vallina et al., 2006; Vallina et al., 2007; Korhonen et al., 2008; Korhonen et al., 2010). Globally, the mean annual contribution of biogenic CCN to total CCNs is estimated to be 30%. In the Arctic the seasonal peak of aerosol concentration (measure by satellite aerosol optical depth, AOD) is achieved in April in the Greenland Sea and Barents Sea, which is approximately one month before the peak in phytoplankton biomass estimated from satellite chlorophyll, (CHL) (Gabric et al., 2018). This suggests that the Arctic atmosphere is strongly affected by continental sources (so-called Arctic haze) in early spring (Gabric et al., 2014; Qu et al., 2014; Qu et al., 2018). Jung et al. (2018) reported higher CCN concentrations in the Arctic spring and summer (due to advection from the mid-latitudes and biogenic emissions in summer), and lower concentrations in the Arctic autumn and early winter when biogenic aerosol formation is reduced and long-range transport into the Arctic is not effective. Similar trends are reported in the Southern Hemisphere by Vallina et al. (2006) with the biogenic contribution to CCN between 35% in wintertime and 80% in summertime. Moreover, DMS oxidation can be an important contributor to the CCNs only over less polluted regions (Vallina et al., 2007).

The CLAW hypothesis has been explored by numerous researchers through climate model simulations that simulate the change in DMS sea-air flux under global warming scenarios (Bopp et al., 2003; Gabric et al., 2003; Gabric et al., 2004; Kloster et al., 2007; Qu & Gabric, 2010; Qu et al., 2016; Qu et al., 2020). The greatest change in DMS flux is consistently found in polar regions, however with notable hemispheric differences. These results indicate that changes to the DMS cycle in the polar oceans may play a significant role in the evolution of future climate. Previous analysis of the DMS flux perturbations for northern hemisphere (NH) and southern hemisphere (SH) (Gabric et al., 2013) indicated that the mean DMS vertical integral increases by 47.3% in SH and 9.9% in NH when comparing baseline and perturbed DMS flux. The DMS flux perturbation causes global mean surface temperature to decrease by 0.6K. with a

mean surface temperature decrease of 0.8°K in the SH and 0.4K in the NH. The change in direct and total radiative forcing at the top of the atmosphere is estimated to be -0.05 Wm^{-2} and -0.48 Wm^{-2} , respectively.

To investigate the radiative impact caused by an increased DMS flux, we have used an atmospheric general circulation model (AGCM) with embedded sulfur chemistry module. Previous research evaluated the impact of warming on the DMS flux and the differences between SH and NH (Gabric et al., 2013). The DMS flux perturbation for 10 degree latitude bands was given by Gabric et al. (2004) and showed that the largest DMS flux change occurred in the polar regions. These DMS sea-air flux perturbations for the polar regions are applied in the present work.

2. MATERIALS AND METHODS

2.1 The Atmospheric Model

The transient climate data was obtained from simulations using the Commonwealth Scientific and Industrial Research Organization (CSIRO) Mark 3 AGCM (Gordon & O'Farrell, 1997). The model used in this study is a low-resolution (spectral R21) version of the AGCM described by Gordon et al. (2002). The AGCM R21 model employs a horizontal resolution of (5.625°E-W x 3.1°N-S) with 18 vertical levels. It is forced by the annual cycle of observed sea surface temperatures (SSTs). The time step during spin up is 24 minutes. The leapfrog scheme is used by the model (Rotstayn & Lohmann, 2002). There is no need for artificial correction to the flux quantities in the model, which connect the atmospheric and oceanic systems (Gordon & O'Farrell, 1997). Advection of water vapor, cloud water and trace quantities are handled via a Semi-Lagrangian Scheme. The model has been used in seasonal prediction experiments and displays only a modest amount of climate drift (Hunt & Davies, 1997).

Rotstayn and Lohmann (2002) describe the detailed simulation process and treatment of chemistry module which is based on the ECHAM3 model developed by Feichter et al. (1996), further developed into ECHAM4 model by Lohmann et al. (1999). The AGCM was run either with prescribed SSTs, or coupled to a mixed layer (“q flux”) ocean model (Rotstayn & Penner, 2001). The monthly SSTs are provided by the UK Met Office. A dynamic treatment of sea ice and interactive snow treatment are used (O'Farrell, 1998), but the albedo of the land surface is prescribed (Rotstayn & Penner, 2001).

2.2 The Simulation Method

We compared the two classes of AGCM outputs: the first state is the control run (Baseline, indicated as B00) with input forcings, anthropogenic and natural sulfur sources representing a contemporary climate (late 20thC) (Figure 2). The AGCM was initially spun up to 50 years to make sure the model is approaching an equilibrium state (Gabric et al., 2013). The second state is the modified run (indicated as B01), that is after applying DMS flux perturbations in the south and north polar regions according to the 10° latitude bands in Table 1. The maximum perturbation of DMS flux is 106.9% and occurs within the 50-60°S band. In both runs (B00 and B01), outputs were obtained by averaging the final 10 years of the simulation. The relative increase in each zonal band is shown in Figure 1 in Gabric et al. (2013).

Table 1 Applied perturbation in zonal mean annual DMS flux by latitude band

Band		Change in annual DMS Flux
80-70°N	ARC	86%
70-60°N		19.5%
60-50°N		28.9%
50-60°S	ANT	106.9%
60-70°S		46.3%

2.3 Sources of Error

We consider some of the caveats in the present analysis. Firstly, the modeling assumes that no significant species distribution changes would occur, as the marine food web gradually adapts to warming. However, planktonic populations can respond to ocean variability rather sensitively and quickly (Coello-Camba & Agustí, 2017).

Secondly, any changes to nutrient supply to the surface ocean under warming have not been included explicitly, although these could occur from changes in either ocean upwelling or wind-driven aeolian deposition (Gabric et al., 2004).

The possible future physical changes (such as variation of sea ice melt, wind speed, sea surface temperature and mixed layer depth (MLD)) can all have large impacts on the DMS flux perturbations applied here. The MLD influences DMS water column concentrations (Simó & Dachs, 2002). Ice melt waters stimulate the growth of phytoplankton biomass (Matrai & Vernet, 1997). The DMS flux is the product of DMS and transfer velocity (related to the wind speed and sea surface temperature)(Liss & Merlivat, 1986; Nightingale et al., 2000).

Moreover, we note that DMS synthesis and emission is the result of whole food-web interactions. Such complex adaptive systems display nonlinearity and multiple feedbacks with future behavior are difficult to predict (Gabric et al., 2004).

3. Results

The monthly means for each model state variable are compared between the baseline (B00) and perturbed simulations (B01) in Table 2 for both ANT and ARC. After perturbation (B01), the DMS vertical integral increases 45.1% in ANT and increases 33.6% in ARC. The sulfur dioxide (SO₂) vertical integral increases 43.1% in ANT but only by 7.5% in ARC. The much higher simulated increase of DMS flux leads to higher SO₂ levels in ANT. Although relevant lower increase rates of DMS and SO₂ in ARC, the SO₂ profiles (for both B00 and B01) are much higher in ARC (Figure 3 blue lines). DMS profiles (Figure 2) in ANT show that it has a maximum in May and minimum in October. Elevated DMS profiles in ANT indicate that there are more biogenic sulfurs emitted in ANT than ARC. SO₂ has its peak in spring (February and March) and minimum during summer (July) (Figure 3).

The higher spring SO₂ in ARC can be affected by Arctic haze which comes mainly from anthropogenic sources of continental aerosols (Shaw, 1995). These aerosols are transported from middle latitude source regions and contribute to the Arctic haze during winter and springtime. These aerosols are primarily composed of sulfate and both directly and indirectly affect Arctic climate (Shaw, 1995; Quinn et al., 2007; Zhao & Garrett, 2015). There is no phenomenon of polar haze in the SH simply because of the absence of anthropogenic pollution near the Antarctic.

The change in annual mean atmospheric DMS vertical integral in both ARC and ANT is shown in Figure 4(a) and 4(b). Notice that the range of values are different for ARC and ANT (on the right). For the same color, ANT has much bigger values than ARC. Both the North Atlantic and North Pacific Oceans show a significant increase in the DMS vertical integral. The Antarctic Ocean has a significant increase of DMS vertical integral within 50°S-70°S, with peaks along 60°S.

Table 2 ARC and ANT Mean Comparisons for Baseline (B00) and Perturbation (B01) Simulations.

Param. Name	Parameter definition	Run	ARC (50°N-70°N)		ANT (50°S-70°S)	
1. DMS	DMS vertical integral (mgS/m ²)	B00	0.0902	+33.6%	0.5331	+45.1%
		B01	0.1205		0.7737	
2. SO ₂	Sulfur dioxide vertical integral(mgS/m ²)	B00	0.8778	+7.5%	0.4274	+43.1%
		B01	0.9439		0.6118	
3. SO ₄	Sulfate vertical integral (mgS/m ²)	B00	1.4347	+5.93%	0.5265	+17%
		B01	1.5198		0.6967	
4. DMO	Oxidation of DMS by OH (10^{-12} kg/m ² /s)	B00	0.1733	+38.2%	0.7415	+24.2%
		B01	0.2395		0.9211	
5. DMN	Oxidation rate of DMS by NO ₃ (10^{-12} kg/m ² /s)	B00	0.1112	+15.2%	0.0127	-1.12%
		B01	0.1281		0.0125	
6. S23	Oxidation of SO ₂ by O ₃ (10^{-12} kg/m ² /s)	B00	0.1901	-0.35%	0.0945	+5.89%
		B01	0.1895		0.1001	
7. S2O	Oxidation of SO ₂ to SO ₄ by OH (10^{-12} kg/m ² /s)	B00	0.1086	+6.6%	0.0563	+44.3%
		B01	0.1157		0.0812	
8. S2H	Oxidation of SO ₂ to SO ₄ by H ₂ O ₂ (10^{-12} kg/m ² /s)	B00	0.2426	+11.4%	0.1783	+28.2%
		B01	0.2703		0.2286	
9. SEM	Sulfur emissions (10^{-12} kg/m ² /s)	B00	0.7742	+9.66%	0.6491	+21%
		B01	0.8490		0.7854	
10. S2D	SO ₂ dry deposition (kg/m ² /s)	B00	0.4005	+7.11%	0.1461	+37.7%
		B01	0.4290		0.2013	
11. S2W	SO ₂ wet deposition (kg/m ² /s)	B00	0.1641	+8.8%	0.0660	+51.67%
		B01	0.1786		0.1000	
12. S4D	SO ₄ dry deposition (kg/m ² /s)	B00	0.1103	+8.81%	0.0613	+37.73%
		B01	0.1200		0.0844	
13. S4W	SO ₄ wet deposition (kg/m ² /s)	B00	0.7101	+3.88%	0.2086	+31%
		B01	0.7378		0.2732	
15.AOD	Aerosol optical depth at 550 nm (TA5)	B00	0.0643	+3.9%	0.0337	+17.5%
		B01	0.0668		0.0396	
16. TSC	Surface temperature (K)	B00	257.25	-0.8K	247.73	-1K
		B01	256.44		246.69	

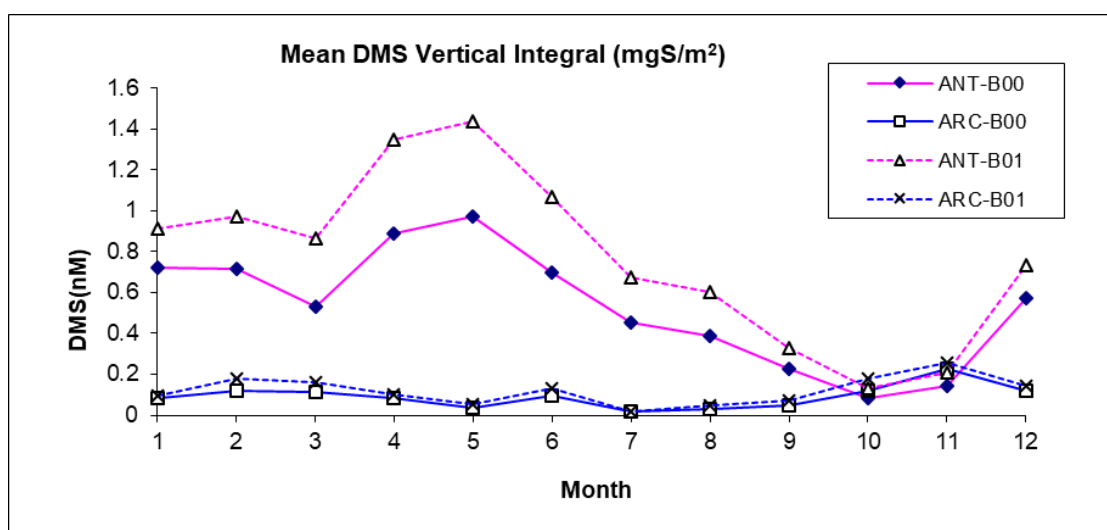


Fig. 2: Seasonal change in DMS vertical integral between baseline (B) and modified (M) simulations for the Antarctic (ANT) and Arctic (ARC).

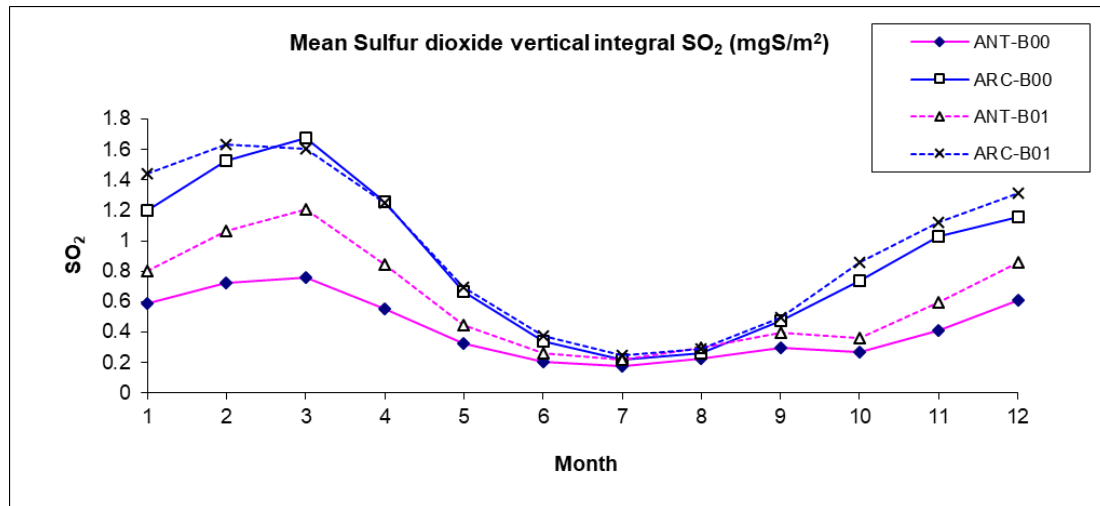
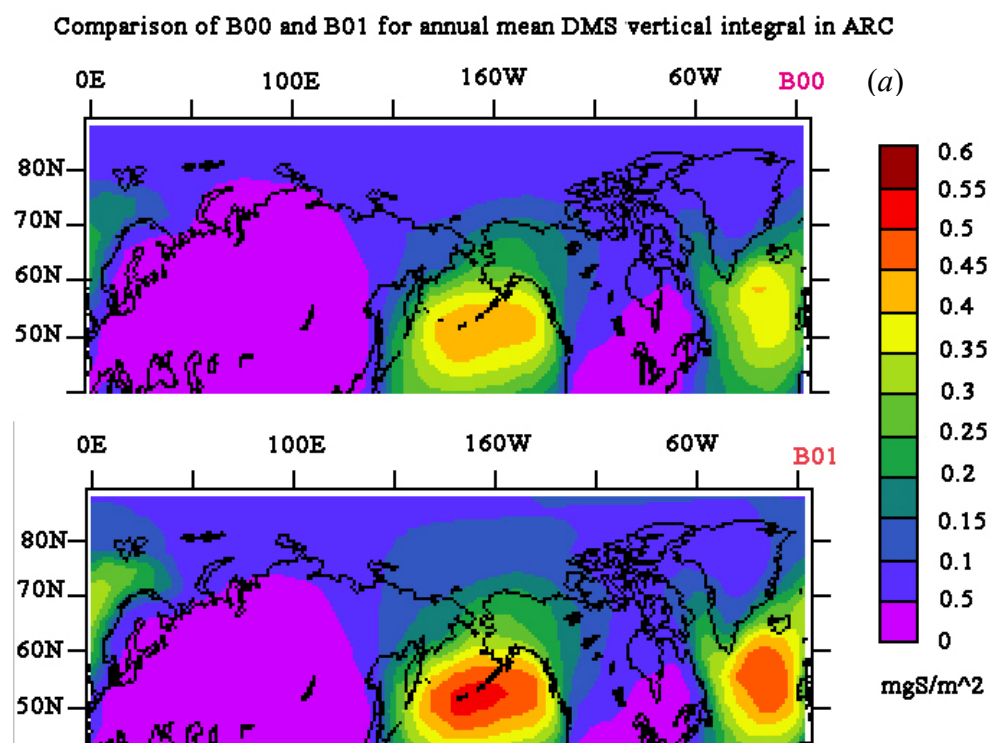


Fig. 3: Seasonal change in Sulfur dioxide vertical integral (SO₂) between baseline (B) and modified (M) simulations for the Antarctic (ANT) and Arctic (ARC).



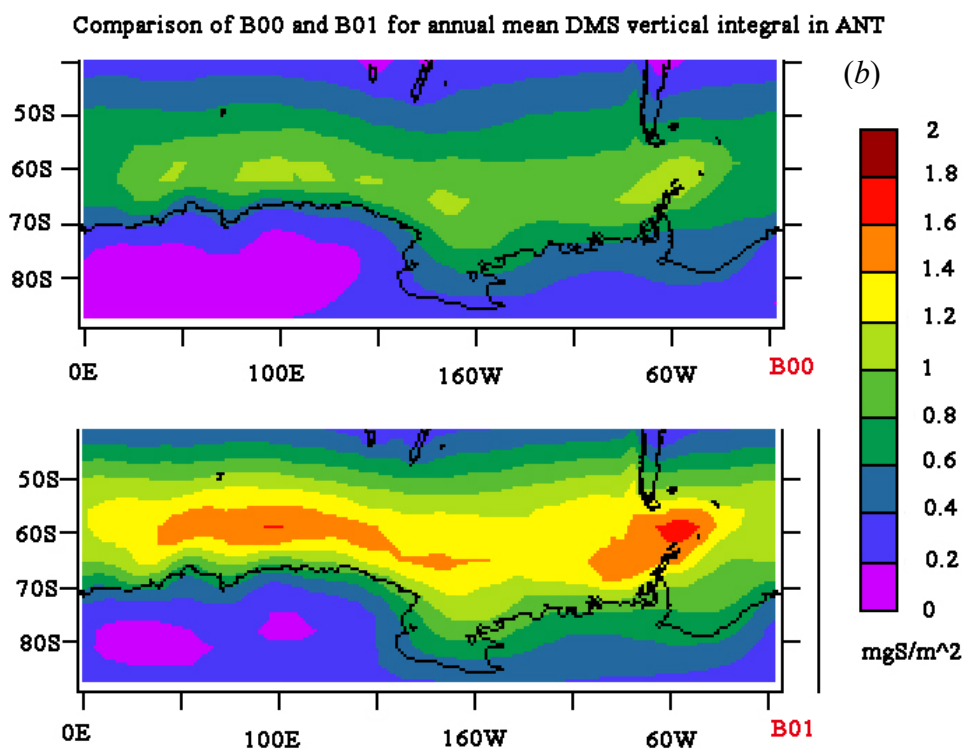


Fig. 4: Annual mean DMS vertical integral for (a) Baseline (B00), (b) Modified (B01) simulations in the Antarctic (ANT) and Arctic (ARC).

Chen et al. (2018) studied the oxidation of DMS and found that the chemical conversion into SO_2 and methane sulfonic acid (MSA) are key processes for the formation and growth of sulfur-containing aerosol and CCN. Their model results indicate that the DMS conversion into SO_2 and MSA is 75% and 15%, respectively. The gas-phase oxidation of DMS by OH and NO_3 are 91% and 9%, respectively. The dominant gas-phase oxidation pathway of DMS by OH has been noted by numerous researchers (Chen et al., 2000; Chen et al., 2018; Lv et al., 2019; Yan et al., 2020). Yan et al. (2020) found that the conversion ratio of MSA to DMS decreases dramatically as DMS concentration increases when DMS is relatively low. The effect of SST and relative humidity on conversion of DMS to MSA is negligible in the Antarctic Ocean. Our model simulation results show that SO_4 increases by 17% in ANT and 5.9% in ARC. Sulfur emissions (SEM) represents the total sulfur emission and is dominated by anthropogenic emissions in ARC but mainly biogenic emissions in ANT. SEM increases 21% in ANT and increases around 10% in ARC. The maximum of SO_2 is in February or March (when Arctic Haze occurs). In ARC, SO_4 has a maximum in May. In ANT, SO_4 reaches a maximum in the austral summer (December and January). The

maximum of SO_4 is similar to DMS and about 3-4 months later than SO_2 in ARC. The maximum of SEM is generally in summer and has austral summer high in ANT (January) and summer maximum (June) in ARC (Figure 5, blue and green lines).

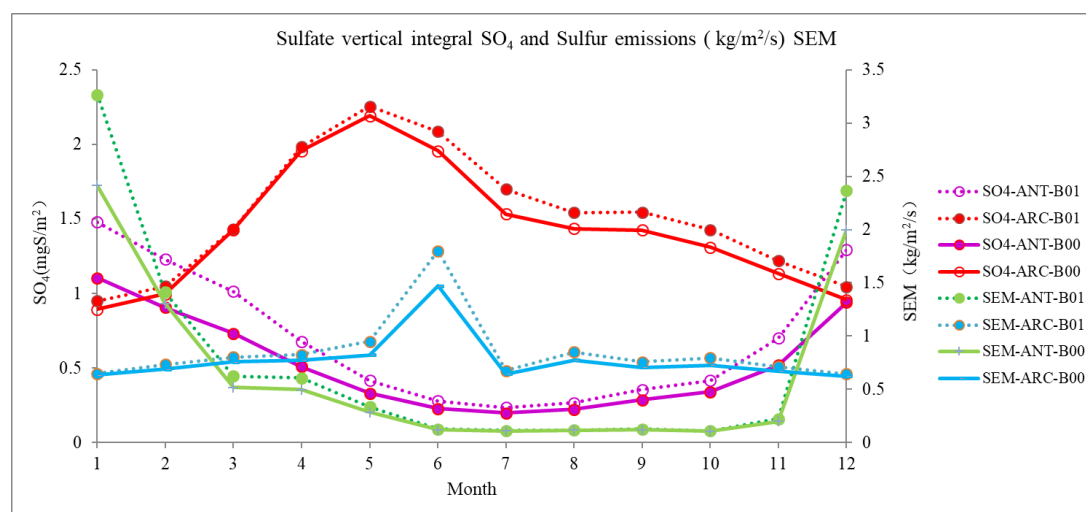


Fig. 5: Comparisons of monthly mean SO_4 and SEM for B01 (dot lines) and B00 (solid lines) for SO_4 (red for Arctic, purple for Antarctic) and SEM (blue for Arctic and green for Antarctic).

Davis et al. (1998) found that the OH/DMS addition reaction is a major source of dimethyl sulfoxide (DMSO). The OH/DMS addition reaction, as well as follow-on reactions involving OH/DMSO, are a major source of SO_2 , Preunkert et al. (2008) reported that OH and NO_3 are the most efficient atmospheric oxidants of DMS in the Antarctic. They found the lifetime of DMS oxidation by OH is very long in the Antarctic and up to 60 days in May. Hoffmann et al. (2016) indicated that the higher OH concentration arises from reduced ozone depletion by halogens, which enhances the photolysis of O_3 as well as OH production. Clouds significantly lower the gas-phase of OH concentrations and modify the prevailing chemistry of the oxidation of DMS and its oxidation products. Hoffmann et al. (2016) also pointed out that during cloudy periods, 78% of DMS is oxidized by O_3 to DMSO. During cloud present periods, the overall rate of DMS degradation decreases and the gas-phase DMS concentration increases slightly.

Importantly, the increase rates of oxidation of DMS by hydroxyl radicals (OH) (DMO) and oxidation of DMS by nitrate radicals (NO_3) (DMN) are all higher in ARC (38.2% and 15.2% respectively) than ANT (24.2% and decreases 1.12% respectively) (Table 2). The monthly mean profiles of oxidation of DMS by OH (DMO) all have summer maxima in both polar regions (Figure 6). The reason could be the OH is most

commonly generated by photolysis and DMO reaches maximum in summer period. The maximum of DMO in ANT is higher than the maximum in ARC. The production rate of DMO is higher during November and December also higher from January to May in ANT (see Figure 6). However, from September to late October, DMO has decreased tendency from B00 to B01, especially during the austral spring season.

Oxidation of DMS by NO_3 (DMN) monthly mean profiles are lower than by OH (DMO) in both polar regions, especially low in ANT (green curve in Figure 6). The peaks of DMN in ARC are in March and October.

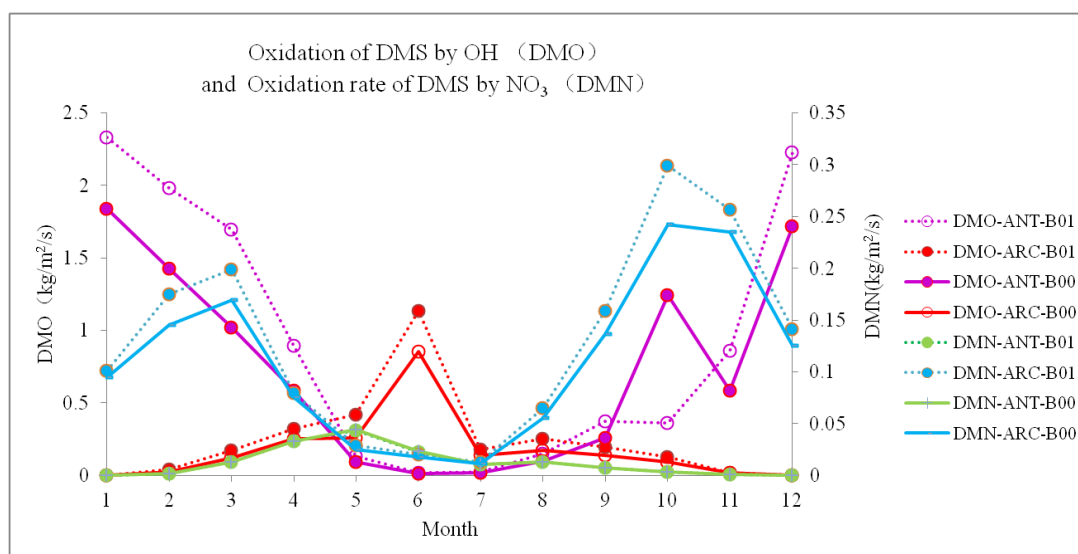


Fig. 6: Comparisons of monthly mean DMO and DMN for B01 (dot lines) and B00 (solid lines) for DMO (red for Arctic, purple for Antarctic) and DMN (blue for Arctic and green for Antarctic).

The rates of oxidation of SO_2 to SO_4 by OH (S2O), oxidation of SO_2 by O_3 (S23), and oxidation of SO_2 to SO_4 by H_2O_2 (S2H) are listed in Table 2. In general, ANT has higher increased rates after DMS flux perturbation (M in Table 2). The largest rate of change among the three is S2O (increases 44.3% in ANT). S23 has a slightly decreased rate in ARC. The profiles of monthly mean of S2O and S23 are shown in Figure 7. Although there are less increase rates in ARC for B01, the S2O and S23 still have higher monthly mean profiles in ARC (red and green curves) compare to ANT (purple and green curves). The maximum value of S2O occurs in May (red curves) in ARC and the maximum value of S23 is in September to October in ARC (blue curves). The maximum values of S2O and S23 are in March and January respectively in ANT. The higher profiles in ARC related to the higher SO_2 in ARC (Figure 3). The relevant higher increase rates of S2O are during January to March in ANT (purple curve) and March in ANT for S23 (green curve).

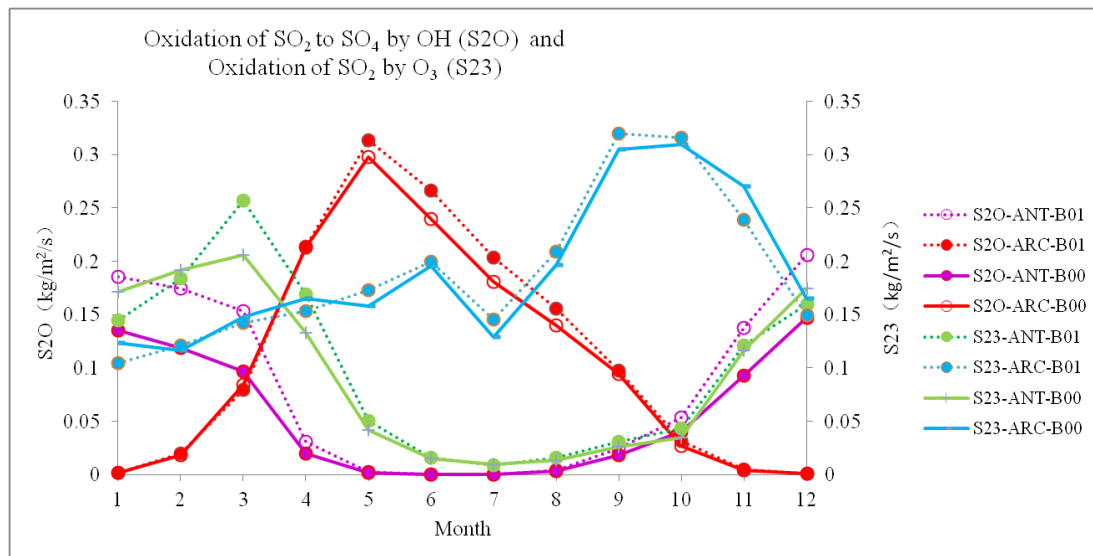


Fig. 7: Comparisons of monthly mean S2O and S23 for B01 (dotted curves) and B00 (solid curves) for S2O (red for Arctic, purple for Antarctic) and S23 (blue for Arctic and green for Antarctic)

Table 2 shows that S2D and S4D increase around 37.7% and 7-8% for ANT and ARC respectively; S2W increases more in ANT (reaching to 51.67%) and S4W increases 31% for ANT and increases 3.88% for ARC. General trends of S2D (Figure 8 red curves) and S4W in ARC (Figure 9 blue curves) are especially higher. In ARC, S2D and S2W have their maximum values in February (Figure 8 red and blue curves) and S4D and S4W have their maximum values in June (Figure 9 red and blue curves). In ANT, both SO₂ and SO₄ related dry and wet depositions also have their maxima during the summer months (January or December). SO₂ related dry and wet depositions in ANT have highest increase rate in March which is just after the austral summer (Figure 8 purple and green curves).

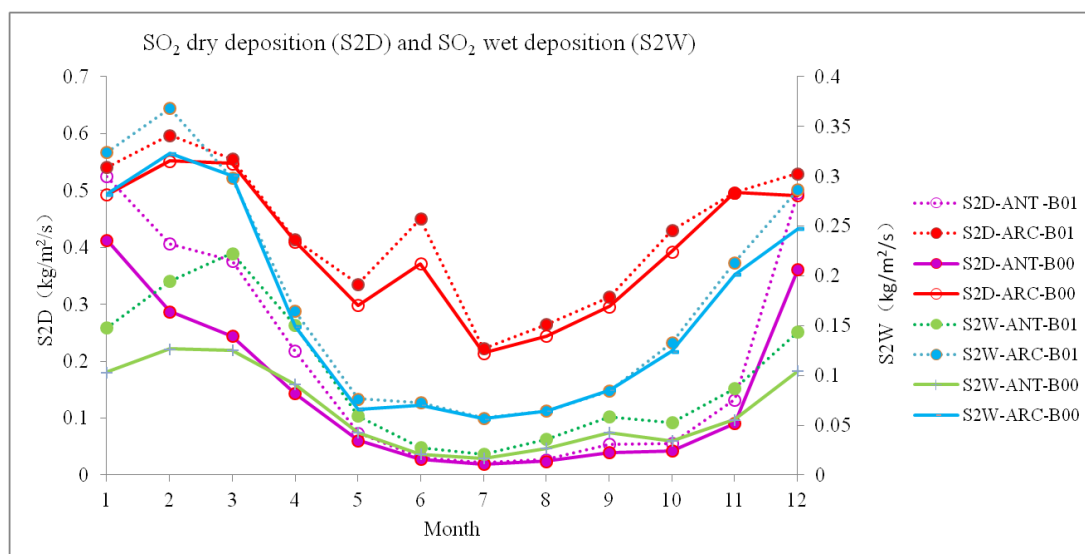


Fig. 8: Comparisons of monthly mean S2D and S2W for ANT (dotted lines) and ARC (solid lines) for S2D (red for Arctic, purple for Antarctic) and S2W (blue for Arctic and green for Antarctic).

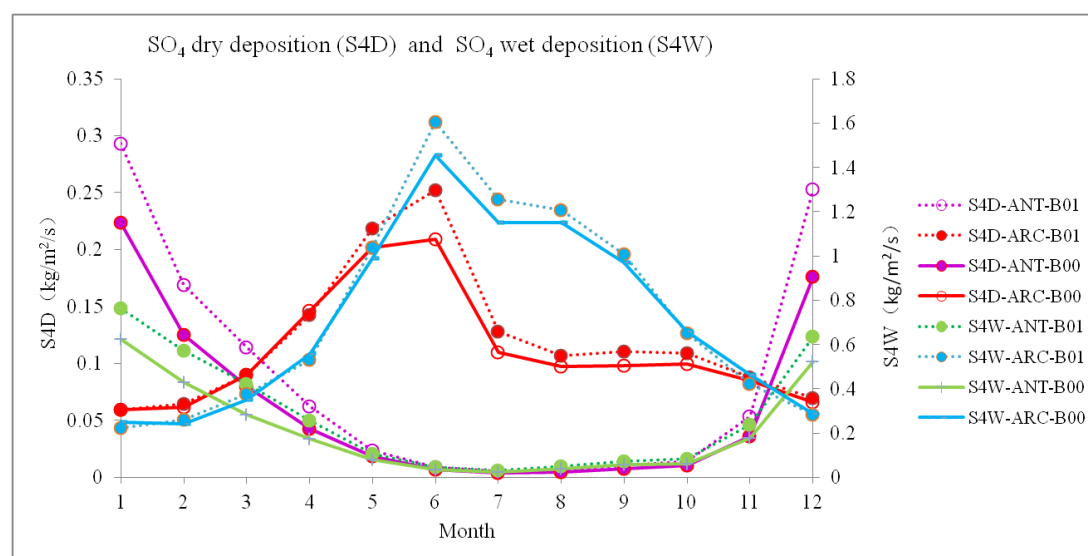


Fig. 9: Comparisons of monthly mean S4D and S4W for ANT (dotted lines) and ARC (solid lines) for S4D (red for Arctic, purple for Antarctic) and S4W (blue for Arctic and green for Antarctic).

After DMS flux perturbation, AOD increases 17.5% in ANT compared with 3.9% in ARC (Table 2). Surface temperature (TSC) decreases 1K in ANT and decrease 0.8K in ARC. Figure 10 shows monthly mean AOD and TSC (surface temperature) for B00(solid lines) and B01(dash lines). In the ARC, maximum AOD occurs in May, and maximum TSC is in July. In ANT, AOD and TSC all have maxima in summertime (December or January). The obvious increment of AOD from B00 to B01 in ANT are shown in Figure 10 especially during austral summer (DJF) (the purple lines). The increment rate of AOD during austral summer (DJF) is 23.8%. The differences of annual mean images of AOD between B00 and B01 are shown in Figure 11. The global mean changes of AOD from B00 to B01 (Figure 11(a)) indicate the most significant increase of AOD is within ANT region. The most significant change of AOD in austral summer (DJF) is shown in the bottom of Figure 11(b). Notice the different scales for the annual mean and summer mean in Figure 11(b).

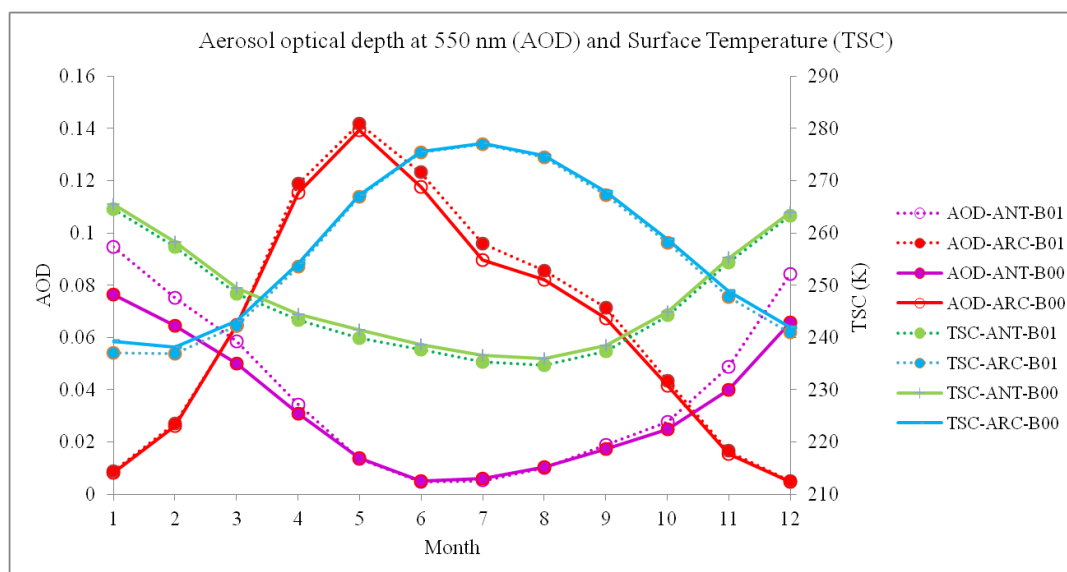
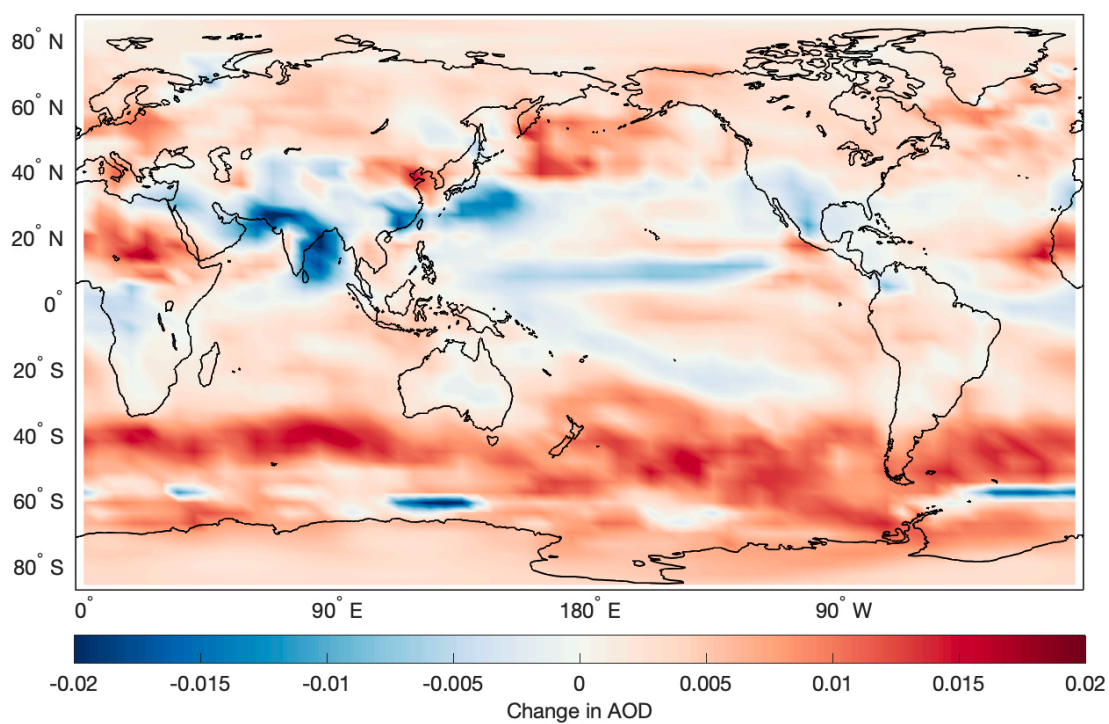


Fig. 10: Comparisons of monthly mean AOD and TSC for ANT (dotted lines) and ARC (solid lines) for AOD (red for Arctic, purple for Antarctic) and TSC (blue for Arctic and green for Antarctic)



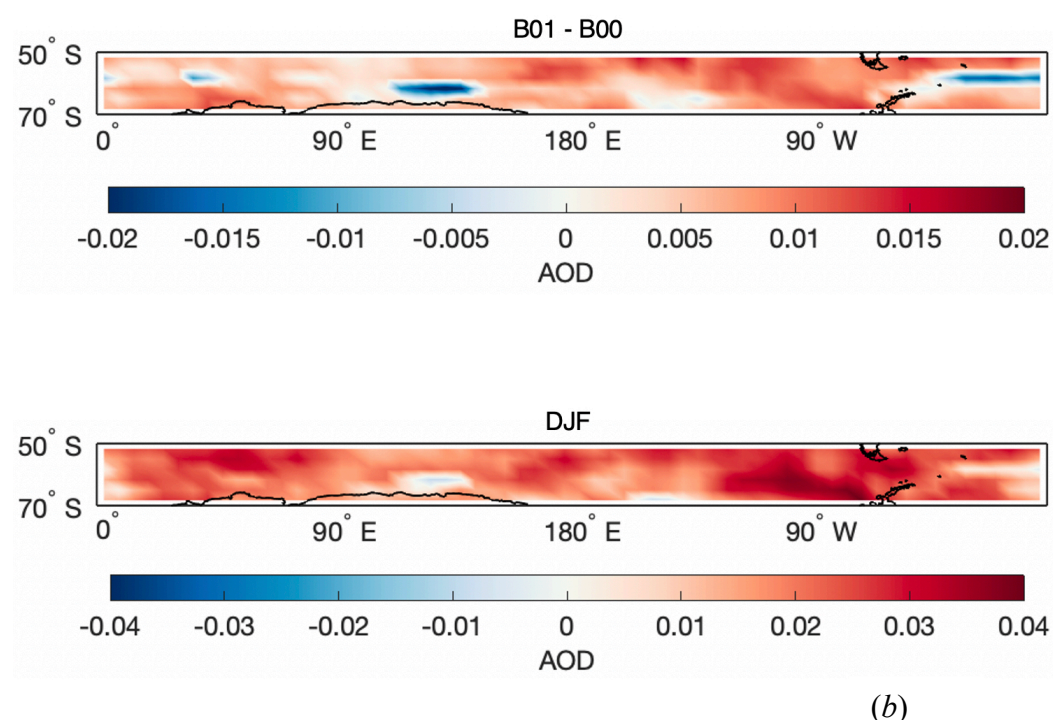


Fig. 11: Aerosol Optical Depth at 550 nm (AOD) images for the difference (B01-B00) for (a) Global annual mean; (b) ANT annual mean and ANT summertime mean (DJF).

4. DISCUSSION AND CONCLUSIONS

We simulate the impact on atmospheric chemistry of a change in DMS flux in both polar regions: ANT (50°S-70°S) and ARC (65°N-80°N). Our results indicate that there is a noticeable difference between the impacts in the two polar regions. In general, most quantities related to the sulfur cycle show higher rates of change in ANT especially during the austral summer. However, the higher sulfurs mostly appear in ARC. The perturbation on DMS flux leads to an increase in the DMS vertical integral of around 45% in ANT and increase 33.6% in ARC.

Shon et al. (2001) found that the conversion from DMS to SO₂ in ANT is as high as 70% or over, giving the lifetime of one day. In Arctic Ocean, sensitivity tests made by Mungall et al. (2016). They found that DMS sources come from non-marine sources (such as continental air-mass originally from land surfaces and sea ice; snow melts and sea salt aerosols from melt ponds; biomass burning plume) as well as marine source.

However, some researchers found the relationship of DMS flux and CCN is rather weak. Woodhouse et al. (2010) pointed out that the sensitivity of CCN to potential future changes in DMS flux is very low. They even suspect the role of DMS in climate regulation is very weak. High concentration of CCN are coincident with strong anthropogenic sources. In high latitude polar oceans, CCN exhibits low concentrations. Quinn and Bates (2011) also suspected the CLAW hypothesis and they ruled out CCN mostly formed by DMS flux which hypothesized by CLAW and pointed out CCN could also formed by sea-salt particles. Liu et al. (2011) discovered that reduced concentrations of H_2SO_4 due to slower oxidation of SO_2 by the OH in winter results in a lower aging rate and thus weaker wet deposition.

Our result shows that the oxidation of SO_2 to SO_4 by OH (S2O) increases 44.3% in ANT but only increases 6.6% in ARC. Sulfur emissions increases 21% in ANT and increases 9.7% in ARC. SO_4 wet and dry depositions all increases more in ANT (more than 30%) and only a little increase in ARC (less than 10%). The changes in sulfate are relatively smaller than the changes in DMS emissions. AOD increases 17.5% in ANT and only increases around 4% in ARC. After DMS flux perturbations. surface temperature (TSC) reduces 1 K in ANT and reduces 0.8 K in ARC.

It is clear, the impact of warming on future DMS flux is model dependent, spatially variable. Numerous researchers confirmed that more contributions of DMS sea-air fluxes are in the polar regions (Gabric et al., 2003; Gabric et al., 2004; Gabric et al., 2005; Korhonen et al., 2008; Gabric, 2010; Korhonen et al., 2010; Qu & Gabric, 2010; Gabric et al., 2013; Qu et al., 2016; Qu et al., 2017). The production of new DMS-derived CCN can take several days. During this time, DMS may be advected large distances, therefore, DMS impacts on aerosol levels are strongly non-local. However, even small changes in CCN may have significant effect on climate in remote unpolluted regions., . DMS emissions could exert a more significant influence on a low aerosol concentrated prevailing area, such as the Arctic in summer according to model simulations by Woodhouse et al. (2013). It is also reinforced by reports linking new particle formation events in the polar atmosphere to DMS emission by numerous researchers (Leck & Bigg, 2010; Croft et al., 2016; Park et al., 2017; Kerminen et al., 2018; Jang et al., 2019) . Our previous results consistently show the future increase of DMS flux in Barents Sea and Greenland Sea due to ice melting in Arctic Ocean (Qu & Gabric, 2010; Qu et al., 2016; Qu et al., 2017). Our decadal studies suggest that the DMS flux would increase significantly in polar regions during the latter part of the 21st

century. The DMS flux perturbations are likely to cause more cooling in surface temperature in the Antarctic and Arctic Oceans due to their relatively unpolluted environment.

ACKNOWLEDGEMENT

We thank Dr. Leon Rotstayn (CSIRO) who conducted the AGCM runs for our analysis. Special thanks should also go to Nantong University, China, for providing this opportunity of further cooperation between China and Australia. We also gratefully acknowledge the financial assistance of an ASAC Grant from the Australian Antarctic Division for providing research funding for this project.

References

- Andreae, M. O., & Crutzen, P. J. (1997). Atmospheric Aerosols: Biogeochemical Sources and Role in Atmospheric Chemistry. *Science*, 276(5315), 1052-1058. doi:10.1126/science.276.5315.1052
- Bailey, S., & Werdell, J. (2006). A multi-sensor approach for the on-orbit validation of ocean color satellite data products. *Remote Sensing of Environment*, 102, 12-23. doi:10.1016/j.rse.2006.01.015
- Bates, T. S., Lamb, B. K., Guenther, A., Dignon, J., & Stoiber, R. E. (1992). Sulfur emissions to the atmosphere from natural sources. *Journal of Atmospheric Chemistry*, 14, 315-337. Retrieved from <https://link.springer.com/article/10.1007/BF00115242>
- Bopp, L., Aumont, O., Sauveur, B., & Patrick, M. (2003). Potential impact of climate change on marine dimethyl sulfide emissions. *Tellus*, 55B, 11-22.
- Bourke, W. (1974). A Multi-Level Spectral Model. I. Formulation and Hemispheric Integrations. *Monthly Weather Review*, 102(10), 687-701. doi:10.1175/1520-0493(1974)102<0687:AMLSMI>2.0.CO;2
- Charlson, R. J., Lovelock, J. E., Andreae, M. O., & Warren, S. G. (1987). Oceanic phytoplankton, atmospheric sulphur, cloud albedo and climate. *Nature*, 326(6114), 655-661. Retrieved from <http://dx.doi.org/10.1038/326655a0>
- Chaves, J. E., Werdell, P. J., Proctor, C. W., Neeley, A. R., Freeman, S. A., Thomas, C. S., & Hooker, S. B. (2015). Assessment of ocean color data records from MODIS-Aqua in the western Arctic Ocean. *Deep Sea Research Part II: Topical Studies in Oceanography*, 118, Part A, 32-43. doi:<http://dx.doi.org/10.1016/j.dsr2.2015.02.011>
- Chen, G., Davis, D. D., Kasibhatla, P., Bandy, A. R., Thornton, D. C., Huebert, B. J., . . . Blomquist, B. W. (2000). A Study of DMS Oxidation in the Tropics: Comparison of Christmas Island Field Observations of DMS, SO₂, and

- DMSO with Model Simulations. *Journal of Atmospheric Chemistry*, 37(2), 137-160. doi:10.1023/A:1006429932403
- Chen, Q., Sherwen, T., Evans, M., & Alexander, B. (2018). DMS oxidation and sulfur aerosol formation in the marine troposphere: a focus on reactive halogen and multiphase chemistry. *Atmos. Chem. Phys.*, 18(18), 13617-13637. doi:10.5194/acp-18-13617-2018
- Coello-Camba, A., & Agustí, S. (2017). Thermal Thresholds of Phytoplankton Growth in Polar Waters and Their Consequences for a Warming Polar Ocean. *Frontiers in Marine Science*, 4(168). doi:10.3389/fmars.2017.00168
- Croft, B., Wentworth, G., Martin, R., Leaitch, W., Murphy, J., Murphy, B., . . . Pierce, J. (2016). Contribution of Arctic seabird-colony ammonia to atmospheric particles and cloud-albedo radiative effect. *Nature Communications*, 7, 13444. doi:10.1038/ncomms13444
- Davis, D., Chen, G., Kasibhatla, P., Jefferson, A., Tanner, D., Eisele, F., . . . Berresheim, H. (1998). DMS oxidation in the Antarctic marine boundary layer: Comparison of model simulations and field observations of DMS, DMSO, DMSO₂, H₂SO₄(g), MSA(g), and MSA(p). *Journal of Geophysical Research*, 103, 1657-1678. doi:10.1029/97JD03452
- Feichter, J., Kjellström, E., Rodhe, H., Dentener, F., Lelieveld, J., & Roelofs, G.-J. (1996). Simulation of the tropospheric sulfur cycle in a global climate model. *Atmospheric Environment*, 30(10), 1693-1707. doi:[https://doi.org/10.1016/1352-2310\(95\)00394-0](https://doi.org/10.1016/1352-2310(95)00394-0)
- Gabric, A. J., Cropp, R., Hirst, T., & Marchant, H. (2003). The sensitivity of dimethyl sulfide production to simulated climate change in the Eastern Antarctic Southern Ocean. *Tellus*, 55B, 966-981.
- Gabric, A. J., Cropp, R. A., McTainsh, G. H., Johnston, B. M., Butler, H., Tilbrook, B., Keywood, M. (2010). Australian dust storms in 2002–2003 and their impact on Southern Ocean biogeochemistry. *Global Biogeochemical Cycles* 24(2).
- Gabric, A. J., Cropp, R., Ayers, G.P., McTaubsh G., and Braddock, R. (2002). Couple between cycles of phytoplankton biomass and aerosol optical depth as derived from SeaWiFS time series in the Subantarctic Southern Ocean. *Geophysical Research Letters*, 29(7), 1112-1146.
- Gabric, A. J., Matrai, P., Jones, G., & Middleton, J. (2018). The Nexus between Sea Ice and Polar Emissions of Marine Biogenic Aerosols. *Bulletin of the American Meteorological Society*, 99(1), 61-81. doi:10.1175/bams-d-16-0254.1
- Gabric, A. J., Qu, B., Matrai, P. A., & Hirst, A. C. (2005). The simulated response of dimethylsulfide production in the Arctic Ocean to global warming. *Tellus B*, 57(5), 391-403. Retrieved from <https://doi.org/10.1111/j.1600-0889.2005.00163.x>
- Gabric, A. J., Qu, B., Matrai, P. A., Murphy, C., Lu, H., Lin, D. R., . . . Zhao, M. (2014). Investigating the coupling between phytoplankton biomass, aerosol optical depth and sea-ice cover in the Greenland Sea. *Dynamics of Atmospheres and Oceans*, 66, 94-109. doi:<http://dx.doi.org/10.1016/j.dynatmoce.2014.03.001>
- Gabric, A. J., Qu, B., Rotstain, L., & Shephard, J. M. (2013). Global simulations of the impact on contemporary climate of a perturbation to the sea-to-air flux of dimethylsulphide. *Australian Meteorology and Oceanographic Journal*, 63, 365-376.

- Gabric, A. J., Shephard, J. M., Knight, J. M., Jones, G., & Trevena, A. J. (2005). Correlations between the satellite-derived seasonal cycles of phytoplankton biomass and aerosol optical depth in the Southern Ocean: Evidence for the influence of sea ice. *Global Biogeochem. Cycles*, *19*, GB4018. doi:10.1029/2005GB002546
- Gabric, A. J., Shephard, J. M., Knight, J. M., Jones, G., & Trevena, A. J. (2005). Correlations between the satellite-derived seasonal cycles of phytoplankton biomass and aerosol optical depth in the Southern Ocean: Evidence for the influence of sea ice. *Global Biogeochemical Cycles*, *19*(4). doi:10.1029/2005gb002546
- Gabric, A. J., Simó, R., Cropp, R. A., Hirst, A. C., & Dachs, J. (2004). Modeling estimates of the global emission of dimethylsulfide under enhanced greenhouse conditions. *Global Biogeochemical Cycles*, *18*(2). doi:10.1029/2003gb002183
- Ghahremaninezhad, R., Gong, W., Galí, M., Norman, A. L., Beagley, S. R., Akingunola, A., . . . Leitch, W. R. (2019). Dimethyl sulfide and its role in aerosol formation and growth in the Arctic summer – a modelling study. *Atmos. Chem. Phys.*, *19*(23), 14455-14476. doi:10.5194/acp-19-14455-2019
- Ghahremaninezhad, R., Norman, A. L., Abbatt, J. P. D., Levasseur, M., & Thomas, J. L. (2016). Biogenic, anthropogenic and sea salt sulfate size-segregated aerosols in the Arctic summer. *Atmos. Chem. Phys.*, *16*(8), 5191-5202. doi:10.5194/acp-16-5191-2016
- Gordon, H. B., & O'Farrell, S. P. (1997). Transient climate change in the CSIRO coupled model with dynamic sea ice. *Mon. Wea. Rev.*, *125*, 875-907.
- Gordon, H. B., Rotstayn, L. D., McGregor, J. L., Dix, M. R., Kowalczyk, E. A., O'Farrell, S. P., . . . Elliott, T. I. (2002). *The CSIRO Mk3 Climate System Model*. (CSIRO Atmospheric Research technical paper (Online) ; 60). Retrieved from
- Gregg, W. W., & Casey, N. W. (2007). Sampling biases in MODIS and SeaWiFS ocean chlorophyll data. *Remote Sensing of Environment*, *111*(1), 25-35. doi:<https://doi.org/10.1016/j.rse.2007.03.008>
- Hoffmann, E. H., Tilgner, A., Schrödner, R., Bräuer, P., Wolke, R., & Herrmann, H. (2016). An advanced modeling study on the impacts and atmospheric implications of multiphase dimethyl sulfide chemistry. *Proceedings of the National Academy of Sciences of the United States of America*, *113*(42), 11776-11781. doi:10.1073/pnas.1606320113
- Hunt, B. G., & Davies, H. L. (1997). Mechanism of Multidecadal Climatic Variability in a Global Climatic Model. *International Journal of Climatology*, *17*(6), 565-580. doi:10.1002/(sici)1097-0088(199705)17:6<565::aid-joc172>3.0.co;2-6
- Jang, E., Park, K. T., Yoon, Y. J., Kim, T. W., Hong, S. B., Becagli, S., . . . Gim, Y. (2019). New particle formation events observed at the King Sejong Station, Antarctic Peninsula – Part 2: Link with the oceanic biological activities. *Atmos. Chem. Phys.*, *19*(11), 7595-7608. doi:10.5194/acp-19-7595-2019
- Jones, A., Roberts, D. L., Woodage, M. J., & Johnson, C. E. (2001). Indirect sulphate aerosol forcing in a climate model with an interactive sulphur cycle. *Journal of Geophysical Research: Atmospheres*, *106*(D17), 20293-20310. doi:10.1029/2000jd000089
- Jung, C. H., Yoon, Y. J., Kang, H. J., Gim, Y., Lee, B. Y., Ström, J., . . . Tunved, P. (2018). The seasonal characteristics of cloud condensation nuclei (CCN) in the

- arctic lower troposphere. *Tellus B: Chemical and Physical Meteorology*, 70(1), 1-13. doi:10.1080/16000889.2018.1513291
- Karl, M., Gross, A., Leck, C., & Pirjola, L. (2007). Intercomparison of dimethylsulfide oxidation mechanisms for the marine boundary layer: Gaseous and particulate sulfur constituents. *Journal of Geophysical Research: Atmospheres*, 112(D15). doi:10.1029/2006jd007914
- Kerminen, V.-M., Chen, X., Vakkari, V., Petäjä, T., Kulmala, M., & Bianchi, F. (2018). Atmospheric new particle formation and growth: review of field observations. *Environmental Research Letters*, 13(10), 103003. doi:10.1088/1748-9326/aadf3c
- Kloster, S., Six, K. D., & Feichter, J. (2007). Response of dimethylsulfide (DMS) in the ocean and atmosphere to global warming. *J. Geophys. Res.*, 112(G03005). doi:10.1029/2006JG000224
- Korhonen, H., Carslaw, K. S., Forster, P. M., Mikkonen, S., Gordon, N. D., & Kokkola, H. (2010). Aerosol climate feedback due to decadal increases in Southern Hemisphere wind speeds. *Geophysical Research Letters*, 37(2). doi:10.1029/2009gl041320
- Korhonen, H., Carslaw, K. S., Spracklen, D. V., Mann, G. W., & Woodhouse, M. T. (2008). Influence of oceanic dimethyl sulfide emissions on cloud condensation nuclei concentrations and seasonality over the remote Southern Hemisphere oceans: A global model study. *Journal of Geophysical Research: Atmospheres*, 113(D15). doi:10.1029/2007jd009718
- Leck, C., & Bigg, E. K. (2010). New Particle Formation of Marine Biological Origin. *Aerosol Science and Technology*, 44, 570-577.
- Levasseur, M. (2013). Impact of Arctic meltdown on microbial cycling of sulphur. *Nat. Geosci*, 6, 691-700. doi: 10.1038/ngeo1910
- Liss, P. S., & Merlivat, L. (1986). *Air-sea gas exchange rates: Introduction and synthesis*. MA: P. Buat-Menard. Reidel, Hingham.
- Liu, J., Fan, S., Horowitz, L. W., & Levy II, H. (2011). Evaluation of factors controlling long-range transport of black carbon to the Arctic. *Journal of Geophysical Research: Atmospheres*, 116(D4). doi:10.1029/2010jd015145
- Lohmann, U., Feichter, J., Chuang, C. C., & Penner, J. E. (1999). Prediction of the number of cloud droplets in the ECHAM GCM. *Journal of Geophysical Research: Atmospheres*, 104(D8), 9169-9198. doi:10.1029/1999jd900046
- Lovelock, J. E., Maggs, R. J., & Rasmussen, R. A. (1972). Atmospheric dimethylsulphide and the natural sulphur cycle. *Nature*, 237, 452-453.
- Lv, G., Zhang, C., & Sun, X. (2019). Understanding the oxidation mechanism of methanesulfinic acid by ozone in the atmosphere. *Scientific Reports*, 9(1), 322. doi:10.1038/s41598-018-36405-0
- Malin, G. (1997). Sulphur, climate and the microbial maze. *Nature*, 387, 857-859.
- Matrai, P. A., & Vernet, M. (1997). Dynamics of the vernal bloom in the marginal ice zone of the Barents Sea: Dimethylsulfide and dimethylsulfoniopropionate budgets. *Journal of Geophysical Research - Ocean.*, 102(C10), 22965-22979.
- Mungall, E. L., Croft, B., Lizotte, M., Thomas, J. L., Murphy, J. G., Levasseur, M., . . . Abbatt, J. P. D. (2016). Dimethyl sulfide in the summertime Arctic atmosphere: measurements and source sensitivity simulations. *Atmos. Chem. Phys.*, 16(11), 6665-6680. doi:10.5194/acp-16-6665-2016
- Nightingale, P. D., Malin, G., Law, C. S., Watson, A. J., Liss, P. S., Liddicoat, M. I., . . . Upstill-Goddard, R. C. (2000). In situ evaluation of air-sea gas exchange

- parameterizations using novel conservative and volatile tracers. *Global Biogeochem. Cycles*, *14*(1), 373–387. doi:10.1029/1999GB900091
- Nunes-Neto, N., S. Carmo, R., & El-Hani, C. (2011). The relationships between marine phytoplankton, dimethylsulphide and the global climate: The CLAW hypothesis as a Lakatosian progressive problems shift. *Marine Phytoplankton*, 169-186.
- O'Farrell, S. P. (1998). Investigation of the dynamic sea ice component of a coupled atmosphere-sea ice general circulation model. *Journal of Geophysical Research: Oceans*, *103*(C8), 15751-15782. doi:10.1029/98jc00815
- Park, K. T., Jang, S., Lee, K., Yoon, Y. J., Kim, M. S., Park, K., . . . Shin, K. H. (2017). Observational evidence for the formation of DMS-derived aerosols during Arctic phytoplankton blooms. *Atmos. Chem. Phys.*, *17*(15), 9665-9675. doi:10.5194/acp-17-9665-2017
- Preunkert, S., Jourdain, B., Legrand, M., Udusti, R., Becagli, S., & Cerri, O. (2008). Seasonality of sulfur species (dimethyl sulfide, sulfate, and methanesulfonate) in Antarctica: Inland versus coastal regions. *Journal of Geophysical Research: Atmospheres*, *113*(D15). doi:10.1029/2008jd009937
- Pszenny, A. A. P., Castelle, A. J., Galloway, J. N., & Duce, R. A. (1989). A study of the sulfur cycle in the Antarctic marine boundary layer. *Journal of Geophysical Research: Atmospheres*, *94*(D7), 9818-9830. doi:10.1029/JD094iD07p09818
- Qu, B., & Gabric, A. J. (2010). Using genetic algorithm to calibrate a dimethylsulfide production model in the Arctic Ocean. *Chinese Journal of Oceanology and Limnology*, *28*(1), 1-10. doi: **10.1007/s00343-010-9062-x**
- Qu, B., Gabric, A. J., Jiang, L., & Li, C. (2020). Comparison Between Early and Late 21stC Phytoplankton Biomass and Dimethylsulfide Flux in the Subantarctic Southern Ocean. *J. Ocean Univ. China (Oceanic and Coastal Sea Research)*, *19*(1), 151-160. Retrieved from <https://doi.org/10.1007/s11802-020-4235>
- Qu, B., Gabric, A. J., Lu, H., & Lin, D. (2014). Spike in phytoplankton biomass in Greenland Sea during 2009 and the correlations among chlorophyll-a, aerosol optical depth and ice cover. *Chinese Journal of Oceanology and Limnology*, *32*(2), 241-254. doi:10.1007/s00343-014-3141-3
- Qu, B., Gabric, A. J., Zeng, M., & Lu, Z. (2016). Dimethylsulfide model calibration in the Barents Sea using a genetic algorithm and neural network. *Environmental Chemistry*, *13*, 413-424. Retrieved from <http://dx.doi.org/10.1071/EN14264>
- Qu, B., Gabric, A. J., Zeng, M., Xi, J., Jiang, L., & Zhao, L. (2017). Dimethylsulfide model calibration and parametric sensitivity analysis for the Greenland Sea. *Polar Science*, *13*, 13-22. doi:<https://doi.org/10.1016/j.polar.2017.07.001>
- Qu, B., Gabric, A. J., Zhao, L., Sun, W., Li, H., Gu, P., & Zeng, M. (2018). The relationships among aerosol optical depth, ice, phytoplankton and dimethylsulfide and the implication for future climate in the Greenland Sea. *Acta Oceanologica Sinica*, *37*(5), 13-21. doi:10.1007/s13131-018-1210-8
- Quinn, P., Coffman, D., Johnson, J., Upchurch, L., & Bates, T. (2017). Small fraction of marine cloud condensation nuclei made up of sea spray aerosol. *Nature Geoscience*, *10*. doi:10.1038/ngeo3003
- Quinn, P. K., & Bates, T. S. (2011). The case against climate regulation via oceanic phytoplankton sulphur emissions. *Nature*, *480*, 51. doi:10.1038/nature10580

- Quinn, P. K., Shaw, G., Andrews, E., Dutton, E. G., Ruoho-Airola, T., & Gong, S. L. (2007). Arctic haze: current trends and knowledge gaps. *Tellus B*, 59(1), 99-114. doi:10.1111/j.1600-0889.2006.00238.x
- Rotstayn, L., & Penner, J. (2001). Indirect Aerosol Forcing, Quasi Forcing, and Climate Response. *J. Climate*, 14, 2960-2975. doi:10.1175/1520-0442(2001)014<2960:IAFQFA>2.0.CO;2
- Rotstayn, L. D., & Lohmann, U. (2002). Simulation of the tropospheric sulfur cycle in a global model with a physically based cloud scheme. *Journal of Geophysical Research: Atmospheres*, 107(D21), AAC 20-21-AAC 20-21. doi:10.1029/2002jd002128
- Shaw, G. E. (1995). The Arctic Haze Phenomenon. *Bulletin of the American Meteorological Society*, 76(12), 2403-2414. doi:10.1175/1520-0477(1995)076<2403:tahp>2.0.co;2
- Shon, Z.-H., Davis, D., Chen, G., Grodzinsky, G., Bandy, A., Thornton, D., . . . Eisele, F. (2001). Evaluation of the DMS flux and its conversion to SO₂ over the southern ocean. *Atmospheric Environment*, 35(1), 159-172. Retrieved from <http://www.sciencedirect.com/science/article/B6VH3-41NTC1S-1W/2/aba7b806152abc0bd482ac8c240612f5>
- Simó, R., & Dachs, J. (2002). Global ocean emission of dimethylsulfide predicted from biogeophysical data. *Global Biogeochem Cycles*, 16, 1078. doi:10.1029/2001GB001829
- Vallina, S., Simó, R., Gassó, S., de Boyer Montégut, C., Del Río, E., Jurado, E., . . . Vallina, C. (2007). Analysis of a potential “solar radiation dose—dimethylsulfide—cloud condensation nuclei” link from globally mapped seasonal correlations. *Global Biogeochemical Cycles*, 21, 1-16. doi:10.1029/2006GB002787
- Vallina, S., Simó, M., R., & Gasso., a. S. (2006). What controls CCN seasonality in the Southern Ocean? A statistical analysis based on satellite-derived chlorophyll and CCN and model-estimated OH radical and rainfall. *Global Biogeochemical Cycles*, 20(1).
- Woodhouse, M. T., Carslaw, K. S., Mann, G. W., Vallina, S. M., Vogt, M., Halloran, P. R., & Boucher, O. (2010). Low sensitivity of cloud condensation nuclei to changes in the sea-air flux of dimethyl-sulphide. *Atmos. Chem. Phys.*, 10(16), 7545-7559. doi:10.5194/acp-10-7545-2010
- Woodhouse, M. T., Mann, G. W., Carslaw, K. S., & Boucher, O. (2013). Sensitivity of cloud condensation nuclei to regional changes in dimethyl-sulphide emissions. *Atmos. Chem. Phys.*, 13(5), 2723-2733. doi:10.5194/acp-13-2723-2013
- Yan, J., Zhang, M., Jung, J., Lin, Q., Zhao, S., Xu, S., & Chen, L. (2020). Influence on the conversion of DMS to MSA and SO₄²⁻ in the Southern Ocean, Antarctica. *Atmospheric Environment*, 233, 117611. doi:<https://doi.org/10.1016/j.atmosenv.2020.117611>
- Zhao, C., & Garrett, T. J. (2015). Effects of Arctic haze on surface cloud radiative forcing. *Geophysical Research Letters*, 42(2), 557-564. doi:10.1002/2014gl062015