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# An advanced modelling study on the role of dimethyl sulfide in new particle formation in the pristine marine boundary layer

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**Abstract.**

New particle formation (NPF) enhances the concentration of cloud condensation nuclei (CCN) over the oceans, thereby affecting the radiative balance and, consequently, Earth's climate. The literature suggest that marine NPF predominantly occurs in the free troposphere, as the extensive surface area of sea spray aerosols and limited precursor gases suppress NPF in the marine boundary layer (MBL). However, such interpretations do not fully account for the observations on nucleation and Aitken-mode particles within the MBL. Here, we demonstrate how natural emissions of dimethyl sulfide (DMS) and $NH_3$ can drive $H_2SO_4$–$NH_3$-derived NPF in the MBL during cloud-free conditions following precipitation events. The newly formed particles manage to grow into the upper Aitken and accumulation mode size range within 3-4 days, with the potential to act as CCN. Through extensive sensitivity runs, we show that DMS-derived NPF and growth exhibits a non-linear response to variations in air temperature and wind speed, whereas their response to changes in sea surface temperature, precipitation rate, and DMS surface ocean concentration remains approximately linear. Sporadic cloud cover is shown to suppress NPF. Finally, we report new rate coefficients and reaction pathways for the OH-initiated oxidation of methane sulphinic acid (MSIA) and assess key uncertainties in the DMS oxidation mechanism, illustrating their impact on the formation and growth of DMS-derived aerosol particles in the MBL.

## 1 Introduction

Cloud condensation nuclei (CCN) over the oceans impact the formation, albedo and lifetime of marine clouds and thereby the global climate system (Charlson et al., 1987; Rosenfeld et al., 2019). The formation of aerosol particles through vapour nucleation, namely new particle formation (NPF) (Kulmala et al., 2013), is believed to give rise to more than half of the CCN

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in the marine boundary layer (MBL) (Merikanto et al., 2009). Observations on NPF in the MBL nevertheless remains scarce, and while certain studies report NPF events during cruise (Baccarini et al., 2021) and flight campaigns (Zheng et al., 2021), it is commonly believed that such events are rare (Pirjola et al., 2000; Quinn and Bates, 2011). Instead, aerosol particles are thought to enter the MBL from the free troposphere, in which low temperatures and low particle concentrations provides more favourable conditions for NPF (Williamson et al., 2019). While the question of open ocean NPF remains ambiguous, measurements made at coastal sites frequently show NPF (Jokinen et al., 2018; Dall´Osto et al., 2018; Beck et al., 2021; Brean et al., 2021)

Throughout the atmosphere, vapours with strong intermolecular interactions can undergo nucleation to form clusters that may grow into aerosol particles (Elm et al., 2020). One such vapour is sulfuric acid (SA: $H_2SO_4$), which is known to nucleate in the presence of a stabilizing base such as $NH_3$ (Korhonen et al., 1999; Kirkby et al., 2011). Over the oceans, dimethyl sulfide (DMS: $(CH_3)_2S$) emitted from phytoplankton comprises the largest source of natural sulfur and thus SA to the atmosphere (Lovelock et al., 1972; Bates et al., 1992). DMS therefore has the potential to influence NPF and CCN concentrations in the marine environment (Charlson et al., 1987; Rosati et al., 2021) and over land (Wollesen de Jonge et al., 2024), although its role in said processes remains to be fully understood. One of the main shortcomings in our current understanding concerns the oxidation mechanism of DMS, which has undergone extensive revision in recent years (Jacob et al., 2024). DMS oxidation is driven by $O_3$, $HO_x$, $NO_x$ and halogen radicals in both the gas-phase and the aqueous-phase of deliquesced aerosol particles and cloud droplets, where it forms the stable species dimethyl sulfoxide (DMSO: $CH_3SOCH_3$), methane sulphinic acid (MSIA: $CH_3SO_2H$), methanesulfonic acid (MSA: $CH_3SO_3H$) and sulfur dioxide ($SO_2$) in addition to SA (Barnes et al., 2006; Hoffmann et al., 2016; Wollesen de Jonge et al., 2021). DMS has also been found to undergo autoxidation to form hydroperoxymethyl thioformate (HPMTF: $HOOCH_2SCHO$) (Wu et al., 2014; Berndt et al., 2019; Ye et al., 2022). Although heavily researched, many of the reactions pathways forming said compounds remain uncertain, with large variations in the reaction rates presented in the literature. These uncertainties influence the distribution of products from DMS oxidation, making it difficult to asses the impact of DMS on the formation and growth of aerosol particles in the atmosphere - including the impact of DMS on NPF within the MBL.

Here, we use advanced process-based modelling to demonstrate the role of DMS in NPF and secondary aerosol growth within the pristine MBL. For this purpose, we construct an open ocean scenario in the box model ADCHAM and examine DMS-driven NPF under different metrological and hydrological conditions, including cloud and non-cloud periods, precipitation events and varying wind-speeds, air temperatures, sea surface temperatures and sea surface concentrations of dissolved DMS and $NH_x$. In addition to ADCHAM, we also include the use of detailed quantum chemical calculations to address uncertainties and alternative reaction pathways in the DMS oxidation mechanism. This is done as a means to reduce the uncertainty related to the role of DMS in NPF over the oceans.

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## 2 Methods

### 2.1 Model Description

Simulations were performed in the gas and particle phase chemistry box model ADCHAM (Roldin et al., 2014). ADCHAM considers state-of-the-art aerosol dynamics, treating the formation, growth, ageing and deposition of aerosol particles in the atmosphere. New particles are formed in the model by use of the Atmosphere Cluster Dynamics Code (ACDC) (McGrath et al., 2012; Olenius et al., 2013). ACDC takes into account both neutral and ion-induced pathways when calculating nucleation rates for various clustering systems, simulating the formation of clusters consisting of maximum five acid molecules and five base molecules. Clusters that manage to grow into the upper size range in ACDC are introduced as particles in ADCHAM in the smallest size bin at 1.08 nm. The setup used in this study models NPF from SA and $NH_3$, taking into account the loss of clusters to collisions, evaporation, coagulation, and scavenging. The SA-$NH_3$ system was calculated using the DLPNO method at the DLPNO-CCSD(T)/aug-cc-pVTZ//$\omega$B97X-D/6-31++G(d,p) quantum chemical level of theory (Besel et al., 2020). The DLPNO method was used in the default model setup as opposed to the RI-CC2 method as RI-CC2 has been shown to overpredict cluster binding energies (Schmitz and Elm, 2020). Nucleation rates obtained with the RI-CC2 method should therefore be interpreted as the upper limit for SA-$NH_3$ driven NPF, whereas nucleation rates obtained with the DLPNO method comprises the lower (and more realistic) limit.

Newly formed or pre-existing aerosol particles grow in the model, either through vapour condensation or through the partitioning and processing of water soluble species in the deliquesced aerosol particles and cloud droplets. The condensation and evaporation of species is solved with the analytical predictor of condensation (APC) scheme (Jacobson, 2005), taking into account the dissociation of condensing compounds in the aerosol particle aqueous-phase. Other water soluble compounds, including oxidation agents, are allowed to partition to and (for certain compounds) dissociate in the aqueous-phase in accordance with their Henry's law solubility and pKa values, respectively. In this study, ADCHAM considers the partitioning of 52 gaseous species to the aerosol particle aqueous-phase. Some of these species contribute to the growth of the aerosol particles by undergoing aqueous-phase oxidation to form low-volatile compounds that remain in the particle-phase upon a decrease in the aerosol particle deliquescence or the evaporation of cloud droplets. Henry's law solubilities and pKa values for the key DMS-derived water-soluble compounds HPMTF, DMSO, MSIA and MSA are based on COSMO*therm* (cos, 2021) calculations obtained from Wollesen de Jonge et al. (2024).

Once formed, aerosol particles in ADCHAM leave the atmosphere through either wet or dry-deposition. Wet-deposition, including bellow cloud-scattering of particles, is calculated for different particle sizes in accordance with the parameterization by Laakso et al. (2003). The parameterization considers the intensity of precipitation in $\mathrm{mm/h}$. Dry-deposition of aerosol particles in an ocean environment relevant for this study is calculated with the parameterization by Slinn and Slinn (1980).

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To investigate the influence of DMS on NPF in the pristine MBL, a model scenario reproducing conditions over the remote open ocean was constructed. In the BaseCase scenario, the movement of an air-parcel within the MBL is simulated for 144 hours, starting and ending at midnight. During the first 48 hours, the air-parcel passes through cloud cover four times - twice during midnight and twice during mid-day. To form clouds, the air-parcel is lifted, causing the air to become supersaturated with respect to water vapour through adiabatic cooling. The clouds are allowed to persist for two hours, until the air-parcel descends and they evaporate. During the fourth cloud event, heavy precipitation at 10 $\mathrm{mm/h}$ is introduced in the model. The cloud is allowed to precipitate for the first hour of its lifetime. During the remaining four days of the simulation, no cloud or precipitation events take place. In this time (and in between cloud periods during the first two days), the relative humidity is kept at $90\%$ and the aerosol particles are assumed to be deliquesced. The scenario is constructed to imitate the conditions during the flight-campaign described in Zheng et al. (2021), where frequent NPF within the MBL was observed following the passage of cold fronts.

The prescribed scenario is designed to spur NPF after the precipitation event on day three of the simulation. Before this event, the model is initiated with a size distribution consisting of $\mathrm{NaCl}$ in the accumulation and coarse mode in addition to $(\mathrm{Na})_2\mathrm{SO}_4$ in the Aitken mode. The initial aerosol concentration is kept high to ensure that new particles are less likely to form during the first two days of the simulation. The precipitation event on day two effectively lowers the aerosol particle concentration, allowing DMS-derived oxidation products to form and grow new particles. The initial size distribution and sea spray emissions are calculated using the parameterization by Salter et al. (2015). This parameterization takes into account the surface layer wind-speed, which is kept fixed at 6 $\mathrm{m/s}$ in the BaseCase simulation but varied in additional sensitivity runs.

DMS emissions in ADCHAM are treated by considering an oceanic DMS dataset and a DMS transfer velocity parameterization. The oceanic DMS dataset by Lana et al. (2011) was used to construct four scenarios with five different surface ocean concentrations of DMS, including low (5 $\mathrm{nmol/L}$), moderate (10 $\mathrm{nmol/L}$), high (15 $\mathrm{nmol/L}$) and very high (20 $\mathrm{nmol/L}$) concentrations. High to very high concentrations of DMS are representative for phytoplankton blooms in the North Atlantic Ocean during May-July, and in the Southern Ocean from December-February (Lana et al., 2011; Hulswar et al., 2022). It should be noted that even higher concentrations can be found in the ocean surrounding Antarctica during sea-ice breakout. A super-linear transfer velocity specifically made for DMS was used to obtain the flux of DMS to the model (Blomquist et al., 2017). We acknowledge that alternative linear and quadratic transfer velocities are also commonly used to calculate the DMS sea-air flux (Liss and Merlivat, 1986; Wanninkhof, 2014; Nightingale et al., 2000). All parameterizations consider the sea surface temperature (SST) and wind-speed when calculating the transfer velocity. Emissions of $\mathrm{NH_3}$ were treated similar to DMS by considering an oceanic dataset and a transfer velocity. The sea surface concentration of total ammonium $\mathrm{NH_x}$ was set to 0.3 $\mathrm{mmol/m^3}$. This values represents a middle ground between $\mathrm{NH_x}$ concentrations observed in the North Atlantic Ocean (May-July: $\sim 0.2\ \mathrm{mmol/m^3}$) and the Southern ocean around Antarctica (December-February: $\sim 0.4\ \mathrm{mmol/m^3}$) when the phytoplankton blooms are at their peak in each respective region (Paulot et al., 2020). Additional sensitivity runs are performed using both higher and lower concentration of sea surface $\mathrm{NH_x}$. The transfer velocity of $\mathrm{NH_3}$ was calculated in accordance with

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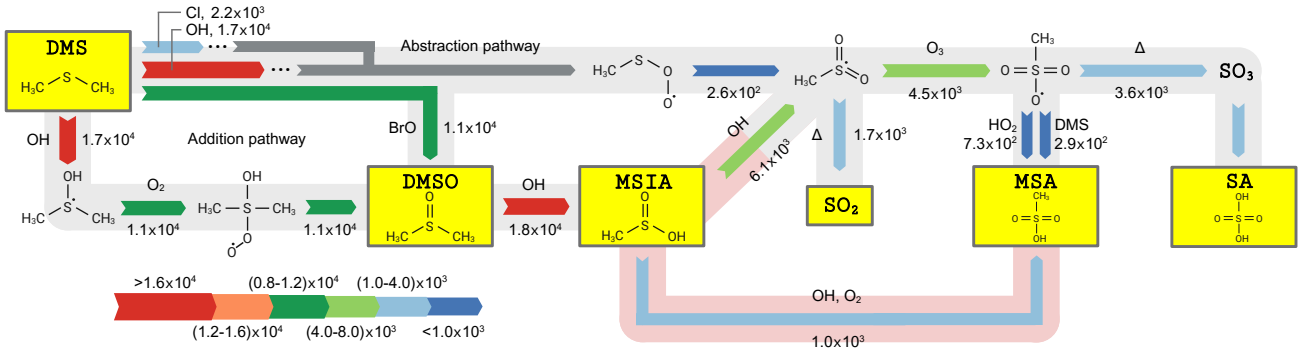


**Figure 1.** Simplified DMS oxidation mechanism for the gas-phase reactions responsible for the direct production of SA in the MBL. Source/sink fluxes for the respective compounds are reported in molecules $cm^{-3}$ $s^{-1}$ and calculated at the conditions given in the BaseCase simulation. The fluxes are shown next to the arrow for each reaction together the reactant for said reaction. Key compounds, all of which are able to partition to the aqueous-phase, are highlighted in yellow. New and modified pathways are marked in red.

the method by Wentworth et al. (2016). It should be noted that the sea surface concentration of both $NH_x$ and DMS can reach considerably higher concentrations near the coast, especially in regions with strong upwelling or nutrient run-off (Lana et al., 2011; Paulot et al., 2020; Hulswar et al., 2022). Emissions of biogenic volatile organic compounds (BVOCs) over the oceans (including isoprene and $\alpha$-pinene) is treated in accordance with the rates reported in Hoffmann et al. (2016).

## 2.2 DMS Oxidation Mechanism

The DMS oxidation reaction scheme used in this study has its basis in the mechanism presented in Wollesen de Jonge et al. (2021). Here, this mechanism is updated to account for the recent advances in the representation of DMS chemistry. In addition to these updates, we also use quantum chemical calculations to present new reaction pathways and temperature dependencies, as a means to address reactions in the DMS oxidation mechanism that still remain uncertain. The full gas-phase and aqueous-phase mechanism is found in Table S1 and S2, respectively. A simplified scheme for the gas-phase reactions that impact the direct formation of SA and thus DMS-drived NPF in the MBL is shown in Figure 1.

The main part of the DMS-derived gas-phase chemistry is taken from the Master Chemical Mechanism version 3.3.1 (MCMv3.3.1) (Jenkin et al., 1997, 2003). This includes the gas-phase oxidation of DMS by OH and $NO_3$ in addition to the fundamental processing of oxidation intermediates and products in the so-called addition and abstraction pathway. Here, the addition pathway refers to the addition of OH to DMS while the abstraction pathway refers to the H-abstraction from DMS by OH. The oxidation of DMS by halogen radicals Cl and BrO (through H-abstraction and addition, respectively) is treated in accordance with the study by Hoffmann et al. (2016). The processing of halogen radicals, including the activation of chlorine and bromine species in the sea spray particles, is obtained from Braeuer et al. (2013). This chemistry is essential for the representation of halogen

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radicals in the MBL and thus the oxidation of DMS. In addition to the halogen driven oxidation of DMS, Hoffmann et al. (2016) also provides the reactions that govern the aqueous-phase processing of DMS and its water soluble oxidation products in both deliquesced aerosol particles and cloud droplets. Amongst others, these reactions include the uptake of DMS, DMSO and MSIA to the aqeoues-phase and their reaction with OH and $O_3$ to form MSA. The uptake of MSIA has been found to be particularly impactful for the production of MSA particle mass (PM), as MSIA is able to partition to deliquesced aerosol particles in between cloud periods (Hoffmann et al., 2016; Wollesen de Jonge et al., 2021). The aqueous-phase processing of $SO_2$ is treated in accordance with Jacobson (2005).

The formation of HPMTF through autoxidation, proposed in theory by Wu et al. (2014), shown first in experiments by Berndt et al. (2019) and observed in the atmosphere by Veres et al. (2020), has undergone numerous revisions in the last couple years. The compound is formed from the $CH_3SCH_2OO$ peroxy radical (produced initially in the DMS abstraction pathway), which undergoes two hydrogen shifts (H-shifts) to form HPMTF. The first of the two H-shift is considerably slower than the second and thus constitutes the rate-limiting step in the formation of HPMTF. Veres et al. (2020) used multiconformer transition state theory to calculate temperature dependant rate coefficients for both H-shifts. Using this approach, the first and rate-limiting H-shift was determined to be 0.047 $s^{-1}$ at 295K. This estimate remains considerably slower than the some of the reaction coefficients determined in experiments, e.g. by Berndt et al. (2019) (0.23$\pm$ 0.12 $s^{-1}$ at 295K) and Ye et al. (2022) (0.13$\pm$ 0.03 $s^{-1}$ at 295K). In this study, we use the temperature dependant rate coefficient by Veres et al. (2020) and scale it to match the rate coefficient obtained by Ye et al. (2022). The rate by Ye et al. (2022) is used as opposed to the rate by Berndt et al. (2019), as the uncertainty associated with the rate is lower. To stay consistent with the use of reaction coefficient from Ye et al. (2022), the subsequent reaction of HPMTF with OH is also implemented from this study. Said rate is considerably higher than the original one presented in the study by Wu et al. (2014) ($2.1\times10^{-11}$ $cm^3$ $s^{-1}$ and $1.4\times10^{-12}$ $cm^3$ $s^{-1}$, respectively), ensuring that a higher fraction of HPMTF is converted to $SO_2$.

Another aspect of the DMS oxidation mechanism that has undergone revision in recent years is the fate of the products formed in the addition-pathway. In MCMv3.3.1, DMS undergoes OH addition to form DMSO, MSIA and finaly $SO_2$. Recent studies, combining smog chamber experiments on DMS oxidation with box modelling, are nevertheless unable to account for the production of MSA in the gas-phase and particle-phase without considering the H-abstraction from MSIA by OH to form the intermediate radical $CH_3SO_2$ (Wollesen de Jonge et al., 2021; Shen et al., 2022). $CH_3SO_2$ subsequently undergoes thermal decomposition to form $SO_2$ (similar to the fate of MSIA in MCMv3.3.1), but may also react with $O_3$ or $O_2$ and NO to form $CH_3SO_3$ and thus SA and MSA. Here it is essential to distinguish between the formation of SA from $CH_3SO_3$ and from $SO_2$, the latter pathway being considerably slower than the first ($2.8\times10^{-2}$ $s^{-1}$ and $8.8\times10^{-7}$ $s^{-1}$ at 283K and an OH concentration of $10^6$ $cm^{-3}$). With a direct impact on the production of SA and MSA, the H-abstraction from MSIA by OH therefore has the potential to impact the formation and growth of aerosol particles in the MBL. The reaction coefficient for said reaction was set to match the experimentally determined rate by Kukui et al. (2003). As this rate was determined at 298K, quantum chemical calculations are used in this study to provide temperature dependency for the reaction (section 2.4). These calculations demon-

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strate that the H-abstraction is more likely to occur at lower temperatures. While the H-abstraction from MSIA by OH has been shown to improve the model representation of MSA in previous publications, others continue to report a missing source of MSA in their model simulations (Ye et al., 2022). Consequently, this study also includes the addition of OH to MSIA, ultimately forming MSA through $O_2$ hydrogen abstraction. This pathway has been proposed theoretically in previous publications (Lucas and Prinn, 2002; Shen et al., 2022; Ye et al., 2022), but the rate of reaction has so far only been based on estimates or taken from similar reactions. Here, we implement quantum chemical calculations to determine the temperature dependant rate coefficient for the production of MSA through OH addition to MSIA. The reaction pathway is incorporated together with the work by Lv et al. (2019), which suggest that $H_2SO_3$ also forms from the addition of OH to MSIA. In this mechanism, $H_2SO_3$ is assumed to decompose directly to $SO_2$. An alternative source of MSA through the reaction of $CH_3SO_3$ with DMS is also considered (Yin et al., 1990; Jacob et al., 2024).

The isomerization of $CH_3SOO$ to $CH_3SO_2$ was included in the mechanism in accordance with the study by Hoffmann et al. (2016), which ensures that SA and MSA forms in the abstraction pathway, even during low $NO_x$ conditions (Turnipseed et al., 1995; Lucas and Prinn, 2002). In MCMv3.3.1, $CH_3SO_2$ is only able to form via the abstraction pathway through the reaction of $CH_3SO$ with $NO_2$ or via $O_2$ addition followed by oxygen abstraction by NO. As $NO_x$ concentrations are known to be low in the pristine MBL, the isomerization of $CH_3SOO$ therefore plays a role in the production of $CH_3SO_2$, SA and thus NPF. The fate of $CH_3SO_2$ nevertheless remains uncertain. $CH_3SO_2$ either undergoes thermal decomposition to form $SO_2$ or reacts with $O_3$, $NO_2$ or $O_2$ followed by NO to form $CH_3SO_3$. While the reaction coefficients for the reactions forming $CH_3SO_3$ are consistent in the literature, the coefficient for the thermal decomposition of $CH_3SO_2$ are not. MCMv3.3.1 reports a temperature dependant reaction coefficient of 0.29 $s^{-1}$ at 295K, which is considerably lower than the estimates used in the box modelling studies by Jacob et al. (2024) (6 $s^{-1}$ at 295K) and Berndt et al. (2023) (20 $s^{-1}$ at 295K). As the two latter reaction coefficients are in fact estimates obtained by fitting box model results to measurements, the rate presented in MCMv3.3.1 is used in this study. Due to the impact of the reaction on the distribution of $SO_2$, SA and MSA (and thereby NPF), the different rates are tested in ADCHAM through sensitivity runs. Similar to $CH_3SO_2$, the thermal decomposition of $CH_3SO_3$ also remains uncertain. Again, MCMv3.3.1 reports a relatively low rate for the reaction (0.11 $s^{-1}$ at 295K) while another study suggests that the reaction coefficient might be considerably higher (9.71 $s^{-1}$ at 295K) (Cao et al., 2013). The rate from MCMv3.3.1 is implemented as the default rate in this study while sensitivity runs are performed with the rate by Cao et al. (2013).

### 2.3 Sensitivity Runs

In addition to the default simulation (named BaseCase), different sensitivity runs were performed to test the impact of meteorological and hydrological conditions along with alternative rate coefficients and reaction pathways in the DMS oxidation mechanism on the role of DMS in NPF in the MBL. Table 1 gives an overview of the different simulations. The $TEMP_{273}$, $TEMP_{278}$, $TEMP_{288}$ and $TEMP_{293}$ sensitivity runs are performed at air temperatures both lower and higher than in the BaseCase simulation, respectively. This is done to demonstrate the impact of temperature on the DMS chemistry in addition to its effect on particle formation and particle growth. $WS_2$, $WS_4$, $WS_8$ and $WS_{10}$ showcase the impact of wind-speed on the emis-

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**Table 1.** An overview of the ADCHAM model setup in the BaseCase simulation and sensitivity runs.

| Model Run | Details |
|---|---|
| BaseCase | T = 283 K, WS = 6 $\mathrm{m/s}$, SST = 283 K, Rain = 10 $\mathrm{mm/h}$, [DMS] = 10 nM, [$\mathrm{NH_x}$] = 0.3 $\mathrm{mmol/m^3}$ |
| TEMP | Air temperature varied between 273K, 278K, 283K, 288K and 293K |
| WS | Wind-speed varied between 2 $\mathrm{m/s}$, 4 $\mathrm{m/s}$, 6 $\mathrm{m/s}$, 8 $\mathrm{m/s}$ and 10 $\mathrm{m/s}$ |
| PRCP | Precipitation varied between 2.5 $\mathrm{mm/h}$, 5 $\mathrm{mm/h}$, 10 $\mathrm{mm/h}$ and 15 $\mathrm{mm/h}$ |
| SST | Sea surface temperature varied between 278 K, 283 K, 288 K and 293 K |
| DMS | Sea surface concentration of DMS varied between 5 nM, 10 nM, 15 nM and 20 nM |
| $\mathrm{NH_x}$ | Sea surface concentration of $\mathrm{NH_x}$ varied between 0.1 $\mathrm{mmol/m^3}$, 0.2 $\mathrm{mmol/m^3}$, 0.3 $\mathrm{mmol/m^3}$ and 0.4 $\mathrm{mmol/m^3}$ |
| CLOUD | Mid-day and midnight clouds are introduced after the precipitation event |
| noMSIAabs | Removes the MSIA abstraction pathway by OH |
| noMSIAadd | Removes the MSIA addition pathway by OH |
| $\Delta\mathrm{CH_3SO_2}$ | Uses the thermal decomposition rate for $\mathrm{CH_3SO_2}$ from Jacob et al. (2024) |
| $\Delta\mathrm{CH_3SO_3}$ | Uses the thermal decomposition rate for $\mathrm{CH_3SO_3}$ from Cao et al. (2013) |

sions of compounds to the model, especially emissions of DMS, $\mathrm{NH_3}$ and sea-spray. These simulations represent conditions of low, moderate and high wind-speed. $\mathrm{PRCP_{2.5}}$, $\mathrm{PRCP_5}$ and $\mathrm{PRCP_{15}}$ show the impact of varying the amount of precipitation on day two of the simulation. Here, precipitation at 2.5-5.0 $\mathrm{mm/h}$ is classified as moderate rain, while precipitation from 10-15 $\mathrm{mm/h}$ is classified as heavy rain. The sea surface concentration of DMS is varied from the concentration used in the BaseCase simulation (10 $\mathrm{nmol/L}$) to 5 $\mathrm{nmol/L}$ in $[\mathrm{DMS}]_5$, 15 $\mathrm{nmol/L}$ in $[\mathrm{DMS}]_{15}$ and 20 $\mathrm{nmol/L}$ in $[\mathrm{DMS}]_{20}$. This represent conditions ranging from weak to moderate and strong phytoplankton blooms. $[\mathrm{NH_x}]_{0.1}$, $[\mathrm{NH_x}]_{0.2}$ and $[\mathrm{NH_x}]_{0.4}$ demonstrate the effect of the sea surface concentration of total dissolved ammonium, which in turn impacts the emissions of $\mathrm{NH_3}$ to the marine atmosphere. $\mathrm{NH_x}$ concentrations of 0.2 $\mathrm{mmol/m^3}$ are representative of conditions in the North Atlantic Ocean between May and July, where phytoplankton blooms are at their peak in the region. The same is true in the Southern Ocean during December to February, where $\mathrm{NH_x}$ concentration of 0.4 $\mathrm{mmol/m^3}$ are common. In the BaseCase simulation, no clouds are introduced in the model after the precipitation event at the end of day two. In the CLOUD sensitivity run, mid-day and mid-night clouds continue to be present after the precipitation event to test the impact of clouds on NPF in the simulation.

In addition to the sensitivity runs focusing on emissions and different meteorological and hydrological conditions, certain aspects of the DMS oxidation chemistry and its impact on DMS-derived NPF are also examined. In $\Delta\mathrm{CH_3SO_2}$, the rate for the thermal decomposition of $\mathrm{CH_3SO_2}$ from Jacob et al. (2024) is used as opposed to the rate from MCMv3.3.1, to test how an increase in $\mathrm{SO_2}$ at the expense of SA and MSA impacts NPF. In $\Delta\mathrm{CH_3SO_3}$, the rate from Cao et al. (2013) for the thermal decomposition of $\mathrm{CH_3SO_3}$ is used as opposed to the one from MCMv3.3.1 to demonstrate the impact from an increase in SA from $\mathrm{CH_3SO_3}$. In noMSIAabs and noMSIAadd, the reactions for the H-abstraction from MSIA by OH and OH addition to

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MSIA are removed from the simulation. This is done to showcase the role of the MSIA compound in the formation and growth of aerosol particles from DMS. In addition to the results depicted in figures 1-4 from the main text, further figures can be found in the SI, sections S1–S10.

### 2.4 Rate coefficients calculations

In this study, two key reactions on the oxidation of MSIA by OH were modified based on quantum chemical calculations. This was done due to their impact on SA and MSA production in the gas-phase (Wollesen de Jonge et al., 2021; Shen et al., 2022) and thus DMS-derived NPF in the MBL. The two reactions concern the H-abstraction from MSIA by OH and the addition of OH to MSIA. Quantum chemical calculations were used on the following principles: [1] If the reaction coefficient had previously been based on estimates, then the quantum chemical calculations were used to obtain both the reaction rate and the temperature dependency for the reaction. [2] If the reaction coefficient has been determined experimentally but at a fixed temperature, then the quantum chemical calculations were used to obtain the temperature dependency for the reaction. In the context of this work, quantum chemical calculations were therefore used to obtain the temperature dependency for the H-abstraction from MSIA by OH, since the rate of reaction had already been determined at a fixed temperate (298K) by Kukui et al. (2003). As no experimental rates exists for the addition of OH to MSIA, both the reaction rate and temperature dependency were calculated using quantum chemical calculations.

For the quantum chemical calculations, all geometry optimizations and harmonic vibrational frequency calculations of the reactants, transition states (TS), intermediates (IM), and products were performed at the M06-2X/6-311+G(3df,2p) level of theory (Zhao and Truhlar, 2008). Intrinsic Reaction Coordinate (IRC) calculations at the same level were carried out to confirm that each TS connects the intended reactants and products. Single-point energy (SPE) calculations were performed at the ROHF-ROCCSD(T)-F12a/cc-pVDZ-F12 (hereafter denoted as $F_{12a}$) level (Adler et al., 2008), including zero-point energy corrections obtained at the M06-2X/6-311+G(3df,2p) level. This combination of methods has been widely applied to study the transformations of peroxy and alkoxy radicals, and its accuracy is well established as a 'gold-standard' approach (Wang et al., 2020; D'Ambro et al., 2022; Møller et al., 2019). All quantum chemical calculations were performed using the Gaussian 16 and Molpro 2024.3 software packages (Frisch et al., 2016; Werner et al., 2020).

To account for the effects of multiple conformers of the reactants and transition states on the reaction mechanism, both single and multi-conformer approaches were employed to balance computational cost and accuracy. Based on the single-conformer results, multi-conformer effects were explicitly considered for key reaction channels, including H-abstraction and OH-addition reactions of MSIA with OH, as well as the subsequent reactions of the addition intermediates ($IM_{add}$). Following previous work (Fu et al., 2022, 2024a, b), a conformational sampling scheme using Molclus and Gaussian 16 was adopted to explore the low-energy conformers of the relevant reactants and transition states. For kinetic analysis, the electronic energies were taken from the $F_{12a}$ calculations, while the partition functions were derived from the M06-2X/6-311+G(3df,2p) results. Rate constants were obtained using multiconformer transition state theory (MC-TST). One-dimensional unsymmetrical Eckart barriers were

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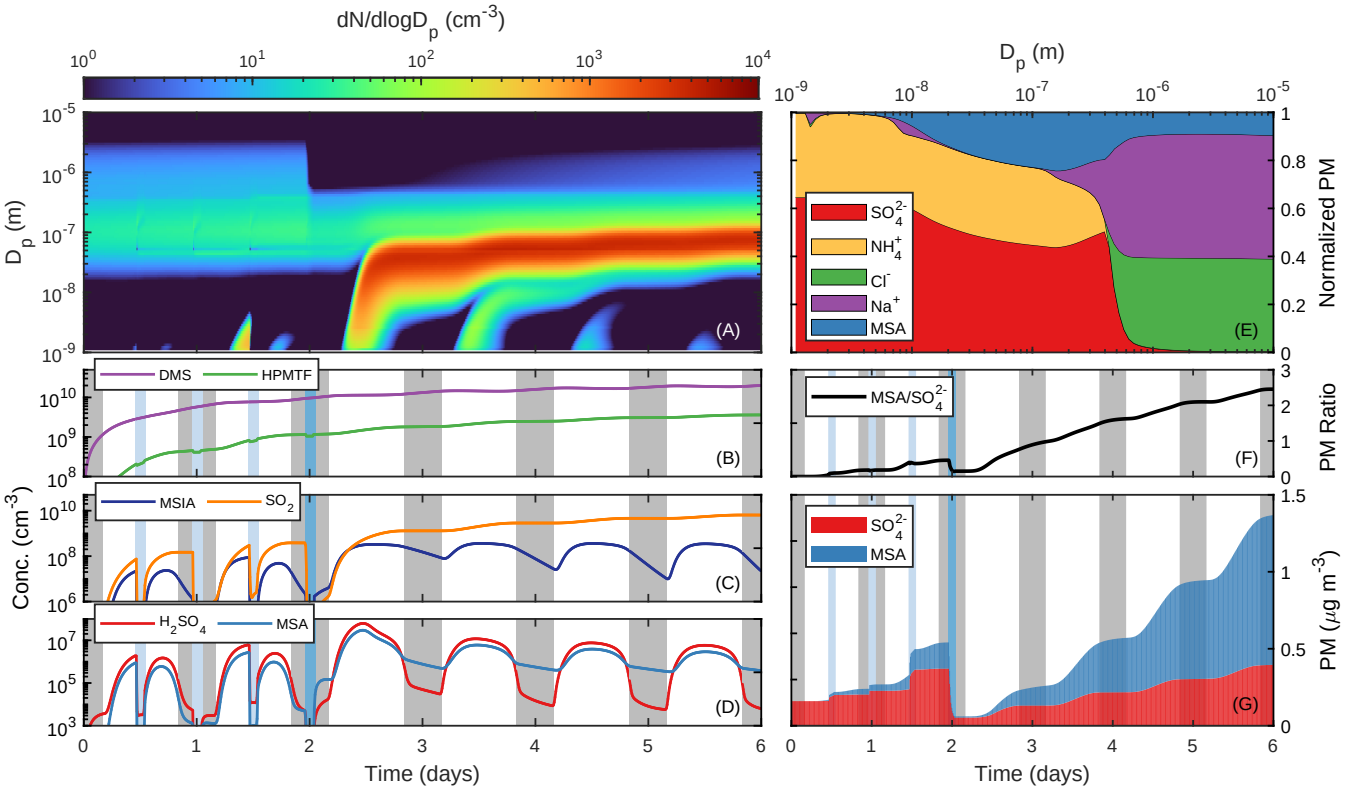


**Figure 2.** DMS driven NPF and growth in the pristine MBL. Panel **(a)** shows the particle number size distribution for the full simulation period, while panel **(b)**, **(c)** and **(d)** show the gas-phase concentrations of DMS and HPMTF, MSIA and $SO_2$ along with SA and MSA, respectively. Panel **(d)** shows the normalized chemical composition for the full size distribution, panel **(e)** the MSA/$SO_4^{2-}$ PM ratio and panel **(f)** the $SO_4^{2-}$ and MSA PM. The grey bars represent night-time conditions while the light and dark blue bars depict cloud and precipitation events, respectively. The results are obtained from the BaseCase simulation.

applied to account for quantum tunnelling in reactions involving H-shift or H-abstraction (Eckart, 1930). All rate constants were calculated with the KiSThelP program (Canneaux et al., 2014). The calculations are discussed in more detail in the SI, Section S1.

## 3 Results and Discussion

### 3.1 DMS-derived NPF and growth

At the conditions given in the BaseCase model setup, a distinct NPF event takes place on the third day of the simulation following the precipitation event (Fig. 2a). The formation and growth of particles is driven by emissions of DMS, which enters the model at $8.3\times10^9$ molecules $\mathrm{cm}^{-2}\ \mathrm{s}^{-1}$ (6 $\mathrm{m/s}$ wind-speed) and gradually builds up to reach a concentration of 0.92 ppb at

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the end of the simulation (Fig. 2b). As the simulation is initiated with high concentrations of sea spray aerosol particles (18.6 $\mu g\ m^{-3}$) and partial cloud cover, NPF is suppressed on day one and day two. The suppression of NPF is driven by the high SA condensation sink ($1.4\times10^{-3}\ s^{-1}$ before the precipitation event) and the uptake of SA and SA precursors to the cloud droplets. These precursors include MSIA and $SO_2$ which partition to the cloud droplets during cloud cover (Fig. 2c) to form MSA and $SO_4^{2-}$, respectively. This means that MSIA and $SO_2$ are almost completely removed from the gas-phase during cloud cover. Consequently, the mean SA gas-phase concentration is lower on day two of the simulation ($1.2\times10^{6}\ cm^{-3}$) compared to day three ($1.6\times10^{7}\ cm^{-3}$). The uptake and processing of water soluble species in the activated cloud droplets causes a small but distinct Hoppel minima to form in the size distribution during days 1-2 (Fig. 2a), driven predominantly by the uptake and aqueous-phase processing of DMSO, MSIA and $SO_2$. The minima persists after the precipitation event and highlights the impact that aqueous-phase chemistry in cloud droplets has on the aerosol particle population over the ocean. MSA is also removed during cloud cover, but since it possesses semi-volatile characteristics (Henry's law solubility of $6.7\times10^{8}$ mol $kg^{-1}\ atm^{-1}$ at 283K) a fraction of it will evaporate back to gas-phase after each cloud period (Fig. 2d). During the cloud free conditions representative of days 3-6, MSA follows a similar diurnal trend as SA with peak production and concentration during midday and lower concentrations at night. HPMTF builds up in the gas-phase in the same way as DMS, reaching a concentration of 166 ppt at the end of the simulation (Fig. 2b).

On day three of the simulation, the precipitation event removes a considerable fraction of the aerosol PM, thereby decreasing the condensation sink to $1.1\times10^{-4}\ s^{-1}$. This spurs an increase in the SA gas-phase concentrations which causes SA and $NH_3$ to cluster and form new particles. The continues condensation of SA and $NH_3$ ensures that the newly formed clusters grow, first into a distinct nucleation mode and thereafter into the Aitken mode which reaches a mode particle diameter of 73 nm (25th-75th prct.: 60-88 nm) at the end of the simulation. Additional NPF on days 4-6 is suppressed due to the increase in the condensation sink from the additional sea-spray PM and the particles formed in the NPF event on day three. The gas-phase concentration of MSIA, MSA and SA decreases correspondingly as they are lost to the increasing concentration of said particles (Fig. 2c and 2d). $SO_2$, on the other hand, accumulates in the gas-phase during days 3-6 as the lack of clouds prevents it from partitioning efficiently to the particle-phase. This also means that the SA source flux from $SO_2$ increases towards the end of the simulation whereas the SA source flux from $CH_3SO_3$ decreases in correspondence with the decrease in MSIA (Fig. S6). Consequently, $SO_2$ comprises 21% of the SA source flux during day six compared to 3% during day three. As a result, $SO_2$ becomes less important for the initial NPF as the conversion of $SO_2$ to SA is considerably slower than the conversion of $CH_3SO_3$ to SA. When $SO_2$ finally reaches a concentration where it contributes significantly to the production of SA, the sea-spray and DMS-derived PM concentration has become too high for new particles to form efficiently. Nucleation rates for the SA-$NH_3$ system obtained with the RI-CC2 method are significantly higher than those obtained with the DLPNO method (maximum nucleation rate of 2.0 $cm^{-3}s^{-1}$ on day three of the simulation using RI-CC2 as opposed to 0.13 $cm^{-3}s^{-1}$ when using DLPNO)(Fig. S12). This rate leads to a 2.2 times increase in the total PN concentration at the end of the simulation. The increase in the PN concentration stunts the growth of the particles as more SA is needed to grow said particles into the nucleation and Aitken mode. As a result, the growth mode only reaches a mode particle diameter of 56 nm (25th-75th prct.:

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46-68 nm) at the end of the simulation. Consequently, using the RI-CC2 method as opposed to the DLPNO method to obtain nucleation rate for the SA-$NH_3$ system will increase the total number of particles but decrease the number of particles that may reach the CCN size range.

$SO_4^{2-}$ and $NH_4^+$ PM dominates the chemical composition of the aerosol particles formed during the NPF event and in the subsequent growth mode (Fig. 2e). This is caused by the ability of SA to condense irreversibly to the particle-phase, with $NH_3$ aiding the growth by neutralizing the otherwise acidic aerosol particles. According to ADCHAM, DMS-derived SA and natural emissions of $NH_3$ from the surface ocean are capable of sustaining the growth of newly formed aerosol particles into the nucleation and Aitken mode. MSA does not contribute significantly to the growth of the smaller particles, as its semi-volatile characteristics mainly allows it to condense on the larger sea-spray particles. MSA PM nevertheless aids the growth of the particles in the Aitken and upper end of the nucleation mode, with particularly high PM concentrations in the accumulation and coarse mode particles (Fig 2e). This happens as 85% of MSA is formed in the aqueous-phase of the deliquesced aerosol particles and cloud droplets from the oxidation of dissolved and dissociated MSIA by $O_3$. The remaining MSA production happens in the gas-phase through the addition of OH to MSIA (8%) and from the reaction of $CH_3SO_3$ with $HO_2$ (6%) and DMS (2%). While MSA formed in the gas-phase is able to condense on particles in the nucleation and Aitken mode size range, MSIA mainly partitions to the coarse mode deliquesced sea-spray particles where it is converted to MSA. This tendency is evident from the decrease in the MSA PM during the precipitation event. Here, the MSA PM decreases by 95% as opposed to 86% for the $SO_4^{2-}$ PM as the coarse mode particles containing most of the MSA PM are removed more efficiently through wet-deposition than particles in the lower size ranges (Fig. 2g). After the precipitation event, the MSA PM increases disproportionally to the $SO_4^{2-}$ PM as the lack of clouds prevents $SO_2$ from being converted to $SO_4^{2-}$. As MSA continues to be produced in the deliquesced sea spray particles, the MSA/$SO_4^{2-}$ PM ratio increases throughout the simulation from an average ratio of 0.3 on day three to 2.3 on day six (Fig. 2f).

### 3.2 Impact of metrological and hydrological conditions

#### 3.2.1 Air temperature

The air temperature within the MBL dictates different aspects that influences the formation and growth of aerosol particles. This includes the gas-phase and aqueous-phase chemistry, the rate of molecular clustering and evaporation, the condensation of low volatile species to the particles and the uptake of water-soluble species to deliquesced particles and cloud droplets. The air temperature therefore constitutes an important factor in NPF and particle growth.

A fundamental role of the air temperature is its ability to control the amount of water that the air can hold. Warmer air holds more water than cold air and as a consequence produces higher concentrations of OH, with a mean concentration throughout the simulation of $5.2\times10^5$ $cm^{-3}$ in $TEMP_{293}$ compared to $1.8\times10^5$ $cm^{-3}$ in $TEMP_{273}$. Higher concentrations of OH also leads to higher concentrations of $HO_2$, which promotes the production of HOX (X = Cl, Br, I) which catalytically activates the halogen species ICl, BrCl and $Cl_2$ from the sea spray particles and thus promotes the concentration of halogen oxidants in the

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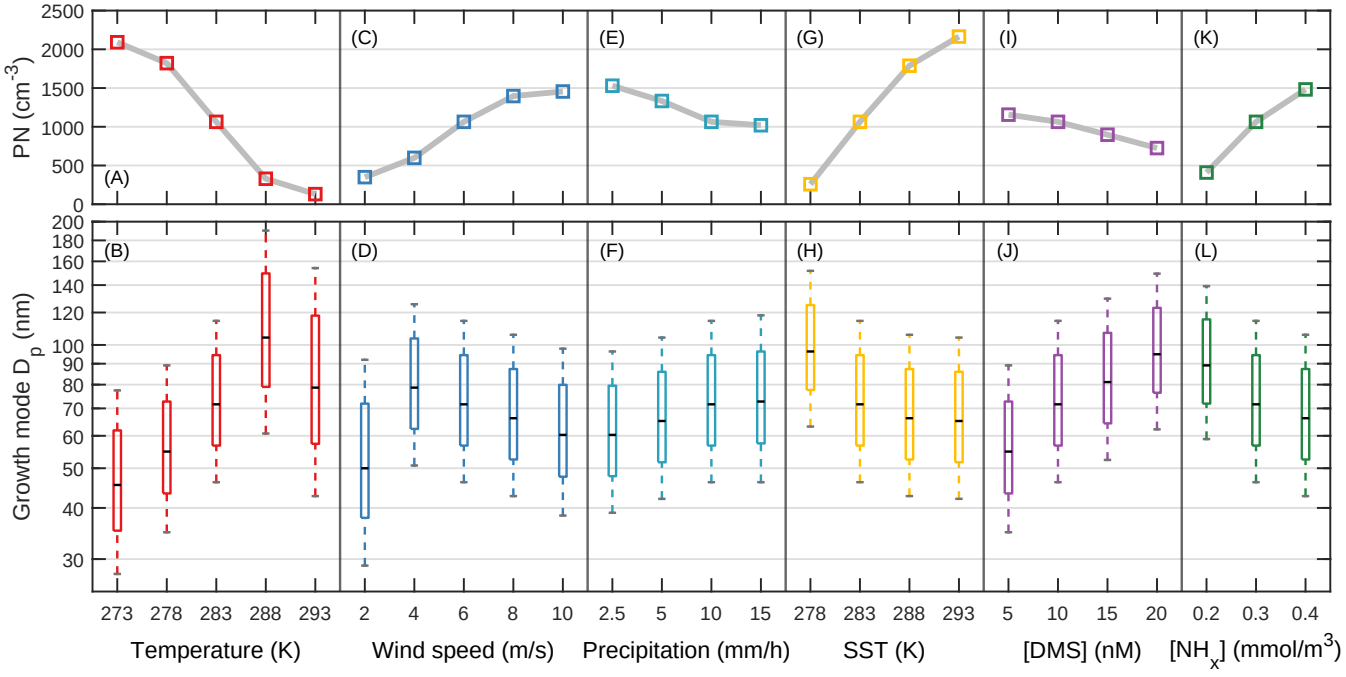


**Figure 3.** DMS-derived growth mode in the pristine MBL. Depicts the aerosol growth mode particle size distribution and total PN concentration at the end of the simulation for (a-b) varying temperatures, (c-d) varying wind-speeds, (e-f) varying rates of precipitation, (g-h) varying sea surface temperatures, (i-j) varying surface ocean concentrations of DMS and (k-l) varying surface ocean concentrations of total dissolved $NH_x$. The box plots represents the 5th, 25th, 75th and 95th percentile of the growth mode and the black line represents the mode particle diameter. Simulations were no NPF event took place are not included in the figure.

gas-phase (Braeuer et al., 2013). The oxidative capacity of the MBL therefore increases with temperature, which is seen in the mean DMS sink flux throughout the simulation which increases from $4.1\times10^4$ $cm^{-3}s^{-1}$ in $TEMP_{273}$ to $4.9\times10^4$ $cm^{-3}s^{-1}$ in $TEMP_{293}$ (Fig. S16). At the same time, temperature also dictates the ratio of the DMS abstraction pathway to the DMS addition pathway, as OH addition to DMS is favoured at lower temperatures ($k_{DMS,abs}/k_{DMS,add}$ = 0.5 at 273 K and 1 atm compared to 1.6 at 293 K). The temperature driven branching of the OH-initiated oxidation of DMS propagates through the mechanism and dictates the production of species in both the abstraction and addition pathway. As a result, the mean source flux of DMSO and MSIA in the addition pathway is higher in $TEMP_{273}$ ($2.4\times10^4$ $cm^{-3}s^{-1}$ and $1.9\times10^4$ $cm^{-3}s^{-1}$, respectively) compared to $TEMP_{293}$ ($1.6\times10^4$ $cm^{-3}s^{-1}$ and $1.4\times10^4$ $cm^{-3}s^{-1}$, respectively) in spite of higher OH concentrations in $TEMP_{293}$ (Fig. S20). The temperature dependency on the initial oxidation of DMS is amplified by the addition of BrO to DMS forming DMSO, which is favoured at lower temperatures. Although cold conditions promotes the production of DMSO and MSIA, the fraction that oxidizes to form $CH_3SO_2$, $CH_3SO_3$ and ultimately SA and MSA in the gas-phase is limited by the uptake of MSIA to the deliquesced aerosol particles. The mean sink flux of MSIA to the deliquesced particles is 4.0 times higher at 273 K compared to 293 K, whereas the sink flux of MSIA through H-abstraction by OH is 3.0 times higher at 293 K

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compared to 273 K. Consequently, colder temperatures promotes the uptake of MSIA to the aqueous-phase whereas warmer temperatures promotes the continues oxidation of MSIA in the gas-phase. The effect is evident from the MSA/$SO_4^{2-}$ PM ratio (7.0 in $TEMP_{273}$ and 0.9 in $TEMP_{293}$) as the uptake of MSIA to the deliquesced aerosol particles promotes the production of MSA through aqueous-phase oxidation by $O_3$.

The continues production of $CH_3SO_2$ originates both from the oxidation of MSIA by OH in the addition pathway and through the propagation of species in the abstraction pathway. However, due to the low $NO_x$ conditions in the simulation (representative of the pristine MBL), the $NO_x$ driven oxidation of $CH_3SO$ and $CH_3SOO_2$ in the abstraction pathway make up < 1% of the $CH_3SO_2$ source flux throughout all temperature sensitivity runs. The isomerization of $CH_3SOO$ comprises the only significant source of $CH_3SO_2$ from the abstraction pathway, making up 4% of the $CH_3SO_2$ source flux in the BaseCase simulation (Fig. S10). The oxidation of MSIA by OH, on the other hand, makes up 96% of the $CH_3SO_2$ source flux. It is evident therefore that the oxidation of species in the addition pathway dictates the production of $CH_3SO_2$, $CH_3SO_3$ and thus direct SA and MSA production in the gas-phase.

While the production of $CH_3SO_2$ continues to increase with temperature, its oxidation by $O_3$ to form $CH_3SO_3$ is impacted by the thermal decomposition of $CH_3SO_2$ into $CH_3OO$ and $SO_2$ (Figure 1). Said decomposition increases with temperature, causing the $F_{CH_3SO_2,\Delta}/F_{CH_3SO_2+O_3}$ sink flux ratio to increase from 0.1 in $TEMP_{273}$ to 1.3 in $TEMP_{293}$. As a consequence, the $CH_3SO_3$ production stagnates as the temperature increases from 273 K to 283 K and starts to drop as the temperature exceeds 283 K (Fig. S22). This directly impacts the production of SA which follows the trend of $CH_3SO_3$ through the thermal decomposition of $CH_3SO_3$ into $CH_3OO$, $SO_3$ and thus SA. As the simulation progresses and additional sea-spray enters the MBL, the temperature effect on the uptake of MSIA to the sea-spray becomes increasingly important for the production of SA. Following the precipitation event on day three, sea-spray concentrations remain relatively low. This in combination with higher concentrations of DMSO ensures that the concentration of MSIA on day three is higher in $TEMP_{273}$ compared to $TEMP_{293}$. On day four-six, however, MSIA concentrations in $TEMP_{273}$ falls bellow that in $TEMP_{293}$ as the colder temperatures ensures that MSIA partitions efficiently to the aqueous-phase. As a result, the $CH_3SO_2$, $CH_3SO_3$ and SA source flux decreases from day three to day six in $TEMP_{273}$ but increases during the same time in $TEMP_{293}$, both following the continues increase in the DMS concentration (Fig. S17, S21 and S22).

In addition to the effect of temperature on the uptake of MSIA to the deliquesced particles, SA production from $SO_2$ also becomes increasingly important with the increase in temperature. The $SO_2$ source flux increases by a factor of 3.8 between 273 K and 293 K, mainly driven by the increase in HPMTF production but also from the thermal decomposition of $CH_3SO_2$ which makes up 17% of the $SO_2$ source flux in $TEMP_{293}$ as opposed to 4% in $TEMP_{273}$ (Fig. S19). The formation of HPMTF is favoured at higher temperatures as the OH addition to DMS becomes less favourable, thereby promoting the abstraction pathway and thus the autoxidation of $CH_3SCH_2O_2$ into HPMTF and ultimately $SO_2$. Furthermore, the autoxidation itself becomes faster as the temperature increases as the internal H-abstractions by the peroxy radicals in $CH_3SCH_2O_2$ and

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$OOCH_2SCH_2OOH$ are favoured at higher temperatures. $SO_2$ therefore reaches a concentration of 519 ppt in $TEMP_{293}$ as opposed to 130 ppt in $TEMP_{273}$, thereby comprising 27% and 7% of the total SA source flux throughout the simulations, respectively. The combination of the decrease in the uptake of MSIA to the sea-spray particles and the increase in the production of $SO_2$ means that the total SA source flux increases from 273 K to 288 K (Fig. S17). Beyond 288 K, however, the thermal decomposition of $CH_3SO_2$ limits the oxidation of $CH_3SO_2$ by $O_3$ to a degree where the production of $CH_3SO_3$ and thus SA starts to decrease. Consequently, the total SA source flux throughout the simulation decreases as the temperature exceeds 288 K.

MSA production in the gas-phase remains relatively stable across the temperature interval, although its source varies. At 273 K, H-abstraction from DMS by $CH_3SO_3$ and the reaction of $HO_2$ with $CH_3SO_3$ makes up 27% and 46% of the MSA gas-phase source flux, respectively. At 293 K, OH addition to MSIA dominates the production of MSA comprising 80% of the MSA gas-phase source flux. The difference comes down to the decrease in MSIA partitioning to the deliquesced particles and higher OH concentrations in warm conditions, which promotes the addition of OH to MSIA despite the inverse relationship between temperature and the addition reaction rate itself. In cold conditions, DMS concentrations are higher due to the limited oxidation capacity of the atmosphere and $CH_3SO_3$ is less likely to undergo thermal decomposition thereby promoting the production of MSA via H-abstraction from DMS by $CH_3SO_3$.

In addition to the impact of temperature on the chemistry and uptake of water soluble species to the aqueous-phase, temperature also impacts the rate by which the initial clusters form and grow. Here, the maximum SA-$NH_3$ derived nucleation rate on day three of the simulation following the precipitation event increases as the temperature decreases from $0.3\times10^{-2}$ $cm^{-3}s^{-1}$ at 293 K to 0.9 $cm^{-3}s^{-1}$ at 273 K (Fig. S15). The difference is driven predominantly by the temperature effect on the cluster stability as the $NH_3$ and SA concentrations increases with increasing temperatures. The higher nucleation rate at 273 K promotes the total PN concentration, which was found to be 15 times higher at the end of the simulation in $TEMP_{273}$ compared to $TEMP_{293}$ (Fig. 3a).

The continues growth of the particles changes throughout the simulation. During day one-two, the particle growth is dictated by the uptake and complete removal of water soluble gas-phase species to the cloud droplets. In terms of the MSA PM, the impact of clouds is less pronounced as MSIA already partitions efficiently to the deliquesced particles during cloud-free periods. Clouds nevertheless promotes the production of $SO_4^{2-}$ PM through the uptake and aqueous-phase processing of $SO_2$. Consequently, the $SO_4^{2-}$ PM increases linearly with the temperature during days one-two. During the remainder of the simulation, however, the total SA source flux and thus the production of $SO_4^{2-}$ PM increases from 273 K to 288 K but decreases from 288 K to 293 K. This happens as the production of $CH_3SO_3$ and in turn SA stagnates and starts to decrease beyond 288 K as the fraction of $CH_3SO_2$ that decomposes into $SO_2$ becomes higher. If left to run for an extended period, the total SA source flux in $TEMP_{293}$ would eventually surpass that of those in the remaining simulations due to the increase in the production of SA from $SO_2$. However, as the production of SA from $CH_3SO_3$ dictates the production of the new particles following the precipitation event, the particles formed at 293 K would not reach the size of those produced at 288 K. As a

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result, the DMS-derived particles reach their maximum mode diameter of 106 nm (25th-75th prct.: 85-136 nm) at 288 K, with the particles reaching only 46 nm (25th-75th prct.: 38-57 nm) at 273 K and 81 nm (25th-75th prct.: 62-106 nm) at 293 K (Fig. 3b). The DMS-derived NPF and growth therefore does not change linearly with temperature, but peaks around moderate temperature conditions. At higher temperatures, the SA production is limited by the thermal decomposition of $CH_3SO_2$ which limits the production of $CH_3SO_3$ and thus SA. At lower temperatures, the SA production is limited by the uptake of MSIA to the deliquesced particles, which decreases the production of $CH_3SO_2$, $CH_3SO_3$ and thus SA. It should be noted that the high nucleation rate at the lower temperatures also lowers the growth of the particles, as more SA is needed to grow the high concentration of newly formed particles into the nucleation and Aitken mode.

### 3.2.2 Wind-speed

The wind-speed adjacent to the sea surface makes up the most important metrological factor in the emission of gases and sea spray particles from the ocean to the MBL. The correlation between the gas-flux and the wind-speed 10 meters above the sea surface ($U_{10}$) may be linear (Liss and Merlivat, 1986), super-linear (Blomquist et al., 2017) ($F \propto U_{10}^{1.33}$) or quadratic (Wanninkhof, 2014; Nightingale et al., 2000) depending on the study that is used to calculate the transfer velocity $k_w$. Well established emission databases such as the Copernicus Atmosphere Monitoring Service (CAMS) relies on the quadratic transfer velocity from Nightingale et al. (2000) to calculate the sea-air flux of DMS, despite the fact that the relationship between the transfer velocity and wind-speed from said study has not been determined specifically for DMS. In this work we utilize the super-linear transfer velocity from Blomquist et al. (2017), as it was calculated specifically for DMS. As a consequence, the DMS flux and atmospheric DMS-derived concentrations reported here are smaller than those in model studies that rely on emissions from CAMS or utilize a quadratic transfer velocity to calculate the flux of DMS in their model, especially during conditions with high wind-speed. Emissions decrease further if using the linear transfer velocity from Liss and Merlivat (1986). For sea spray, the current parameterizations generally agree on using an empirical power law fit for the sea spray flux as a function of wind-speed ($F \propto U_{10}^{3.41}$) (Sofiev et al., 2011; Salter et al., 2015). Concentrations of sea spray in the MBL consequently depends heavily on wind-speed, with much higher emissions during strong winds compared to calm conditions.

In the sensitivity runs $WS_2$, $WS_4$, $WS_8$ and $WS_{10}$, the wind-speed in the simulation is varied from 2 $m/s$ to 10 $m/s$ in addition to the 6 $m/s$ used in the BaseCase simulation. DMS emissions vary by close to an order of magnitude across this wind-speed interval, ranging from $1.9\times10^9$ molecules $cm^{-2}$ $s^{-1}$ at 2 $m/s$ to $1.6\times10^{10}$ molecules $cm^{-2}$ $s^{-1}$ at 10 $m/s$. The DMS concentrations consequently reaches 229 ppt in $WS_2$ and 808 ppt in $WS_{10}$ (Fig. S23). Higher concentrations of DMS are seen in BaseCase (922 ppt) and $WS_8$ (1089 ppt), as the substantial sea spray particle concentrations in $WS_{10}$ (65 $\mu g/m^3$ at the end of the simulation as opposed to 0.3 $\mu g/m^3$ in $WS_2$) ensures higher concentrations of halogen oxidants BrO and Cl and thus a higher DMS sink flux than in the remaining simulations (Fig. S26). The increase in DMS emissions and the oxidative capacity of the MBL also ensures that the secondary aerosol PM increases in accordance with the wind-speed (0.2 $\mu g/m^3$ in $WS_2$ and 6.0 $\mu g/m^3$ in $WS_{10}$). Strong winds favour the production of MSA as opposed to $SO_4^{2-}$, as the increase in sea spray increases the uptake of MSIA to the deliquesced aerosol particles and thus promotes the aqueous-phase production of MSA. As a result,

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the MSA/$SO_4^{2-}$ PM ratio is 0.5 in $WS_2$ and 8.3 in $WS_{10}$.

The formation and growth of DMS derived particles in the MBL at different wind-speeds is dictated by the emissions of DMS, $NH_3$ and sea spray. In $WS_2$, sea spray emissions and thus the condensation sink remains low ($0.6\times10^{-3}$ $s^{-1}$ at the end of the simulation as opposed to $4.6\times10^{-3}$ $s^{-1}$ in $WS_{10}$). The low condensation sink allows DMS-derived SA and $NH_3$ to form and grow particles during days 3-6 in the simulation (Fig. S24), although the maximum nucleation rate during these days remains moderately low at $1.5\times10^{-2}$ $cm^{-3}s^{-1}$. New particles are able to form on day six in $WS_2$ as the sea spray concentration builds up slowly, thus keeping the condensation sink low. Nucleation and growth rates in $WS_2$ remain low compared to the other simulations, as the low wind-speed also limits the emissions of DMS and $NH_3$. The opposite is true in $WS_{10}$, where emissions of DMS and $NH_3$ are high but the growth is limited by the high concentration of sea spray. As a results, new particles are able to form relatively efficiently on day three (following the precipitation event) when sea spray concentrations have not yet reached a level where they efficiently suppress NPF. On day four to six, however, the increasing condensation sink (both from the sea spray and from the DMS-derived growth event) prevents any new particles from forming. As the high condensation sink in $WS_{10}$ also limits the growth of the newly formed particles, said particles only reach a mode particle diameter of 61 nm (25th-75th prct.: 51-74 nm) at the end of the simulation (Fig. 3d). In $WS_2$, the particles reach a mode diameter of 52 nm (25th-75th prct.: 41-65 nm). These two scenarios illustrate that an optimal wind-speed exists where the condensation sink is sufficiently low and the concentration of precursor gases sufficiently high for particles to grow. Here, we demonstrate that the overall growth of the particles peaks in $WS_4$ at a mode diameter of 80 nm (25th-75th prct.: 66-96 nm). The total PN concentration, however, increases in according with the wind-speed from $4.1\times10^{2}$ $cm^{-3}$ in $WS_2$ to $1.5\times10^{3}$ $cm^{-3}$ in $WS_{10}$ (Fig. 3c). In conclusion, moderate wind-speeds (4-6 $m/s$) comprises the optimal conditions for DMS-derived particles to grow within the MBL. During conditions of light winds, the growth of the new particles is limited by the lack DMS and $NH_3$. During strong winds, the growth is limited by the high condensation sink caused by the sea spray emissions. As the concentration of sea spray particles remains low on day three of the simulation following the precipitation event in $WS_{2-10}$, the rate of nucleation and thus the total PN concentration increases in accordance with the wind-speed due to higher emissions of DMS and $NH_3$.

### 3.2.3 Precipitation

Over the open ocean, precipitation is essential for the formation of new particles as it efficiently lowers the concentration of accumulation and coarse mode particles. The decrease in particle surface area lowers the condensation sink and allows SA to reach higher concentrations in the gas-phase. In the BaseCase simulation, a heavy rainfall of 10 $mm/h$ is introduced to the model for one hour during the night-time cloud event between day two and day three. This rainfall efficiently lowers the sea spray PM concentration by 99% which causes the mean SA gas-phase concentration to increase by an order of magnitude (factor 12.3) on day three compared to day two. The increase in the gas-phase concentrations of SA subsequently sparks a distinct NPF event on day three. In the $PRCP_{2.5}$ and $PRCP_5$ sensitivity runs, representing conditions of moderate precipitation, the growth mode on day three remains present in the simulation despite lower concentrations of SA (Fig. S34). This happens as these precipitation rates still remove 89% and 96%, respectively, of the available sea-spray PM. At 2.5 $mm/h$ precipitation, the

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growth rate of the NPF event on day three was found to be 2.8 $\mathrm{nm/h}$ compared to 3.3 $\mathrm{nm/h}$ at 5 $\mathrm{mm/h}$ precipitation and 4.0 $\mathrm{nm/h}$ at 10 $\mathrm{mm/h}$ precipitation. The newly formed particles continue to grow and reach a mode diameter of 61 nm (25th-75th prct.: 51-74 nm), 66 nm (25th-75th prct.: 55-80 nm) and 73 nm (25th-75th prct.: 60-88 nm) towards the end of the simulation in $\mathrm{PRCP}_{2.5}$, $\mathrm{PRCP}_{5}$ and BaseCase, respectively (Fig. 3f). Our results, therefore, indicate that new particles formed over the ocean can reach the Aitken mode size range within a couple of days, even at moderate rates of precipitation. Precipitation beyond 10 $\mathrm{mm/h}$ has less impact on the NPF and growth since the far majority of the coarse mode sea spray particles has already been removed at this precipitation rate. As a consequence, the growth rate on day three of the simulation in $\mathrm{PRCP}_{15}$ increases to just 4.3 $\mathrm{nm/h}$ with the newly formed particles reaching a mode diameter of 74 nm (25th-75th prct.: 61-89 nm) at the end of the simulation. The total PN concentration at the end of the simulation is higher in $\mathrm{PRCP}_{2.5}$ compared to $\mathrm{PRCP}_{10}$ (Fig. 3e), as less of the $\mathrm{NH}_4^+$ PM has been removed from the atmosphere. As a result, more $\mathrm{NH}_3$ evaporates back into the gas-phase following the precipitation event which helps to drive the initial NPF. The continues growth of these particles are nevertheless stunted by the decreased production of SA in the gas-phase.

#### 3.2.4 Sea surface temperature

All marine emissions, be it sea spray particles or gases, depend on the sea surface temperature. For gases, the sea to air flux is generally calculated as the product between the gas exchange coefficient k and the concentration gradient between the air-sea interface (Eq. 1) (Ziska et al., 2013).

$$F = k(C_w - C_a H^{-1}) \tag{1}$$

Here, $C_w$ is the concentration of the gas in water, $C_a$ is the concentration of the gas in air and H is the dimensionless Henry's law solubility. The gas exchange coefficient depends both on the wind-speed and the sea surface temperature through the Schmidt number for each gas. The Schmidt number, which prescribes the ratio of the kinematic viscosity of water to the diffusivity of a specific gas in water, decreases for increasing sea surface temperatures as water becomes less viscous and gases diffuse easier in warmer waters. From the inverse relationship between the gas exchange coefficient and the Schmidt number it follows that higher sea surface temperatures increases the rate by which the gas leaves the surface ocean. In addition, the Henrys law solubility dictates that gases are less soluble in warm as opposed to cold water, thereby increasing the concentration gradient between the air-sea interface in warmer waters.

For the emission flux of sea spray particles, the sea surface temperature impacts both the size of the particles emitted as well as total emitted PM. While uncertain, it is currently believed that the emission rate of smaller particles is favoured at low temperature as opposed to the emission rate of larger particles which is favoured at higher temperatures (Barthel et al., 2019). While the emitted particles are smaller in cold waters the number of emitted particles tend to be higher than in warm waters. Overall, this leads to less PM but higher PN when the sea surface temperature is low as opposed to higher PM but lower PN

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when the sea surface temperature is high.

The $SST_{278}$, $SST_{288}$ and $SST_{293}$ sensitivity runs demonstrate how the emissions of gases and sea spray PM increases with increasing sea surface temperature. Comparing results from the $SST_{278}$ and $SST_{293}$ sensitivity runs, the emission of $NH_3$ increases by a factor of 4.9 while the emissions of DMS increases by 50%. Sea spray emissions increase as well, reaching a concentration of 9.3 $\mu g/m^3$ and 15.9 $\mu g/m^3$ at the end of the simulation in $SST_{278}$ and $SST_{293}$, respectively (Fig. S45). The effects of the emission increase across all the mentioned species are twofold. First, the overall production of secondary aerosol PM increases from 1.1 $\mu g/m^3$ in $SST_{278}$ to 2.1 $\mu g/m^3$ in $SST_{293}$, following the higher emissions of DMS which promotes the production of $SO_4^{2-}$ and MSA PM. Second, the MSA/$SO_4^{2-}$ PM ratio increases correspondingly from 2.0 to 3.4 as the production of MSA PM is favoured to the production of $SO_4^{2-}$ PM due to the higher uptake of MSIA to the higher concentration of deliquesced sea spray particles. The uptake of MSIA to said particles constitutes 56% of the MSIA sink flux in $SST_{278}$ and 69 % in $SST_{293}$. The increase in DMS emissions with the increase in SST nevertheless outweighs the increase in the uptake of MSIA to the sea spray particles, ensuring that the SA production in the gas-phase becomes 33% higher in $SST_{293}$ compared to $SST_{278}$ (Fig. S47). The increase in the SA production along with the increase in $NH_3$ emissions also ensures that the maximum nucleation rate on day three of the simulation increases with the increase in SST, from $2.0\times10^{-2}$ $cm^{-3}s^{-1}$ in $SST_{278}$ to 0.8 $cm^{-3}s^{-1}$ in $SST_{293}$ resulting in the total PN concentration being 8.3 times higher in $SST_{293}$ compared to $SST_{278}$ (Fig. 3g). In conclusion, higher SST promotes DMS-derived NPF through an increase in the emissions of $NH_3$ and DMS and thus the production of SA. At the same time, said processes are suppressed by the increase in the sea spray PM concentration which promotes the uptake of MSIA and SA to the particle-phase. At the same time, the high concentration of new particles formed in $SST_{293}$ stagnates the growth of said particles as more SA is needed to grow the particles into the nucleation and Aitken mode. In $SST_{278}$, where significantly less particles are able to form, the particles are able to grow into larger sizes. As a result, the newly formed particles in $SST_{293}$ reach a particle mode diameter of 66 nm (25th-75th prct.: 54-80 nm) at the end of the simulation as opposed to 98 nm (25th-75th prct.: 82-116 nm) in $SST_{278}$ (Fig. 3h). It should be noted that strong blooms of phytoplankton are generally found in colder waters where nutrients are more readily available. As a consequence, warmer waters tend to have lower sea surface concentrations of DMS and $NH_x$ (Lana et al., 2011; Hulswar et al., 2022; Paulot et al., 2015).

### 3.2.5 DMS surface ocean concentration

The concentration of DMS in the surface ocean varies globally in accordance with the presence of phytoplankton. These plankton species in turn depend on external factors such as nutrient availability and sunlight, resulting in substantial spatial and temporal variations in plankton blooms, and consequently in the surface ocean DMS concentration. In $[DMS]_5$, BaseCase, $[DMS]_{15}$ and $[DMS]_{20}$, we demonstrate the impact that low, moderate, and high concentrations of DMS may have on the DMS-derived NPF and growth within in the MBL. It should be noted that the concentration of DMS may reach even higher concentrations in nutrient rich waters near certain coastlines (Lana et al., 2011; Hulswar et al., 2022). The concentrations ap-

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plied here are nevertheless representative of the pristine MBL governed by natural nutrient availability.

Unsurprisingly, higher surface ocean concentrations of DMS leads to higher gas-phase concentrations of DMS and thereby DMS-derived secondary aerosol PM in the MBL. The impact on the chemistry, NPF and particle growth, however, is found to be sub-linear. At a surface ocean concentration of 5 nM, DMS enters the MBL at 0.4 $\times 10^{10}$ molecules $\mathrm{cm}^{-2}$ $\mathrm{s}^{-1}$ and reaches a gas-phase concentration of 427 ppt at the end of the simulation. At 20 nM, the sea-air flux increases to 1.7 $\times 10^{10}$ molecules $\mathrm{cm}^{-2}$ $\mathrm{s}^{-1}$ and the concentration reaches 2.1 ppb. The ensuing processing of DMS and its reaction intermediates and products changes in accordance with the availability of oxidant species. The source flux of halogen radicals remains relatively unchanged following the increase in DMS concentrations from $[\mathrm{DMS}]_5$ to $[\mathrm{DMS}]_{20}$. The concentrations of OH and $O_3$, however, are found to decrease as the DMS concentration increases (Fig. S53). On the final day of the simulation, the mean OH and $O_3$ concentrations are 24% and 3% lower, respectively, in $[\mathrm{DMS}]_{20}$ compared to $[\mathrm{DMS}]_5$. As a result, the DMS concentration in the gas-phase stagnates and becomes relatively stable as the simulation progresses in $[\mathrm{DMS}]_5$ and BaseCase as opposed to $[\mathrm{DMS}]_{15}$ and $[\mathrm{DMS}]_{20}$ where it accumulates. While the concentration of DMS-derived oxidation products increases in accordance with the increase in DMS emissions, said increase stagnates as the DMS loading becomes higher. For instance, a power law fit for the source flux of $SO_2$, MSA and SA to the sea surface DMS concentration shows a sublinear response for all species, with scaling exponents of 0.81, 0.92, and 0.66, respectively. The incremental increase in the MSA source flux drops disproportionally to the other species as the production of MSA through the H-abstraction from DMS by $CH_3SO_3$ increases with the concentration of DMS. Said reaction therefore makes up 7% of the MSA gas-phase source flux in $[\mathrm{DMS}]_5$ as opposed to 25% in $[\mathrm{DMS}]_{20}$. The increase in MSA happens at the expense of SA production, as $CH_3SO_3$ is less likely to undergo thermal decomposition into $SO_3$ and thus SA.

The rate of particle formation on day three of the simulation is governed by the production of SA and the uptake of $NH_3$ to the particle phase. As the simulation progresses, the higher DMS loading acidifies the particles (2.1 and 1.2 mean bulk particle-phase pH during days three-six in $[\mathrm{DMS}]_5$ and $[\mathrm{DMS}]_{20}$, respectively) thereby driving $NH_3$ into the aqueous-phase (Fig. S55). This effect is most pronounced towards the end of the simulation, but even on day three the concentration of $NH_3$ is 67% lower in $\mathrm{DMS}_{20}$ compared to $\mathrm{DMS}_5$. The source flux of SA and thus the SA gas-phase concentration, however, continues to increase with higher sea surface concentrations of DMS (Fig. S57). Still, the nucleation rate on day of three of the simulation peaks at 0.15 $\mathrm{cm}^{-3}\mathrm{s}^{-1}$ in $[\mathrm{DMS}]_5$ and decreases to 0.10 $\mathrm{cm}^{-3}\mathrm{s}^{-1}$ in $[\mathrm{DMS}]_{20}$. The nucleation rate also impacts the total PN concentration in the Aitken mode, which decreases from $[\mathrm{DMS}]_5$ to $[\mathrm{DMS}]_{20}$ (Fig. 3i). As the continues growth of the particles relies mainly on the availability of SA in the gas-phase, the growth rate on day three of the simulation peaks in $[\mathrm{DMS}]_{20}$ at 6.2 $\mathrm{nm/h}$, compared to 2.8 $\mathrm{nm/h}$ in $[\mathrm{DMS}]_5$. The same is true for the particle growth during the remainder of the simulation, where the particles reach a mode diameter of 96 nm (25th-75th prct.: 81-114 nm) in $[\mathrm{DMS}]_{20}$ compared to 56 nm (25th-75th prct.: 46-89 nm) in $[\mathrm{DMS}]_5$ (Fig. 3j). In conclusion, natural emissions of DMS during moderate to high sea surface concentrations of DMS are able to form and grow aerosol particles that reach into the upper Aitken and accumulation mode particle size range with the potential to act as CCN in the pristine MBL.

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### 3.2.6 $NH_x$ surface ocean concentration

It is well documented that the ocean can constitute a source of $NH_3$ to the atmosphere from dissolved $NH_x$ in the surface ocean (Johnson et al., 2008; Paulot et al., 2020). This is particularly true at high latitudes in highly productive regions of the oceans with intense biological recycling of nitrogen. These same regions also experience the highest occurrence of phytoplankton blooms. Once in the atmosphere, $NH_3$ aids the SA-$NH_3$ clustering and therefore constitutes one of the most important precursors that drives NPF in the MBL. In addition, $NH_3$ helps to neutralize the otherwise acidic marine aerosol particles, ensuring that less acidic and more volatile species such as MSIA and MSA are able to partition to and dissociate in the aqueous-phase.

In $[NH_x]_{0.1}$, $[NH_x]_{0.2}$, BaseCase and $[NH_x]_{0.4}$ we perform simulations with low (0.1 $mmol/m^3$), moderate (0.2-0.3 $mmol/m^3$) and high (0.4 $mmol/m^3$) concentrations of dissolved $NH_x$ in the surface ocean. Higher concentrations of $NH_x$ naturally leads to a higher emissions of $NH_3$, with the $NH_3$ sea-air flux being 3.7 times higher in $[NH_x]_{0.4}$ compared to $[NH_x]_{0.1}$. The increase is sub-linear as the flux is regulated based on the concentration of $NH_3$ in the atmosphere. Once in the air, $NH_3$ helps to increase the pH of the predominantly acidic marine particles from 1.4 in $[NH_x]_{0.1}$ to 1.7 in $[NH_x]_{0.4}$ (Fig. S65). The increase in pH incentivize the uptake and dissociation of semi-volatile and moderately acidic species such as MSIA, which aids the production of MSA in the aqueous-phase. The MSA/$SO_4^{2-}$ PM ratio consequently increases from 2.1 in $[NH_x]_{0.1}$ to 2.5 in $[NH_x]_{0.4}$.

The biggest impact from changes in the $NH_x$ concentration nevertheless concerns the rate of SA-$NH_3$ driven nucleation. On the third day of the simulation, the gas-phase $NH_3$ concentration in $[NH_x]_{0.4}$ is 7.3 times higher than in $[NH_x]_{0.1}$, which in turn increases the SA–$NH_3$ nucleation rate by a factor of 22.9. As a result, the nucleation rate in $[NH_x]_{0.1}$ is insufficient to initiate a distinct growth event and, consequently, to form and sustain an Aitken mode throughout the simulation (Fig. S64). At a concentration of 0.2 $mmol/m^3$, however, the $NH_3$ gas-phase concentration becomes sufficiently high to allow the particles to form and grow into the Aitken mode. Increasing the $NH_x$ concentration further mainly impacts the nucleation rate and thus the PN concentration in the DMS-derived growth mode. Consequently, the total PN concentration increases from $4.1\times10^2$ $cm^{-3}$ in $[NH_x]_{0.2}$ to $1.1\times10^3$ $cm^{-3}$ in $[NH_x]_{0.3}$ and $1.5\times10^3$ $cm^{-3}$ in $[NH_x]_{0.4}$ (Fig. 3k). The mode diameter at the end of the simulation is impacted by the rate of nucleation. As a result, more SA is needed to grow the particles in $[NH_x]_{0.4}$ which stunts their growth compared to the particles in $[NH_x]_{0.2}$. The newly formed particles therefore reach a mode diameter at the end of the simulation of 90 nm (25th-75th prct.: 76-107 nm) in $[NH_x]_{0.2}$ and 67 nm (25th-75th prct.: 56-81 nm) in $[NH_x]_{0.4}$ (Fig. 3l).

### 3.2.7 Clouds

In the BaseCase model setup, the first two days of the simulation includes partial cloud cover during midday and midnight. The following four days contain no clouds. In the CLOUD sensitivity run, clouds are introduced at midday and midnight throughout the simulation. As a consequence, the total source flux of $CH_3SO_2$, $CH_3SO_3$ and SA decreases as the water soluble compounds DMSO, MSIA and $SO_2$ are lost to the aqueous-phase during cloud cover (Fig. S81 and S82). The gas-phase concentration of $SO_2$ is affected in particular by the presence of clouds, as it does not partition readily to the deliquesced

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particles. Therefore, $SO_2$ becomes insignificant in the production of SA during cloudy conditions compared to the decomposition of $CH_3SO_3$ which makes up 97% of the SA source flux throughout the CLOUD sensitivity run as opposed to 89 % in BaseCase. The combination of the uptake of MSIA and $SO_2$ during the additional cloud-periods lowers the total SA source flux from $4.1\times10^3$ $cm^{-3}s^{-1}$ in BaseCase to $1.9\times10^3$ $cm^{-3}s^{-1}$ in CLOUD.

The total DMS-derived production of secondary aerosol PM nevertheless increases by 71% as the $SO_2$ taken up during the cloud periods is transformed efficiently to $SO_4^{2-}$ PM. The impact is evident from the MSA/$SO_4^{2-}$ PM ratio which drops from 2.5 to 0.7, almost exclusively driven by the increase in $SO_4^{2-}$ PM as MSA is produced efficiently in the absence of clouds through the uptake and aqueous-phase processing of MSIA in the deliquesced aerosol particles. On day three of the simulation, the NPF event initiates in similar fashion to the event in the BaseCase simulation, but looses momentum after the first midday cloud period (Fig. S74). This happens as the uptake of DMSO, MSIA, $SO_2$ and SA to the aqueous-phase in addition to the aqueous-phase processing of DMSO, MSIA and $SO_2$ ensures that the gas-phase concentration of these species must rebuild after each midday cloud period (Fig. S73). The same goes for $NH_3$, which is not able to reach sufficient concentrations in the gas-phase in order to drive additional NPF or neutralize the newly formed particles. As a consequence, additional NPF after the cloud-event on day three of the simulation becomes negligible as the SA-concentration in the gas-phase is not sufficient to sustain the growth into the nucleation mode. Therefore, no distinct growth mode forms after the precipitation event in the CLOUD sensitivity run. The overall effect of clouds are therefore to terminate both the formation of DMS-derived particles and their growth into the nucleation and Aitken mode size range.

### 3.3 Impact of chemistry

Although this study has demonstrated that DMS is able to drive the formation and growth of aerosol particles within the pristine MBL under various metrological and hydrological conditions, some uncertainty still remains due to present representation of the DMS oxidation mechanism. Most of this uncertainty lies in the fate of MSIA and its successors $CH_3SO_2$ and $CH_3SO_3$, due to their role in the production of SA and MSA. $CH_3SO_2$ and $CH_3SO_3$ are also formed in the DMS abstraction pathway, but since HPMTF and $SO_2$ make up the major products from said pathway the production of $CH_3SO_2$ and $CH_3SO_3$ remains small. At 283K, MSIA oxidation by OH makes up 96% of the $CH_3SO_2$ source flux while the isomerization of $CH_3SOO$ makes up 4%. At the low $NO_x$ conditions representative of the pristine MBL, $CH_3SO_2$ formation through the reaction of $CH_3SO$ with $NO_2$ or $CH_3SOO_2$ with NO becomes insignificant. The role of MSIA in the production of SA through $CH_3SO_2$ and $CH_3SO_3$ is evident from the 'noMSIAabs' sensitivity run. Here, the source flux of SA decreases by 87% throughout the simulation, thus decreasing the strength of the NPF event following the precipitation event on day three (Figure 4a and S10.2). This is caused by SA being formed predominantly through $SO_2$ which is slower than the production of SA through the thermal decomposition of $CH_3SO_3$. Consequently, SA is not formed fast enough to initiate a strong NPF and growth event before the concentration of sea spray becomes to high. Some new particles are able to form on days 4-6 of the simulation when the $SO_2$ concentration has had time to accumulate, but the nucleation and growth rate remains limited. The rate of the H-abstraction from MSIA by OH was originally determined experimentally at 298K by Kukui et al. (2003). In this work, we extend the rate

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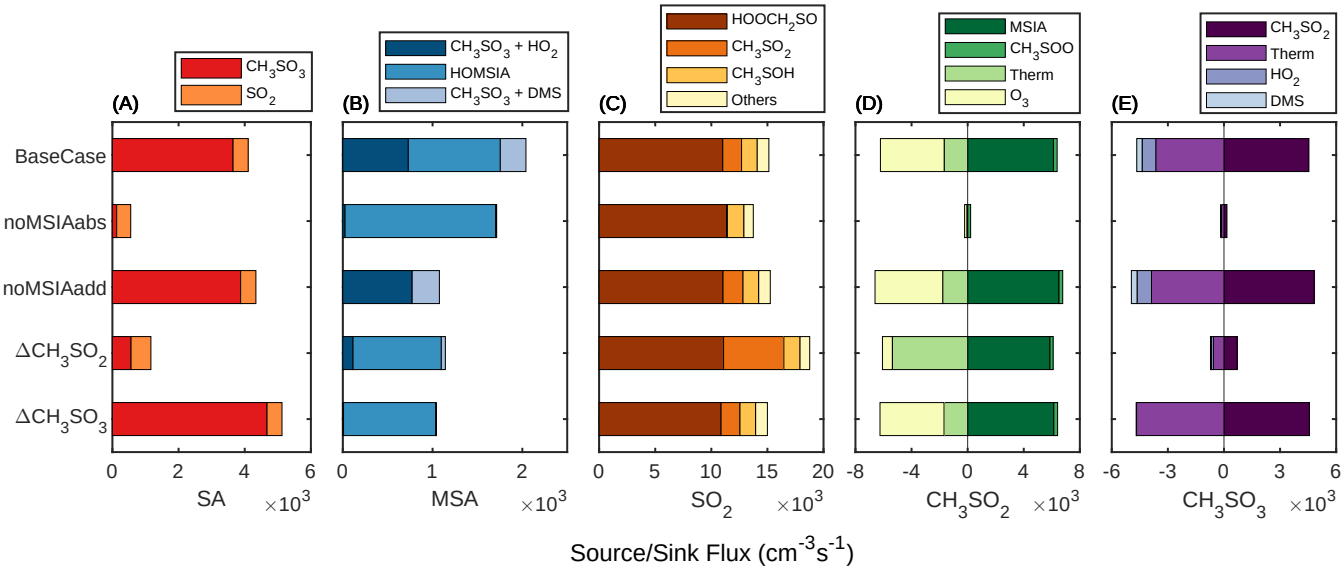


**Figure 4.** Gas-phase sink and/or source fluxes for SA, MSA, $SO_2$, $CH_3SO_2$, and $CH_3SO_3$. The legend for the source flux refers to the precursor of the compound in question, while for the sink flux it refers to the oxidant or process that reacts with or transforms the compound. 'Therm' denotes the thermal decomposition of either $CH_3SO_2$ or $CH_3SO_3$.

determined by Kukui et al. (2003) with a theoretical temperature dependency based on quantum chemical calculations. Said temperature dependency predicts a slight increase in the rate of H-abstraction at lower temperatures, e.g. $9.0\times10^{-11}$ $cm^3$ $s^{-1}$ at 298K and $1.2\times10^{-10}$ $cm^3$ $s^{-1}$ at 273K. It should be noted that in the simulation the increase in the H-abstraction rate is counterbalanced by the decrease in the OH concentration at lower temperatures.

In addition to adding temperature dependency to the rate for H-abstraction from MSIA by OH, this study also presents the temperature dependant reaction rate for the addition of OH to MSIA and subsequent production of MSA through H-abstraction by $O_2$. This pathway has been discussed in previous publications (Lucas and Prinn, 2002; Shen et al., 2022; Ye et al., 2022), but so far no experimental nor theoretical reaction rates have been determined. Here, quantum chemical calculations are used to provide the reaction rate. The noMSIAadd sensitivity run demonstrates the impact of the reaction, which has little influence on the formation and initial growth of the aerosol particles as it does not significantly influence the production of SA. It does however impact the gas-phase production of MSA which decreases by 47% throughout the simulation (Fig. 4b). As a result, including this reaction pathway might help to improve model representations of MSA in the gas-phase. The HO-MSIA intermediate that forms after the OH-addition to MSIA has also been shown to form $H_2SO_3$ (and thus eventually $SO_2$) in other studies by the loss of a methyl group (Lv et al., 2019; Berndt et al., 2024). In accordance with the calculations performed in this study, however, the H-abstraction by $O_2$ forming MSA is considerably faster than the decomposition to $H_2SO_3$ ($2.4\times10^{13}$

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$s^{-1}$ and $6.4\times10^{10}$ $s^{-1}$ at 283K and 1 atm, respectively).

Another aspect of the DMS oxidation mechanism that adds uncertainty to the role of DMS in NPF in the MBL is the rate for the thermal decomposition of $CH_3SO_2$ and $CH_3SO_3$ into $SO_2$ and $SO_3$, respectively. Unfortunately, it is challenging to calculate the transition state for the decomposition of both these species and therefore a theoretical rate has not been determined in this study. Instead we demonstrate the impact that these rates have on DMS-derived NPF in the MBL through sensitivity runs performed with the experimentally determined or estimated rates that are currently available in the literature. In this study we use the rates prescribed by MCMv3.3.1 in the BaseCase setup as they are in line with the experimental rate for the $CH_3SO_2$ decomposition obtained by Borissenko et al. (2003) (e.g. < 1 $s^{-1}$ at 298K). Higher rates for the decomposition of $CH_3SO_2$ have been estimated in the studies by Jacob et al. (2024) (8.3 $s^{-1}$ at 298K) and Berndt et al. (2023) (20 $s^{-1}$). As for the decomposition of $CH_3SO_3$, Cao et al. (2013) calculated an upper limit of 12.7 $s^{-1}$ at 298K while an estimate based on experimental results by Berndt et al. (2023) falls in line with the rate presented in MCMv3.3.1 (0.1 $s^{-1}$ at 298K).

In the $\Delta CH_3SO_2$ sensitivity run, the rate for the thermal decomposition of $CH_3SO_2$ was increased in accordance with the rate estimated by Jacob et al. (2024). This increase favours the production of $SO_2$, the source flux of which increases by 24% throughout the simulation at the expense of $CH_3SO_3$ and thus SA, the source flux of which decreases by 72% (Fig. 4c and 4a). The decrease in SA lowers the nucleation rate on day three from 0.13 $cm^{-3}s^{-1}$ to $8.7\times10^{-2}$ $cm^{-3}s^{-1}$ and causes the particles to reach a mode diameter of 52 nm (25th-75th prct.: 41-65 nm) at the end of the simulation compared to 73 nm (25th-75th prct.: 60-88 nm) in BaseCase. Due to the decrease in the $CH_3SO_3$ concentration, $SO_2$ becomes more important for the production of SA making up 52% of the SA source flux as opposed to 11% in the BaseCase simulation. The conversion of $SO_2$ to $SO_3$ and thus SA nevertheless remains slow, meaning that new particles are not able to form efficiently before the concentration of sea spray particles and thus the SA condensation sink becomes to high (Fig. S84). Using the rate by Jacob et al. (2024) also impacts the source flux of MSA in the gas-phase which decreases by 44% as a result of the decrease in the $CH_3SO_3$ concentration. As a consequence, MSA production through OH addition to MSIA becomes the dominating source of MSA in the gas-phase comprising 86% of the MSA gas-phase source flux compared to 50% in the BaseCase simulation. In summery, a higher rate for the thermal decomposition of $CH_3SO_2$ would make DMS-driven NPF in the MBL less favourable as the direct production of SA is suppressed.

A higher rate for the thermal decomposition of $CH_3SO_3$, however, is seen to have the opposite effect. Increasing said rate favours the production of $SO_3$ and SA as opposed to MSA. This is evident from the $\Delta CH_3SO_3$ sensitivity run where the rate for the thermal decomposition of $\Delta CH_3SO_3$ was increased in accordance with the study by Cao et al. (2013). As a consequence, the total SA source flux showed a 25% increase compared to the BaseCase run at the expense of the MSA source flux in the gas-phase which decreases by 49%. Said decrease originates from the reaction of $CH_3SO_3$ with $HO_2$ and DMS, respectively, which make up $\sim$ 1% of the MSA source in the $\Delta CH_3SO_3$ sensitivity run. Consequently, MSA production through OH addition to MSIA as proposed in this study becomes the almost exclusive source of MSA in the gas phase. The impact of the

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increase in the SA source flux from the increase in the thermal decomposition of $CH_3SO_3$ is evident from the the SA-$NH_3$ derived nucleation rate. On day three of the simulation, the nucleation rate increases by 19%, ultimately increasing the total PN concentration at the end of the simulation from $1.1\times10^3$ $cm^{-3}$ in BaseCase to $1.2\times10^3$ $cm^{-3}$ in $\Delta CH_3SO_3$. The increase in the PN concentration counterbalances the increase in the growth for the individual aerosol particles as more SA is needed to grow the newly formed particles into the nucleation and Aitken mode size range. As a result, the mode diameter of the growth mode at the end of simulation is lower at 68 nm (25th-75th prct.: 57-82 nm) in $\Delta CH_3SO_3$ compared to 73 nm (25th-75th prct.: 60-88 nm) in BaseCase, despite the increase in the SA source flux.

The rate calculated by Cao et al. (2013) nevertheless remains uncertain. In the review article by Barnes et al. (2006), it is mentioned that the rate for the thermal decomposition of $CH_3SO_3$ should be similar or much lower than the one by $CH_3SO_2$. This is supported by a recent experimental study by Berndt et al. (2023), where they estimate said rate to be similar to the one presented in the MCMv3.3.1. It remains evident however that the rate for the thermal decomposition of both $CH_3SO_2$ and $CH_3SO_3$ has an impact on the formation and growth of DMS-derived aerosol particles in the MBL. At the moment, any claim that these rates should be higher than those presented in the MCMv3.3.1 are based on estimates and theoretical calculations. It remains essential therefore that the thermal decomposition of both $CH_3SO_2$ and $CH_3SO_3$ are examined further in laboratory studies so as to decrease the uncertainty linked to their role in the formation and growth of aerosol particles from DMS.

## 4 Conclusions

Advanced simulations of atmospheric chemistry and aerosol dynamics in a pristine ocean scenario shows that natural emissions of DMS and $NH_3$ are able to drive SA-$NH_3$-derived NPF within the MBL, the particles of which are able to grow into the upper Aitken and accumulation mode size range with the potential to act as CCN. The formation and growth of said particles is favoured during cloud-free conditions following an event of moderate to heavy precipitation. Precipitation effectively lowers the concentrations of sea spray aerosol PM in the MBL, allowing SA to reach concentrations where they are able to cluster with $NH_3$ and grow into the nucleation and Aitken mode size range.

The formation and growth of the particles are impacted by various metrological and hydrological conditions. Low temperatures favour SA-$NH_3$ NPF by preventing cluster evaporation, but at the same impair NPF and growth as they promote the uptake of MSIA to the sea spray particles which lowers the production of SA. High temperatures, on the other hand, prevent NPF and growth by favouring the DMS abstraction pathway over the addition pathway. Moreover, the thermal decomposition of $CH_3SO_2$ into $CH_3OO$ and $SO_2$ reduces the production of $CH_3SO_3$, thereby lowering the formation of SA. This leads to optimal DMS-derived particle growth at moderate temperatures (283-288 K). Varying wind-speed conditions produce similar results: low wind speeds limit NPF and growth due to reduced emissions of DMS and $NH_3$, whereas high wind speeds constrain particle growth by increasing the sea spray PM, which enhances the uptake of MSIA and SA to the particle phase. Consequently, DMS-derived particles in the MBL grow most efficiently at moderate wind-speeds around 4-6 $m/s$. Sensitivity

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runs utilizing different rates of precipitation demonstrates that DMS and $NH_3$ are able to drive NPF and growth in the MBL, even during conditions with a moderate rainfall (2.5-5.0 $mm/h$). At 10 $mm/h$ and beyond, the far majority (> 98%) of sea spray aerosol PM has been removed, providing optimal conditions for NPF and growth. Increasing the SST promotes the ocean-air flux of DMS and $NH_3$, which in turn favours the formation and growth of DMS-derived aerosol particles despite the increase in sea-spray PM. For the surface ocean concentrations of DMS, the SA production and subsequent aerosol particle growth shows a sub-linear response to an increase in concentration due to the impact of DMS on the concentration of $O_3$ and OH. The acidification of the particles with higher emissions of DMS also limits the $NH_3$ concentrations in the gas-phase, ultimately lowering the rate of nucleation. For the sea surface concentration of $NH_x$, 0.2 $mmol/m^3$ was sufficient to initiate and sustain a DMS-derived growth event, with higher concentrations promoting the rate of SA-$NH_3$ nucleation and neutralization of the aerosol particles. If sporadic cloud cover is introduced in the model following the precipitation event, NPF is terminated and the particles are not able to form a distinct growth event.

The degree to which DMS is able to form and sustain the growth of new particles within the MBL also depends heavily on the representation of the DMS oxidation mechanism. MSIA is found to be one of the key components in this process, as it governs the direct production of SA through the formation of $CH_3SO_2$ and $CH_3SO_3$. Omitting the H-abstraction from MSIA by OH from the model decreases the SA production to a point where NPF is heavily limited and the particles that do form are unlikely to reach the Aitken mode. Omitting the addition of OH to MSIA (as presented in this study) does not impact NPF significantly. It does, however, decrease the production of MSA in the gas-phase substantially. The spread in the rate for the thermal decomposition of $CH_3SO_2$ and $CH_3SO_3$ as presented in the literature proves to be a big source of uncertainty in the direct production of SA and thus DMS-derived NPF and growth. High estimates for $k_{\Delta CH_3SO_2}$ promotes $SO_2$ production at the expense of $CH_3SO_3$, slowing down the formation SA and thus limiting NPF and growth. High estimates for $k_{\Delta CH_3SO_3}$, on the other hand, promotes direct SA production and thus NPF. Future work, therefore, should focus on improving the rate coefficients for these reactions.

As the observations on NPF over the oceans remains scarce, we also urge the scientific community to to provide more and better measurements from the marine environment. Given that the current observations on NPF in the MBL is based mainly on flight and ship campaigns (Baccarini et al., 2021; Zheng et al., 2021), long term measurements in pristine ocean conditions are needed to better quantify the impact of NPF on CCN concentrations in the MBL.

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

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