Response to RC1 and RC2 : 'Comment on egusphere-2025-2829'

October 22, 2025

We are grateful to the reviewer for taking the time to review our manuscript and for offering such valuable feedback. Your observations and helpful recommendations contributed to enhancing the clarity and quality of our work. Please find below the response (in blue) to your comments (in black)

RC1

The authors have undergone an extensive modelling study to understand the impact of several factors (sea ice extent, wind speed, SST) on the emission of speciated PMOA over the last several decades. They have done the analysis on a regional basis and searched for trends relating decreases in sea ice area to increases in PMOA emissions. As they discuss in section 5, all of this is very difficult to do considering the lack of PMOA seawater and atmospheric aerosol data, especially speciated, in the Arctic. Given the lack of data and the many uncertainties involved, the paper advances the understanding of factors controlling the emission, seasonality, and trends in Arctic PMOA.

1. Lines 184 – 185: Were open leads and melt ponds considered in estimating PMOA concentrations?
   Leads and melt ponds were not included in the model; we have added a sentence at line 186 to explicitly state this: "However, in the present study, open leads and melt ponds are not included in the model simulations."

2. Table 1: Is an analysis of annually averaged data justified since there is so much seasonality in the factors controlling emission flux, burden, and deposition?
   We agree, annually averaged data would not be justified in this case given the strong seasonality shown, for example, in Fig. 5. However, Table 1 does not show the annual average values, but rather the multi-year average over a period of 15 or 30 years of total annual emissions over the Arctic. Since the table header was misleading, we changed it as follows: "Table 1: Total emission flux, atmospheric burden, and deposition of marine aerosol particles, calculated by summing daily

values across all Arctic grid cells and averaging yearly totals over the two 15-year periods and the full 30-year period." Following this comment, and for consistency with Table 1 and Table 3, we also decided to show total seasonal emissions as just explained in Fig. 5 and Fig. 11 for July-August-September, and Fig. F5 for April-May-June. Additionally, for better alignment with Fig. 9, Fig. 10 shows the trends of regionally averaged emission fluxes.

3. Lines 318: Is there a reference for the SST correction factor for the SS emission flux?

   The sea surface temperature (SST) dependence of the sea spray emission flux is implemented following Sofiev et al. (2011). This reference has now been included in the text.

4. Figure 5: The order of figures for e) and f) is different than what is stated in the caption.

   We have corrected this error in the figure caption.

5. Lines 339 – 341: It is stated on lines 301 – 302 that SS emissions from the model are a sum of both the accumulation and coarse modes. Earlier in the paper it says that PMOA fluxes are based on SS fluxes which are based on temperature. Yet, it is stated here (lines 339 – 341) that the SST correction factor used in SS model simulations remains relatively similar for the accumulation mode. Is only the SST correction for the accumulation mode used for the speciated PMOA fluxes? It seems confusing if the speciated PMOA fluxes are coming from size independent (accumulation + coarse modes) SST emissions but size a dependent (accumulation mode only) SST correction.

   PMOA is only emitted into the accumulation mode, based on SS emission of the same mode, which depends on SST. PMOA is not emitted into the coarse mode directly, and the mass emission fluxes of PMOA do not encompass the coarse-size particles. In contrast, SS is additionally emitted into the coarse mode. Hence, the SST correction only affects the accumulation-mode PMOA emissions while for SS, it influences both the finer and coarse modes.

   In the model output, the emission fluxes are not mode-dependent. Therefore, in lines 301 – 302, we specify that the SS emissions are not accumulation mode alone but also coarse mode.

   To make these aspects clearer, we modified lines 339-341 as follows: "Overall, SST ranges between -2 to 6 °C. Within this temperature range, the Sofiev et al. (2011) SST correction factor used in the SS model representation remains relatively similar for the particles in the accumulation mode, which is the only size class contributing to PMOA emissions. Therefore, in this case, SST has a lesser effect on marine emissions. "

6. Figure 8: Should this be Beaufort Sea for (b)?

   That is correct, it should be Beaufort Sea. We have changed this in the figure caption.

7. Line 611: Change “along” to “alone”.

   Thanks for pointing this out. We corrected it.

RC2

1. Abstract: what you mean by accumulated aerosol burden? It has not been introduced before so reader might find it difficult to understand what you mean by accumulated

   We agree with the reviewer that the concept of accumulated burden has not been clearly introduced at this point, and its meaning may therefore be unclear. We now use the more common term, ”total aerosol burden”, which is calculated as follows: Annual values were obtained by aggregating daily results from all grid cells across the Arctic region, which were then averaged over the 30-year period. We changed this in all the instances in the text. This also includes the header of Table 1 in Section 3.3.1.

2. Abstract: These two lines almost say the same thing. Why you need both? “These quantities peak from May to September, coinciding with the phytoplankton bloom and seasonal sea ice minimum” and “Summer trend analysis (June–August) reveals a strong reduction in sea ice that correlates with rising concentrations of organic groups in seawater in the inner Arctic.”

   We understand that the overlap of the time periods in these two sentences may have caused confusion and given the impression of duplicated information. However, the sentences indeed refer to distinct findings of the analysis. To improve clarity, we have revised the text accordingly. We have removed the sentence “These quantities peak from May to September, coinciding with [...]” and modified the one before: ”Results indicate that the strong seasonality in biomolecule concentrations and PMOA emissions is driven by marine productivity and sea salt emissions, with the peak occurring from May to September.”

   In the case of the second sentence, we slightly modified it for clarity: ”Summer (June–August) trend analysis over the 30 years reveals a pronounced reduction in sea ice that correlates with rising concentrations of organic groups in seawater in the inner Arctic”.

3. Abstract: This line says the rate of increase has decreased from 7 to 4 % in the second half of the study. “ Accumulated aerosol emissions and burdens over the Arctic increased by at least 7 % and 4 %, respectively, between the first and second halves of the study period.”.

But this line says emission have become more frequent in last 15 years. "Positive emission anomalies have become more frequent over the past 15 years"

I think it's contradicting as your trends say the emission rate has rather decreased from 7 to 4 %

We understand that the sentence, as is, lacks clarity. The message is that the accumulated aerosol emissions increased by at least 7 % and the burden increased by 4 % from the first half (1990-2004) to the second half (2005-2019) of the studied period. While revising the text and results from Table 1, we noticed that the percentage value of the increase in emissions between periods (7 %) was incorrect. Considering also this, we have modified the sentence in the Abstract as follows: "Total aerosol emissions and burdens over the Arctic increased by at least 12 % and 4 %, respectively, between 1990–2004 and 2005–2019."

Related to this topic, we added new results of the relative changes of the aerosol burden for all marine species. This can be found in section 4.3 and Fig. 12.

1. Discuss why the rate of increase has decreased from 7 % to 4 %

   Please, refer to the response to the previous comment.

2. Abstract: "PCHO showing the largest relative increase" mention a number here

   Thanks for the suggestion. We have included the amounts in the Abstract as follows: "... PCHO showing the largest relative increase, with 1.3 % and 0.8 % per year for the emissions and aerosol concentration, respectively."

3. Is the 'peak' season constant in a particular month for all the years? Mention this in the abstract if its changing or staying constant. Pernov (2022) mentioned peak MSA concentration will shift its peak month in next 50 years. It would be interesting to see if this shift in peak in other parameters has started showing in long-term data already

   We thank the reviewer for this excellent question and valuable suggestion. We performed the analysis of the annual seasonality of marine biomolecules and PMOA emissions. For the emissions, the changes in the peak season are weak and not robust enough to support definitive conclusions. However, ocean biomolecules did show indications of a shift in emissions towards an earlier month. This was included in the manuscript in lines 280-286 and lines 398-400:

   "Lastly, we analyse the yearly seasonality in Arctic subregions to examine how the initiation and duration of biomolecule production have changed over the 30-year period. While the seasonal patterns remained stable for the Canadian Archipelago, Baffin Bay and, Barents, Greenland and Norwegian Seas, a pronounced interannual variability occurs for the inner Arctic seas. Among these, the Beaufort and Kara seas show strong indications that biomolecule release initiates one

month earlier during the second half of the study period compared to 1990-2004 (see Fig. C1). Other studies based on satellite products have found trends in phytoplankton blooms shifting towards an earlier maxima (Kahru et al., 2011; Zhao et al., 2022). Similarly, recent modelling analysis by Manizza et al. (2023) also points towards earlier spring blooms in the inner Arctic seas."

"Analysis of the annual seasonality of PMOA emissions did not reveal a clear shift toward earlier onset. In the Beaufort Sea, emissions show a tendency to occur approximately one month earlier during the second half of the study period; however, the patterns are weak and not sufficiently robust to draw conclusions (not shown)."

Please find them in the text towards the end of sections 3.2 and 3.3.2, respectively. Fig. C1, Appendix C, was consequently added to the manuscript.

4. Line 43: "and the relevance of PMOA for cloud formation in the Arctic": add citations

   Thank you for the suggestion. We added the following citations: (Leck and Bigg, 2005; Bigg and Leck, 2001; Irish et al., 2017; Hartmann et al., 2021; Creamean et al., 2022; Porter et al., 2022).

5. Line 63: Cite Russell for carbohydrates. Also mention some literature on lipids.

   Thank you for the suggestion. We added Russell et al. (2010) reference in line 60: "... melt ponds (Zeppenfeld et al., 2023). This supports previous findings by Russell et al. (2010) of saccharide compounds in Arctic marine aerosols." We also included an additional reference related to this topic and to lipid's detection in line 63: "In addition to carbohydrate-like substances, Hawkins and Russell (2010), also found evidence of marine proteinaceous material in aerosol particles. Lipid-like molecules (e.g. n-alkanes and fatty acids) have also been analysed in the Bering Sea, with significant contributions to marine aerosols in summer Hu et al. (2023)."

6. Line 88: Any particular reason why only polysaccharides, amino acids and lipids were chosen as components to represent PMOA? How much fraction of PMOA does each represent? "highly abundant" mention number here if possible

   Note that the trend analysis of the organic species presented here is a follow-up study of Leon-Marcos et al. (2025), who introduced and thoroughly evaluated the species considered in this study. To clarify this, we added this reference to line 88.

   According to observations, polysaccharides, amino acids, and lipids are abundant on the ocean surface and effectively transported to aerosols (Triesch et al., 2021a,b; Zeppenfeld et al., 2021;

van Pinxteren et al., 2023; Jayarathne et al., 2023). This has also been confirmed in bubble bursting experiments by Rastelli et al. (2017). In the present Arctic-focused study and that by Leon-Marcos et al. (2025), the computed organic species represent a fraction of total PMOA. However, since the contribution and origin of each compound emitted via bubble bursting could significantly vary per region and season (e.g. Keene et al., 2007; Facchini et al., 2008; Russell et al., 2010), and measurement techniques and analysed compounds are not uniform (Cavalli et al., 2004; Facchini et al., 2008; Jayarathne et al., 2016; van Pinxteren et al., 2023), estimating what fraction of the total PMOA, the simulated groups in our study represent is not possible. Nonetheless, given the detailed evaluation against seawater and aerosol measurements performed by Leon-Marcos et al. (2025), the individual contribution of the simulated species is reasonably well represented.

7. Line 113: add citations about the accuracy of HAM model with the given assumptions. Do organics have large uncertainty in representation? If so, then taking results from this model and using them as input for another model will only lead to uncertainties. Its important to quantify this or at least cite.

   A comprehensive evaluation of aerosol species within the standard ECHAM6.3–HAM2.3 model version was performed by Tegen et al. (2019). In addition, the marine organic species considered in the present studies were also thoroughly evaluated by Leon-Marcos et al. (2025) with species-resolved aerosol observations. As the model uncertainties are quantified in Leon-Marcos et al. (2025) and Tegen et al. (2019), additional evaluation would be beyond the scope and represent an overload for the scope of this paper.

   Having said this, there may be a misunderstanding regarding the use of HAM (i.e., ECHAM6.3–HAM2.3) model results in another model. We think that the reviewer refers to the accuracy of the marine biogeochemical model FESOM-REcoM (e.g. Zeising et al., 2025), on which the computation of the biomolecule ocean concentration is based and serves as a surface boundary condition to the aerosol-climate model. The computed ocean biomolecules were also evaluated against seawater samples by Leon-Marcos et al. (2025).

   We agree with the reviewer that these points should be specified in the manuscript, and have included the corresponding references to the model evaluation studies as follows:

   Lines 112-114 as follows: "The model includes several aerosol species such as sulphate (SO_4), organic carbon (OC), black carbon (BC), mineral dust (DU) and sea salt (SS), which were evaluated by Tegen et al. (2019). Leon-Marcos et al. (2025) implemented PMOA species in the model as additional tracers in the accumulation size mode and performed a thorough evaluation of the

model results."

Lines 134-136: "A more extensive explanation of the model characteristics, the methodology employed to compute the biomolecules, and the evaluation against seawater samples can be found in Leon-Marcos et al. (2025)."

8. Line 6322; is it PMOA? Or POMA?

   We thank the reviewer for pointing that out. We have corrected and used the correct abbreviation "PMOA".

9. Line 655: "This represents a relative change of 1.1, 1 and 0.8 % yr^{-1} for each group." The group order mentioned is as follows: PL_{aer}, $DCAA_{aer}$ and $PCHO_{aer}$. So PCHO relative change is 0.8 % which is less then PL and DCAA. Then why In line 662, it is mentioned that PCHO has the most prominent relative change?

   Thanks to the reviewer's comment, we noticed there was a mistake in that sentence, and the order of the percentages was incorrect. The correct order is 0.8, 1.1, 1.3 % yr^{-1} for PL_{aer}, $DCAA_{aer}$ and $PCHO_{aer}$, respectively. Hence, $PCHO_{aer}$ has the most prominent change, as shown in the top panel of Fig. 11. This was corrected in the manuscript. Note that the percentages are different as they represent total emission fluxes (see also response to comment 2 of RC1).

10. It would be nice to include how much % change in CCN or INP do you think these relative changes in PMOA will cause. I ask this because the relative increase is around 1 % which seems pretty small. So I want to get an idea if this small change will affect CCN/INP significantly

    We agree with the reviewer that including the relative change in cloud parameters over the 30 years as a response to the PMOA trends would be very interesting. While this could indeed provide further scientific insight, it lies beyond the scope of the present manuscript and would require considerable additional effort in both model development and analysis. The paper, in its present form, provides a consistent and coherent focus on aerosols, specifically, the climate-driven trends of PMOA species in the Arctic. Therefore, we plan to address this topic in future follow-up studies aimed at modelling and evaluating the role of PMOA-species-resolved interactions in Arctic clouds (i.e., CCN and INP activation) and their associated climate effects.

    In the ECHAM6.3-HAM2.3 model, CCN is calculated for each aerosol mode following Abdul-Razzak and Ghan (2000) and encompasses the contribution of all species within a mode. However, the ice nucleation potential of PMOA has not been implemented yet in ECHAM6.3-HAM2.3.

The latter is especially relevant in the Arctic, given the observational evidence of the dominance of biological INPs during summer (e.g. Irish et al., 2017; Hartmann et al., 2021; Porter et al., 2022; Creamean et al., 2022). Studies have also shown that some organic species (e.g. polysaccharides and proteins) could preferably activate as INP (McCluskey et al., 2018; Alpert et al., 2022). Hence, when examining the ice nucleation potential of PMOA, the marine aerosol composition should also be carefully considered. For the time available for answering the reviewers' questions, it is not feasible to provide a detailed analysis of aerosol-cloud and cloud microphysical processes.

Nevertheless, we performed an offline analysis as a test study to compute the nucleation potential of PCHO, the aerosol species undergoing the most significant relative changes. For the calculation, we used the novel parameterisation introduced by Hartmann et al. (2025) to estimate the INP concentrations from polysaccharides. Based on the PCHO concentration at the lowest model layer, we computed the INP concentration at -15 ^{o}C. We found reasonable results with climatological INP concentrations between 10^{-6} and 10^{-3} m^{-3} during the Arctic summer. In addition, we performed the trend analysis over the Arctic for 1990–2019 and found statistically significant increasing trends of nearly $1\%\,yr^{-1}$, and higher rates for the inner Arctic subregions. Note that the relative changes are always provided in units of per cent per year, so a rate of $1\%\,yr^{-1}$ represents a substantial change. Although this analysis sparked our interest to provide the scientific community with preliminary findings on the potential impact of marine species on INP concentrations in the Arctic, the results require further validation to be conclusive and well-founded.

11. Line 585. Agreed but it would be nice if you could also add these observational data points wherever and whenever available with a different symbol in your figures. That way we get an idea of how accurate your model estimates are.

    The idea of this paragraph is to stress that there is no available data (i.e. seawater samples and aerosol observations) to derive trends in the Arctic. Nonetheless, for short-term observations, Leon-Marcos et al. (2025) performed a detailed evaluation of the model outputs of marine and aerosol variables against available species-resolved measurements, including those within the Arctic Circle (e.g. Svalbard and the Norwegian Sea). Following Leon-Marcos et al. (2025), we consider the results used for the trend analysis in this manuscript to be representative of regions without any observations available and expect them to behave similarly over time.

12. Line 620: typo: remove '?'

    Thanks for pointing this out. This interrogation symbol was in place of a missing citation, which we have now incorporated.

13. Figure 1: add different observation stations in the Arctic (for reader to get a clearer picture)

    We thank the reviewer's suggestion; however, it is out of the scope of this manuscript to include a comparison of model results to observations, as this was previously performed by Leon-Marcos et al. (2025). Please refer to our response to comment 7, which specifies the reference to the preceding paper, which includes the model evaluation. For additional information, see also our response to comment 11.

14. Figure 3b. Maybe add residual as well to indicate how much fraction of total OMF is contributed by these three? Try including a stacked bar plot with errorbars for each month? Its nice when all components of OMF sums to 1.

    We agree that representing the organic mass fraction (OMF) so that the sum of all contributions equals 1 would provide more complete information on the origin of each organic component. However, we believe there might be a misunderstanding regarding the concept of the OMF in the PMOA emission calculations. As defined in Section 2.1, the OMF refers to the species-specific fraction within the sea spray aerosol, not to the fraction of a species within the total organic component. Since the remaining organic fraction is not known from measurements, the focus here is limited to the contribution of the three species considered in this study (and in the preceding work by Leon-Marcos et al., 2025a). As discussed in Section 5, several components emitted via bubble bursting and contributing to PMOA are not considered in the study, and they would contribute to the remaining OMF.

    The stacked plot is an excellent idea; however, this kind of plot is not suitable for this case as the species have different orders of magnitude, which we highlighted by adding two y-axes for different species in Fig. 3b.

15. Line 250. What are your thoughts about SST? Why don't you see how emissions at a particular location has changed with SST in the last 30 years? Add SST to Figure 8

    We thank the reviewer for these questions. PMOA emissions are primarily driven by 10-m wind speed, open ocean fraction (1-SIC), SST and OMF (as a proxy for marine productivity). We examined their linear correlation with emission fluxes, and the results are shown in Table 2,

Section 3.3.2 of the revised manuscript (see lines 408-415). This table indicates that while 10-m winds and SIC strongly modulate emissions in Arctic sub-regions, SST and OMF have a lesser influence, generally showing a moderate correlation with emissions. The correlation between emissions and SST is slightly lower than that of SIC in all cases.

The SST time series was included in Figure 8. In addition, Table D1 in the supplement summarises the correlation between anomalies and emission drivers. In the manuscript, the discussion of SST time series was included in lines 508-512 and lines 523-526.

16. Why not add years till 2024 to make the data more up-to-date, since it's modelling and does not require observation data availability?

    We agree that using the most recent years would bring the dataset to the latest possible state. However, the FESOM-REcoM model output used for this study was only available until 2019; simulations beyond this year are not yet available. Nonetheless, the 30-year period (1990–2019) used in this study corresponds to the standard climatological period commonly applied in climate research (WMO, 2017). Moreover, we believe that extending this period would not significantly change the overall outcome of our study.

References

Abdul-Razzak, H. and Ghan, S. J.: A parameterization of aerosol activation: 2. Multiple aerosol types, Journal of Geophysical Research: Atmospheres, 105, 6837–6844, https://doi.org/10.1029/1999JD901161, 2000.

Alpert, P. A., Kilthau, W. P., O'Brien, R. E., Moffet, R. C., Gilles, M. K., Wang, B., Laskin, A., Aller, J. Y., and Knopf, D. A.: Ice-nucleating agents in sea spray aerosol identified and quantified with a holistic multimodal freezing model, Science Advances, 8, https://doi.org/10.1126/sciadv.abq6842, 2022.

Bigg, E. K. and Leck, C.: Cloud-active particles over the central Arctic Ocean, Journal of Geophysical Research: Atmospheres, 106, 32 155–32 166, https://doi.org/10.1029/1999JD901152, 2001.

Cavalli, F., Facchini, M. C., Decesari, S., Mircea, M., Emblico, L., Fuzzi, S., Ceburnis, D., Yoon, Y. J., O'Dowd, C. D., Putaud, J., and Dell'Acqua, A.: Advances in characterization of size-resolved organic matter in marine aerosol over the North Atlantic, Journal of Geophysical Research: Atmospheres, 109, https://doi.org/10.1029/2004JD005137, 2004.

Creamean, J. M., Barry, K., Hill, T. C. J., Hume, C., DeMott, P. J., Shupe, M. D., Dahlke, S., Willmes, S., Schmale, J., Beck, I., Hoppe, C. J. M., Fong, A., Chamberlain, E., Bowman, J., Scharien, R., and Persson, O.: Annual cycle observations of aerosols capable of ice formation in central Arctic clouds, Nature Communications, 13, 3537, https://doi.org/10.1038/s41467-022-31182-x, 2022.

Facchini, M. C., Rinaldi, M., Decesari, S., Carbone, C., Finessi, E., Mircea, M., Fuzzi, S., Ceburnis, D., Flanagan, R., Nilsson, E. D., de Leeuw, G., Martino, M., Woeltjen, J., and O'Dowd, C. D.: Primary submicron marine aerosol dominated by insoluble organic colloids and aggregates, Geophysical Research Letters, 35, https://doi.org/10.1029/2008GL034210, 2008.

Hartmann, M., Gong, X., Kecorius, S., van Pinxteren, M., Vogl, T., Welti, A., Wex, H., Zeppenfeld, S., Herrmann, H., Wiedensohler, A., and Stratmann, F.: Terrestrial or marine-indications towards the origin of ice-nucleating particles during melt season in the European Arctic up to 83.7°N, Atmospheric Chemistry and Physics, 21, 11 613–11 636, https://doi.org/10.5194/acp-21-11613-2021, 2021.

Hartmann, S., Schrödner, R., Hassett, B. T., Hartmann, M., van Pinxteren, M., Fomba, K. W., Stratmann, F., Herrmann, H., Pöhlker, M., and Zeppenfeld, S.: Polysaccharides–Important Constituents of Ice-Nucleating Particles of Marine Origin, Environmental Science and Technology, https://doi.org/10.1021/acs.est.4c08014, 2025.

Hawkins, L. N. and Russell, L. M.: Polysaccharides, Proteins, and Phytoplankton Fragments: Four Chemically Distinct Types of Marine Primary Organic Aerosol Classified by Single Particle Spectromicroscopy, Advances in Meteorology, 2010, 1–14, https://doi.org/10.1155/2010/612132, 2010.

Hu, C., Yue, F., Zhan, H., Leung, K. M., Zhang, R., Gu, W., Liu, H., Chen, A., Cao, Y., Wang, X., and Xie, Z.: Homologous series of n-alkanes and fatty acids in the summer atmosphere from the Bering Sea to the western North Pacific, Atmospheric Research, 285, 106 633, https://doi.org/10.1016/j.atmosres.2023.106633, 2023.

Irish, V. E., Elizondo, P., Chen, J., Chou, C., Charette, J., Lizotte, M., Ladino, L. A., Wilson, T. W., Gosselin, M., Murray, B. J., Polishchuk, E., Abbatt, J. P. D., Miller, L. A., and Bertram, A. K.: Ice-nucleating particles in Canadian Arctic sea-surface microlayer and bulk seawater, Atmospheric Chemistry and Physics, 17, 10 583–10 595, https://doi.org/10.5194/acp-17-10583-2017, 2017.

Jayarathne, T., Sultana, C. M., Lee, C., Malfatti, F., Cox, J. L., Pendergraft, M. A., Moore, K. A., Azam, F., Tivanski, A. V., Cappa, C. D., Bertram, T. H., Grassian, V. H., Prather, K. A., and Stone, E. A.: Enrichment of Saccharides and Divalent Cations in Sea Spray Aerosol During Two

Phytoplankton Blooms, Environmental Science and Technology, 50, 11 511–11 520, https://doi.org/10.1021/acs.est.6b02988, 2016.

Jayarathne, T., Gamage, D. K., Prather, K. A., and Stone, E. A.: Enrichment of saccharides at the air–water interface: a quantitative comparison of sea surface microlayer and foam, Environmental Chemistry, 19, 506–516, https://doi.org/10.1071/EN22094, 2023.

Kahru, M., Brotas, V., Manzano-Sarabia, M., and Mitchell, B. G.: Are phytoplankton blooms occurring earlier in the Arctic?, Global Change Biology, 17, 1733–1739, https://doi.org/10.1111/j.1365-2486.2010.02312.x, 2011.

Keene, W. C., Maring, H., Maben, J. R., Kieber, D. J., Pszenny, A. A. P., Dahl, E. E., Izaguirre, M. A., Davis, A. J., Long, M. S., Zhou, X., Smoydzin, L., and Sander, R.: Chemical and physical characteristics of nascent aerosols produced by bursting bubbles at a model air-sea interface, Journal of Geophysical Research: Atmospheres, 112, https://doi.org/10.1029/2007JD008464, 2007.

Leck, C. and Bigg, E. K.: Source and evolution of the marine aerosol—A new perspective, Geophysical Research Letters, 32, https://doi.org/10.1029/2005GL023651, 2005.

Leon-Marcos, A., Zeising, M., van Pinxteren, M., Zeppenfeld, S., Bracher, A., Barbaro, E., Engel, A., Feltracco, M., Tegen, I., and Heinold, B.: Modelling emission and transport of key components of primary marine organic aerosol using the global aerosol–climate model ECHAM6.3–HAM2.3, Geoscientific Model Development, 18, 4183–4213, https://doi.org/10.5194/gmd-18-4183-2025, 2025.

Manizza, M., Carroll, D., Menemenlis, D., Zhang, H., and Miller, C. E.: Modeling the Recent Changes of Phytoplankton Blooms Dynamics in the Arctic Ocean, Journal of Geophysical Research: Oceans, 128, https://doi.org/10.1029/2022JC019152, 2023.

McCluskey, C. S., Ovadnevaite, J., Rinaldi, M., Atkinson, J., Belosi, F., Ceburnis, D., Marullo, S., Hill, T. C. J., Lohmann, U., Kanji, Z. A., O'Dowd, C., Kreidenweis, S. M., and DeMott, P. J.: Marine and Terrestrial Organic Ice-Nucleating Particles in Pristine Marine to Continentally Influenced Northeast Atlantic Air Masses, Journal of Geophysical Research: Atmospheres, 123, 6196–6212, https://doi.org/10.1029/2017JD028033, 2018.

Porter, G. C. E., Adams, M. P., Brooks, I. M., Ickes, L., Karlsson, L., Leck, C., Salter, M. E., Schmale, J., Siegel, K., Sikora, S. N. F., Tarn, M. D., Vüllers, J., Wernli, H., Zieger, P., Zinke, J., and Murray, B. J.: Highly Active Ice-Nucleating Particles at the Summer North Pole, Journal of Geophysical Research: Atmospheres, 127, https://doi.org/10.1029/2021JD036059, 2022.

Rastelli, E., Corinaldesi, C., Dell'Anno, A., Martire, M. L., Greco, S., Facchini, M. C., Rinaldi, M., O'Dowd, C., Ceburnis, D., and Danovaro, R.: Transfer of labile organic matter and microbes from the ocean surface to the marine aerosol: an experimental approach, Scientific Reports, 7, 11 475, https://doi.org/10.1038/s41598-017-10563-z, 2017.

Russell, L. M., Hawkins, L. N., Frossard, A. A., Quinn, P. K., and Bates, T. S.: Carbohydrate-like composition of submicron atmospheric particles and their production from ocean bubble bursting, Proceedings of the National Academy of Sciences, 107, 6652–6657, https://doi.org/10.1073/pnas.0908905107, 2010.

Sofiev, M., Soares, J., Prank, M., de Leeuw, G., and Kukkonen, J.: A regional-to-global model of emission and transport of sea salt particles in the atmosphere, Journal of Geophysical Research: Atmospheres, 116, https://doi.org/10.1029/2010JD014713, 2011.

Tegen, I., Neubauer, D., Ferrachat, S., Drian, C. S.-L., Bey, I., Schutgens, N., Stier, P., Watson-Parris, D., Stanelle, T., Schmidt, H., Rast, S., Kokkola, H., Schultz, M., Schroeder, S., Daskalakis, N., Barthel, S., Heinold, B., and Lohmann, U.: The global aerosol–climate model ECHAM6.3–HAM2.3 – Part 1: Aerosol evaluation, Geoscientific Model Development, 12, 1643–1677, https://doi.org/10.5194/gmd-12-1643-2019, 2019.

Triesch, N., Pinxteren, M. V., Engel, A., and Herrmann, H.: Concerted measurements of free amino acids at the Cabo Verde islands: High enrichments in submicron sea spray aerosol particles and cloud droplets, Atmospheric Chemistry and Physics, 21, 163–181, https://doi.org/10.5194/acp-21-163-2021, 2021a.

Triesch, N., Pinxteren, M. V., Frka, S., Stolle, C., Spranger, T., Hoffmann, E. H., Gong, X., Wex, H., Schulz-Bull, D., Gasparovic, B., and Herrmann, H.: Concerted measurements of lipids in seawater and on submicrometer aerosol particles at the Cabo Verde islands: Biogenic sources, selective transfer and high enrichments, Atmospheric Chemistry and Physics, 21, 4267–4283, https://doi.org/10.5194/acp-21-4267-2021, 2021b.

van Pinxteren, M., Zeppenfeld, S., Fomba, K. W., Triesch, N., Frka, S., and Herrmann, H.: Amino acids, carbohydrates, and lipids in the tropical oligotrophic Atlantic Ocean: sea-to-air transfer and atmospheric in situ formation, Atmospheric Chemistry and Physics, 23, 6571–6590, https://doi.org/10.5194/acp-23-6571-2023, 2023.

WMO: Weather Meteorological Organization, WMO Guidelines on the Calculation of Climate Normals, Tech. rep., `https://community.wmo.int/en/wmo-climatological-normals`, 2017.

Zeising, M., Oziel, L., Thoms, S., Özgür Gürses, Hauck, J., Heinold, B., Losa, S. N., van Pinxteren, M., Völker, C., Zeppenfeld, S., and Bracher, A.: Assessment of transparent exopolymer particles in the Arctic Ocean implemented into the coupled ocean–sea ice–biogeochemistry model FESOM2.1–REcoM3, https://doi.org/10.5194/egusphere-2025-4190, 2025.

Zeppenfeld, S., Pinxteren, M. V., Pinxteren, D. V., Wex, H., Berdalet, E., Vaqué, D., Dall'osto, M., and Herrmann, H.: Aerosol Marine Primary Carbohydrates and Atmospheric Transformation in the Western Antarctic Peninsula, ACS Earth and Space Chemistry, 5, 1032–1047, https://doi.org/10.1021/acsearthspacechem.0c00351, 2021.

Zhao, H., Matsuoka, A., Manizza, M., and Winter, A.: Recent Changes of Phytoplankton Bloom Phenology in the Northern High-Latitude Oceans (2003–2020), Journal of Geophysical Research: Oceans, 127, https://doi.org/10.1029/2021JC018346, 2022.