Iodine observed in new particle formation events in the Arctic atmosphere during ACCACIA

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Abstract

Accurately accounting for new particle formation (NPF) is crucial to our ability to predict aerosol number concentrations in many environments and thus cloud properties, which is in turn vital in simulating radiative transfer and climate. Here we present an analysis of NPF events observed in the Greenland Sea during the summertime as part of the Aerosol-Cloud Coupling And Climate Interactions in the Arctic (ACCACIA) project. While NPF events have been reported in the Arctic before, we were able, for the first time, to detect iodine in the growing particles using an Aerosol Mass Spectrometer (AMS) during a persistent event in the region of the coastal sea ice near Greenland. Given the potency of iodine as a nucleation precursor, the results imply that iodine was responsible for the initial NPF, a phenomenon that has been reported at lower latitudes and associated with molecular iodine emissions from coastal macroalgae. The initial source of iodine in this instance is not clear, but it was associated with air originating approximately 1 day previously over melting coastal sea ice. These results show that atmospheric models must consider iodine as a source of new particles in addition to established precursors such as sulphur compounds.

1 Introduction

In the Arctic, clouds are the dominant factor in the control of the incoming and outgoing energy balance at the Earth's surface and, here and throughout the troposphere, the largest single source of uncertainty in climate predictions. Understanding processes governing atmospheric aerosol concentrations is critically important to improved prediction of clouds and thus weather and climate (Boucher et al., 2013). The optical thickness and lifetime of clouds can be strongly influenced by the population of aerosol particles available to act as cloud condensation nuclei (CCN) (Haywood and Boucher, 2000). Particle concentrations in the summertime Arctic are typically very low (of the order of 10^2 cm^{-3}) and therefore cloud properties in this region are highly sensitive to the mechanisms by which new particles are formed and are grown to viable CCN sizes (roughly 50-100 nm, depending on the cloud conditions) (Merikanto et al., 2009). Understanding these processes is crucial to our predictive capability of climate in the Arctic, as clouds can have a strong warming or cooling effect, depending on a variety of conditions (Hodson et al., 2013).

New particle formation (NPF) can dramatically increase aerosol number concentrations in the atmosphere (Kulmala et al., 2004; Spracklen et al., 2006), alongside direct emissions of particles (e.g. through combustion, sea spray, dust suspension etc.), contributing up to half of the global CCN burden (Merikanto et al., 2009; Yu and Luo, 2009). NPF generally occurs through the rapid photochemical production of low vapour pressure secondary material such that stable molecular clusters are able to grow to viable sizes (nm) (Kulmala et al., 2013; Kulmala et al., 2000). As they grow, the freshly nucleated particles act as sinks for the secondary condensable material, potentially shutting off the nucleation process. NPF has been observed in a variety of different environments across the world. The role of sulphuric acid (produced in the atmosphere from the gas phase oxidation of marine biogenic dimethyl sulphide or SO_2 from fossil fuel burning or volcanoes) and organic matter (chiefly from terrestrial biogenic sources) has been extensively studied (e.g. Laaksonen et al., 2008; Zhang et al., 2004a; Riccobono et al., 2014) and it has also been shown that ammonia and amines have very important roles in promoting NPF through ternary processes (Kirkby et al., 2011; Almeida et al., 2013; Berndt et al., 2014).

Because of the generally low CCN number concentrations present, the Arctic atmosphere is highly sensitive to NPF. This in turn means that predictions of CCN are highly sensitive to the

processes responsible for NPF, which are currently highly uncertain in this environment (Lee et al., 2012). NPF has previously been observed during Arctic ship-based measurements and given the lack of significant biogenic or anthropogenic sources of organic precursors, most efforts to model these observations have only invoked NPF from the oxidation of sulphur species (Korhonen et al., 2008). An alternative hypothesis is that rather than nucleation, the initial source of the new particles is the fission of organic biogels (aggregations of biological macromolecules) in primary particles (Karl et al., 2013; Karl et al., 2012).

In coastal environments at lower latitudes, frequent daytime NPF events have been observed associated with gaseous iodine at low tide. This suggests that in these environments, iodine is the dominant source of nanoparticles, which have been observed to grow to larger sizes able to scatter radiation and contribute to CCN (McFiggans et al., 2004; McFiggans et al., 2010; O'Dowd et al., 2002; Whitehead et al., 2009; Yoon et al., 2006; Lehtipalo et al., 2010). Gaseous I_2 is produced in abundance by macroalgae species (*Laminaria digitata*, Fucus vesiculosus and Ascophyllum nodosum have been identified as being responsible for NPF) in response to being exposed to the atmosphere (Küpper et al., 2008; Huang et al., 2013) and is rapidly photooxidised to iodine monoxide (IO) and higher iodine oxides, which polymerise to form particles (Saiz-Lopez et al., 2012; Saunders et al., 2010). To date, iodine-initiated NPF has most commonly been observed in seaweed-rich coastal areas but the theoretical potential exists in low background aerosol conditions with associated high iodine fluxes (Mahajan et al., 2010). Atkinson et al. (2012) attributed NPF events observed in the Weddell Sea in Antarctica to iodine emissions from sea ice, although no data on aerosol composition was presented.

Here we present data on NPF events recorded aboard the RRS James Clark Ross in the Greenland Sea during the summer ACCACIA cruise. Through the analysis of a particularly strong and persistent case study, we show evidence for the role of iodine in NPF events in this region.

2 Methods

As part of the Aerosol-Cloud Coupling And Climate Interactions in the Arctic (ACCACIA) project, intensive measurements of aerosol composition and properties were made aboard the RRS *James Clark Ross*, an ice-hardened research vessel. The cruise (JR288) consisted of a

number of traverses in and out of the sea ice margin in the region of Greenland and Svalbard during July and August 2013 (see Fig. 1).

The University of Manchester instrumentation was located in an instrumented sea container on the foredeck of the *James Clark Ross*, sampling air through a 5 metre stack via a 3.5 µm cut cyclone, as has been performed during previous measurement campaigns (Allan et al., 2009). No attempt to correct for size-dependent particle losses has been made for this work, as it will not affect the qualitative results presented here. No in-line drier was used, as the relative humidity (RH) in the container was maintained low due to the temperature differential. A number of instruments sub-sampled from the main inlet manifold.

A Differential Mobility Particle Sizer (DMPS) system was used to measure size-resolved particle number concentrations. This was built at the University of Manchester (Williams et al., 2007) using dual 'Vienna' design Differential Mobility Analysers (DMAs) (Winklmayr et al., 1991) of different lengths (to cover different particle size ranges) with stepping voltages, selecting negatively-charged particles. TSI (Shoreview, MN, USA) model 3010 and 3025a Condensation Particle Counters (CPCs) were used to count the particles and the Wiedensohler (1988) charging parameterisation used to invert the data. The sheath air system uses a recirculating system dried to a low (<20% RH) humidity using a membrane drier linked to a dry compressed air system. Total number concentrations were provided by a TSI model 3776 CPC.

An Aerodyne (Billerica, MA, USA) Aerosol Mass Spectrometer (AMS) of the High Resolution Time-of-Flight (HR-TOF) design (Canagaratna et al., 2007) was also used to measure particle composition. Calibrations were performed using monodisperse ammonium nitrate for mass and NIST-certified Polystyrene Latex (PSL) Spheres (Thermo Scientific) for size. The data was collected in 'V' and 'W' mass spectral modes, which have $m/\Delta m$ resolutions of 2100 and 4300 at m/z=200 respectively (DeCarlo et al., 2006), although only 'V' mode data is presented here due because of the low signal-to-noise ratio of the 'W' mode data.

A Droplet Measurement Technologies (Boulder, CO, USA) Single Particle Soot Photometer (SP2) was used to measure black carbon. This was a version 'D' instrument, calibrated using monodisperse Aquadag, scaled by a factor of 0.75 as recommended by Laborde et al. (2012)

Sub-saturated particle growth factors were measured using a Hygroscopicity Tandem Differential Mobility Analyser (HTDMA). This was the second Manchester-built instrument

(Whitehead et al., 2014), conforming to EUSAAR specifications (Duplissy et al., 2009). This uses two Brechtel Manufacturing Inc. (Hayward, CA, USA) DMAs housed in temperature-controlled boxes and linked in series. The first had dry sheath air (<20% RH) while the sheath air in the second was maintained at 90% RH, using a membrane humidification system on a feedback loop with an Edgetech (Marlborough, MA, USA) dew point monitor. The particles were counted using a TSI model 3782 water-based CPC. Sizes were calibrated with PSL spheres and humidity was validated through the comparison of the measured deliquescence humidities of ammonium sulphate and sodium chloride with modelled values (Topping et al., 2005). Data were inverted using the method of Gysel et al. (2009).

Halocarbons were quantified in air and seawater using two Agilent 6850 gas chromatographs (GC) with 5975C mass selective detectors (MSDs) coupled to commercial thermal desorption units (TD, Markes Unity2-CIA8) in a system described by Andrews et al. (2015). One instrument was dedicated to air analysis and the other to water, and both instruments were calibrated daily for halocarbons using NOAA gas standard SX-3570 (Jones et al., 2011). Instrument drift was corrected for during (air analyses) or after (water analyses) each sample using atmospheric carbon tetrachloride as an internal standard. Underway seawater samples were collected from the pumped non-toxic seawater supply of the ship using a semi-automated purge and trap system plumbed directly into the underway supply. The sample lines and valves were flushed with underway water before each sample. 20 mL water samples was pumped into the purge vessel (2 minute sampling time) and purged with 1 L of zero-grade nitrogen gas. Purge efficiencies were 100 $\pm$ 2% for bromocarbons and 90 $\pm$ 10% for iodocarbons. All water samples were passed through an in-line pre-combusted grade GF/F filter. A bake-out program was also run between each pair of air and water samples. The duration of each sampling cycle (air-water-bake) was 65 minutes.

Back trajectory analysis was performed using HYSPLIT 4 (Draxler and Hess, 1998), employing GDAS reanalysis wind fields (NOAA Air Resources Laboratory, Boulder, CO, USA). Back trajectories were started at 20 m above mean sea level and run using modelled vertical velocities.

3 Results

During the measurements, a number of events were noted in the DMPS data whereby a large number of small particles contributed dramatically to the ambient population. Contributions

from combustion sources (e.g. ship plumes) were eliminated by the lack of black carbon (BC) detectable by the SP2. The data were also filtered according to short-lived spikes seen with the CPC that could be associated with other sources from within the ship. The DMPS occasionally showed 'open' distributions, whereby the peak existed at or below the lower size limit of the instrument (3 nm), providing evidence for NPF (Fig. 2). Time periods where a significant portion of the detected particles were smaller than 10 nm are identified on Fig. 1a, on an overlay of the cruise track and sea ice concentration data using the polar stereographic product from the Special Sensor Microwave Imager/Sounder (SSMIS) instrument on the Defense Meteorological Satellite Program (DMSP) F17 platform (Cavalieri et al., 2013).

These periods all occurred in proximity to coastal locations around Iceland, Greenland and Svalbard and the influence of terrestrial air is seen in the lowering of the RH in Fig 2, which is otherwise close to saturation. The most significant and persistent of these events occurred between the 25th and 27th of July, when the ship was close to the sea ice margin off the coast of northeastern Greenland and the air had previously travelled over the breaking sea ice off Greenland. (Fig. 1b). Markers for microalgal activity in the form of CH_2Br_2 were also observed to be elevated during this period (Fig 1c). During this period, the nonrefractory aerosol composition was mainly organic, with only around 0.1 μg m^{-3} of sulphate present (Fig. 3).

The candidate NPF events were also associated with elevated number concentrations, with transitions over periods of hours (Figs. 2 and 4), indicating that the new particles last long enough to grow to the larger sizes that can contribute to CCN. It is likely that the transitions in the size distributions resulted from changes to the source footprint in relation to the position of the ship rather than in situ growth of the observed new particles. While the growth events reported here may seem to resemble the characteristic 'banana' events observed at coastal sites and other locations (Kulmala et al., 2004; Ehn et al., 2010; Yli-Juuti et al., 2011), they differ in the following behaviour: 1) There are breaks in the growth observed (e.g. 25 Jul 00:00) 2) The apparent growth around 26 Jul 20:00 is exponential rather than linear in diameter space 3) The growth apparently reverses at 26 Jul 00:30 and 27 Jul 09:00. It is worth noting that the previously reported behaviours result from the diurnal modulation of boundary layer dynamics and photochemistry caused by the local day-night cycle in conjunction with a stable source footprint. This is not the case here, due to continuous insolation and reduced dynamics of the marine boundary layer, combined with a varying source footprint (due to the

movement of the ship and varying wind direction). Therefore, analogies with the temporal behaviour at other locations cannot necessarily be drawn.

Aerosol Mass Spectrometer (AMS) data during the 25-27th July showed a signal at *m*/*z*=127 during the periods when larger particles were present (Fig. 4), which is identified as I^+ ions by its precise mass/charge ratio of 126.90 (Fig. S1.1) (Wang et al., 2012). I^+ has previously been reported as the largest peak in photochemically-produced iodine oxide AMS mass spectra in the laboratory (McFiggans et al., 2004; Jimenez et al., 2003), but this is the first time that it has been reported in ambient particles. In previous coastal studies, owing to the proximity to the initial source of iodine, particles did not grow to sizes large enough (around 30 nm) to be transmitted by the AMS aerodynamic lens inlet (Liu et al., 2007; Zhang et al., 2004b; Zhang et al., 2004a). In this study, the particles grew to sufficient sizes, however it should be noted that the AMS is still not able to observe iodine during the periods where the particles were smaller than this, so does not see iodine during the very early stages of growth.

To investigate whether the I^+ signal could be associated with processes governing the formation of organic aerosols (Fig. 3.), Positive Matrix Factorisation (PMF) was performed on the data (Paatero and Tapper, 1994; Ulbrich et al., 2009). This assigns the organic mass to different 'factors' according to the temporal behaviour of the mass spectral matrix and is detailed in section 2 of the supplementary material. Once shipping emissions and misattributed sea salt are excluded, this analysis found that the organic matter detected by the AMS could be attributed to methyl sulphonic acid (MSA) (Phinney et al., 2006; Decesari et al., 2011) and highly-oxygenated organic material (McFiggans et al., 2005; Jimenez et al., 2009). The I^+ signal was not represented in any of the factors derived, only manifested in the residual data, which implies that the particulate iodine had a source that was distinct from the processes controlling the formation of particulate organic matter (be they primary or secondary). A further implication of the MSA observation is that this compound was at least partly responsible for the reported sulphate concentrations, as this also produces SO^+ and SO_2^+ ions in the mass spectrum (Zorn et al., 2008). Therefore, the actual non-seasalt sulphate concentration is likely to be lower than what is reported, but the quantitative fraction of MSA is difficult to estimate, as the fragmentation behaviour is highly variable and not calibrated during this study.

4 Discussion

To link the I^+ signals detected by the AMS to the particles seen by the DMPS, the size-resolved data from the two instruments were quantitatively compared through the fitting of lognormal distributions. Shown in Fig. 5 are the DMPS volume-weighted size distributions from the period of peak I^+ concentrations (26 July 22:50-23:45 UTC), together with the AMS Particle Time-of-Flight size-resolved data for I^+, organics and sulphate. The AMS data was of a low signal-to-noise ratio, due to the short averaging time and low signal levels (Allan et al., 2003), however the fits converged consistently using a standard Levenberg-Marquardt algorithm, with the peak centres, widths and heights allowed to vary freely. The DMPS distribution is bimodal, with the Aitken mode related to the I^+ peak in the AMS data and the accumulation mode related to the sulphate and organic modes. The ratio of the fitted Aitken mode diameters yields a particle effective density of 1.77 ± 0.23 g cm^{-3}, which is typical of an inorganic aerosol (Cross et al., 2007). Given that this quantity is a product of the material density and the Jayne shape factor (DeCarlo et al., 2004; Jayne et al., 2000), this may be an underestimate of the material density if the particles are nonspherical, as has been suggested by electron microscopy of laboratory-generated particles (McFiggans et al., 2004).

The shift in composition of these particles is also reflected in the HTDMA data, which shows that during this period, the growth factor of 50 nm dry particles at 90 % RH is 1.34, whereas for the rest of the cruise, values were always greater than 1.5 (Fig. 6). The low growth factor and the density estimate are consistent with iodine oxide making up a significant portion of the particulate volume; I_2O_5 has a material density of 5 g cm^{-3} and laboratory studies have shown iodine oxide particles to exhibit low growth factors (Jimenez et al., 2003; McFiggans et al., 2004; Murray et al., 2012). This is different to what would be expected of organic matter, which tends to be of a low density and low growth factor, and inorganic salts and sulphuric acid, which are high density and high growth factor (Cross et al., 2007; Gysel et al., 2007).

While the data discussed above provides strong evidence for the presence of iodine in the particles during these events, it does not prove that iodine was responsible for the initial NPF, which will have occurred upwind prior to measurement. However, given the rapidity of the iodine oxidation process and the very low volatility of the products (McFiggans et al., 2010; Whitehead et al., 2009; Lehtipalo et al., 2010), it is reasonable to assume that the presence of iodine-based secondary particulate matter implies that iodine-initiated NPF was also

occurring. It is also worth noting that sulphate concentrations were low during the main case study, so this NPF event did not occur during a period of particularly strong sulphuric acid production.

In situ sea-air fluxes and atmospheric mixing ratios of iodocarbons (CH_3I, CH_2I_2 and CH_2ICl) measured during the NPF event were very low (< 2 nmol m^{-2} d^{-1} and ≈ 0.5 pptv for CH_3I; < 1 nmol m^{-2} d^{-1} and < 0.02 pptv for both CH_2I_2 and CH_2ICl, see Fig. S1.2). Although these compounds are found in sea-ice (Atkinson et al., 2012; Granfors et al., 2014) and have been shown to cause NPF in the laboratory (Jimenez et al., 2003), the iodocarbon emissions and atmospheric concentrations found in this and earlier studies are insufficient to sustain the very high local concentrations of IO required for iodine nucleation (McFiggans et al., 2004), suggesting the gaseous precursor may have been an inorganic form of iodine such as I2.

The initial source of the iodine responsible for these events is not known. Macroalgae have been identified as a molecular iodine source in midlatitude coastal studies (Küpper et al., 2008; Huang et al., 2013) and macroalgae beds containing kelps and wracks also occur on the northeast coast of Greenland (Borum et al., 2002), albeit with a different species composition. Elevated CH_2Br_2 levels would be consistent with a macroalgal source (e.g. Laturnus, 1996). However, the biomass density of the north-east Greenland kelp beds may be considerably less than found at temperate locations such as Galway Bay (Werner and Kraan, 2004), and ice scouring may reduce macroalgal density in shallower waters where the algae are more likely to be exposed to the atmosphere (Wiencke and Amsler, 2012; Borum et al., 2002).

A source of inorganic iodine from the marginal sea-ice zone is plausible, and would be consistent with the findings of Atkinson et al. (2012). Microalgae, particularly diatoms, may be considered as a potential source of iodine in this region. Diatoms are prominent members of microalgal blooms occurring at the receding ice edge, and also in communities growing within the ice itself. Ice diatoms have previously been shown to be a potential direct source of HOI and I_2 to the Arctic atmosphere (Hill and Manley, 2009). The presence of elevated levels of CH_2Br_2 in air compared to levels in seawater during the iodine particle event (Fig 1c) is consistent with this suggestion, as polar diatoms are known to be a strong source of bromocarbons (Sturges et al., 1992; Sturges et al., 1993). Note that it is not expected that the observed bromocarbons directly participate in the NPF; the molecules are too small to form low volatility organic oxidation products and bromine, unlike iodine, does not form a series of

stable condensed-phase oxides. Furthermore, there was no trace of any bromine-containing signal in the AMS data.

I_2 and HOI may also be formed by the abiotic oxidation of iodide, either by gaseous ozone on the sea surface (Carpenter et al., 2013), or within sea-ice brine channels followed by emissions from the quasi-liquid layer on the surface of the sea-ice (Saiz-Lopez et al., 2015). High levels of iodide associated with biological activity in the sea ice region have sometimes been observed (Chance et al., 2010). More recently, microalgal aggregates released from melting sea-ice have also been proposed as an iodide source (Assmy et al., 2013; Boetius et al., 2013). Although such aggregates were not observed from the ship during this work, given that the initial source of the iodine was upwind, the possibility this was an iodine source is not ruled out. (Indeed, we note previous observations of elevated iodide associated with microalgal aggregates were made at higher latitudes than the ship position during the NPF event). An additional suggestion for the source of iodine is chemical production from the ice surface itself, promoted by the freezing of sea salt in the presence of nitrite ions (O'Driscoll et al., 2006) It should be noted that no NPF events were recorded near the ice margin to the northeast of Svalbard during the latter stages of the cruise, so it may be that the phenomenon observed here is restricted to coastal areas or certain stages of the ice melt process.

5 Conclusions

Herein we show observations of new particle formation (NPF) over the Greenland Sea in summer. A long-lasting event, associated with air originating over the breaking sea ice off Greenland, featured NPF and particles growing to sizes in excess of 50 nm. During this period, iodine was unambiguously detected by an Aerodyne Aerosol Mass Spectrometer. Furthermore, measurements of hygroscopicity and effective density were consistent with iodine oxide comprising a significant portion of the particulate volume. This strongly implies that iodine had a role in the initial NPF events, which is a phenomenon previously associated with coastal locations at lower latitudes (Huang et al., 2013; McFiggans et al., 2010; McFiggans et al., 2004). The initial source of the iodine in this case is unlikely to be the macroalgae identified during previous studies, but could be speculatively related to other macroalgae species or microalgae associated with the sea ice, which would be consistent with the findings of Atkinson et al. (2012) based on measurements in Antarctica.

These results show that correct prediction of Arctic aerosol number concentrations requires knowledge of iodine processes in new particle nucleation and growth. Our observations suggest that the source of iodine is related to processes associated with coastal sea ice, so this could represent a potentially significant source of particles during periods of ice loss and thus a potential climate feedback mechanism. As yet we have insufficient data to predict how widespread these processes are, but if this phenomenon is limited to coastal areas, it would not explain the events above 80 °N studied by Karl et al. (2012). More work is required to identify the initial source of the iodine and the exact mechanisms for iodine NPF at a molecular level (Kulmala et al., 2013).

Data Availability

Processed data are archived at the British Atmospheric Data Centre ACCACIA archive. Raw data available on request.

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References

Allan, J. D., Jimenez, J. L., Williams, P. I., Alfarra, M. R., Bower, K. N., Jayne, J. T., Coe, H., and Worsnop, D. R.: Quantitative sampling using an Aerodyne aerosol mass spectrometer - 1. Techniques of data interpretation and error analysis, J. Geophys. Res.-Atmos., 108, 4090, doi:10.1029/2002JD002358, 2003.

Allan, J. D., Topping, D. O., Good, N., Irwin, M., Flynn, M., Williams, P. I., Coe, H., Baker, A. R., Martino, M., Niedermeier, N., Wiedensohler, A., Lehmann, S., Muller, K., Herrmann, H., and McFiggans, G.: Composition and properties of atmospheric particles in the eastern Atlantic and impacts on gas phase uptake rates, Atmos. Chem. Phys., 9, 9299-9314, 2009.

Almeida, J., Schobesberger, S., Kurten, A., Ortega, I. K., Kupiainen-Maatta, O., Praplan, A. P., Adamov, A., Amorim, A., Bianchi, F., Breitenlechner, M., David, A., Dommen, J., Donahue, N. M., Downard, A., Dunne, E., Duplissy, J., Ehrhart, S., Flagan, R. C., Franchin, A., Guida, R., Hakala, J., Hansel, A., Heinritzi, M., Henschel, H., Jokinen, T., Junninen, H., Kajos, M., Kangasluoma, J., Keskinen, H., Kupc, A., Kurten, T., Kvashin, A. N., Laaksonen, A., Lehtipalo, K., Leiminger, M., Leppa, J., Loukonen, V., Makhmutov, V., Mathot, S., McGrath, M. J., Nieminen, T., Olenius, T., Onnela, A., Petaja, T., Riccobono, F., Riipinen, I., Rissanen, M., Rondo, L., Ruuskanen, T., Santos, F. D., Sarnela, N., Schallhart, S., Schnitzhofer, R., Seinfeld, J. H., Simon, M., Sipila, M., Stozhkov, Y., Stratmann, F., Tome, A., Trostl, J., Tsagkogeorgas, G., Vaattovaara, P., Viisanen, Y., Virtanen, A., Vrtala, A., Wagner, P. E., Weingartner, E., Wex, H., Williamson, C., Wimmer, D., Ye, P. L., Yli-Juuti, T., Carslaw, K. S., Kulmala, M., Curtius, J., Baltensperger, U., Worsnop, D. R., Vehkamaki, H., and Kirkby, J.: Molecular understanding of sulphuric acid-amine particle nucleation in the atmosphere, Nature, 502, 359-363, Doi 10.1038/Nature12663, 2013.

Andrews, S. J., Hackenberg, S. C., and Carpenter, L. J.: Technical Note: A fully automated purge and trap GC-MS system for quantification of volatile organic compound (VOC) fluxes between the ocean and atmosphere, Ocean Sci., 11, 313-321, doi:10.5194/os-11-313-2015, 2015..

Assmy, P., Ehn, J. K., Fernandez-Mendez, M., Hop, H., Katlein, C., Sundfjord, A., Bluhm, K., Daase, M., Engel, A., Fransson, A., Granskog, M. A., Hudson, S. R., Kristiansen, S., Nicolaus, M., Peeken, I., Renner, A. H. H., Spreen, G., Tatarek, A., and Wiktor, J.: Floating Ice-Algal Aggregates below Melting Arctic Sea Ice, Plos One, 8, ARTN e76599, DOI 10.1371/journal.pone.0076599, 2013.

Atkinson, H. M., Huang, R. J., Chance, R., Roscoe, H. K., Hughes, C., Davison, B., Schönhardt, A., Mahajan, A. S., Saiz-Lopez, A., Hoffmann, T., and Liss, P. S.: Iodine emissions from the sea ice of the Weddell Sea, Atmos. Chem. Phys., 12, 11229-11244, 10.5194/acp-12-11229-2012, 2012.

Berndt, T., Sipila, M., Stratmann, F., Petaja, T., Vanhanen, J., Mikkila, J., Patokoski, J., Taipale, R., Mauldin, R. L., and Kulmala, M.: Enhancement of atmospheric H2SO4/H2O nucleation: organic oxidation products versus amines, Atmos. Chem. Phys., 14, 751-764, DOI 10.5194/acp-14-751-2014, 2014.

Boetius, A., Albrecht, S., Bakker, K., Bienhold, C., Felden, J., Fernandez-Mendez, M., Hendricks, S., Katlein, C., Lalande, C., Krumpen, T., Nicolaus, M., Peeken, I., Rabe, B., Rogacheva, A., Rybakova, E., Somavilla, R., Wenzhofer, F., and Sc, R. P. A.-.-S.: Export of Algal Biomass from the Melting Arctic Sea Ice, Science, 339, 1430-1432, DOI 10.1126/science.1231346, 2013.

Borum, J., Pedersen, M. F., Krause-Jensen, D., Christensen, P. B., and Nielsen, K.: Biomass, photosynthesis and growth of Laminaria saccharina in a high-arctic fjord, NE Greenland, Mar Biol, 141, 11-19, DOI 10.1007/s00227-002-0806-9, 2002.

Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., Forster, P., Kerminen, V. M., Kondo, Y., liao, H., lohmann, U., Rasch, P., Satheesh, S. K., Sherwood, S., Stevens, B., and Zhang, X. Y.: Clouds and Aerosols, in: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, edited by: Stocker, T. F., Qin, D., Plattner, G. K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., and Midgley, P. M., Cambridge University Press, Cambridge, United Kingdom; New York, NY, USA., 2013.

Canagaratna, M. R., Jayne, J. T., Jimenez, J. L., Allan, J. D., Alfarra, M. R., Zhang, Q., Onasch, T. B., Drewnick, F., Coe, H., Middlebrook, A., Delia, A., Williams, L. R., Trimborn, A. M., Northway, M. J., DeCarlo, P. F., Kolb, C. E., Davidovits, P., and Worsnop, D. R.: Chemical and microphysical characterization of ambient aerosols with the aerodyne aerosol mass spectrometer, Mass Spectrom. Rev., 26, 185-222, Doi 10.1002/Mas.20115, 2007.

Carpenter, L. J., MacDonald, S. M., Shaw, M. D., Kumar, R., Saunders, R. W., Parthipan, R., Wilson, J., and Plane, J. M. C.: Atmospheric iodine levels influenced by sea surface emissions of inorganic iodine, Nat Geosci, 6, 108-111, Doi 10.1038/Ngeo1687, 2013.

Cavalieri, D., Parkinson, C., Gloersen, P., and Zwally., H. J.: Sea Ice Concentrations from Nimbus-7 SMMR and DMSP SSM/I-SSMIS Passive Microwave Data. [nt_20130726_f17_v01_n], NASA DAAC at the National Snow and Ice Data Center, Boulder, Colorado USA, 2013.

Chance, R., Weston, K., Baker, A. R., Hughes, C., Malin, G., Carpenter, L., Meredith, M. P., Clarke, A., Jickells, T. D., Mann, P., and Rossetti, H.: Seasonal and interannual variation of dissolved iodine speciation at a coastal Antarctic site, Mar. Chem., 118, 171-181, DOI 10.1016/j.marchem.2009.11.009, 2010.

Cross, E. S., Slowik, J. G., Davidovits, P., Allan, J. D., Worsnop, D. R., Jayne, J. T., Lewis, D. K., Canagaratna, M., and Onasch, T. B.: Laboratory and ambient particle density determinations using light scattering in conjunction with aerosol mass spectrometry, Aerosol Sci. Technol., 41, 343-359, 2007.

DeCarlo, P. F., Slowik, J. G., Worsnop, D. R., Davidovits, P., and Jimenez, J. L.: Particle Morphology and Density Characterization by Combined Mobility and Aerodynamic Diameter Measurements. Part 1: Theory, Aerosol Sci. Technol., 38, 1185–1205, 2004.

DeCarlo, P. F., Kimmel, J. R., Trimborn, A., Northway, M. J., Jayne, J. T., Aiken, A. C., Gonin, M., Fuhrer, K., Horvath, T., Docherty, K. S., Worsnop, D. R., and Jimenez, J. L.: Field-deployable, high-resolution, time-of-flight aerosol mass spectrometer, Anal. Chem., 78, 8281-8289, 10.1021/ac061249n, 2006.

Decesari, S., Finessi, E., Rinaldi, M., Paglione, M., Fuzzi, S., Stephanou, E. G., Tziaras, T., Spyros, A., Ceburnis, D., O'Dowd, C., Dall'Osto, M., Harrison, R. M., Allan, J., Coe, H., and Facchini, M. C.: Primary and secondary marine organic aerosols over the North Atlantic Ocean during the MAP experiment, J. Geophys. Res.-Atmos., 116, Artn D22210, Doi 10.1029/2011jd016204, 2011.

Draxler, R. R., and Hess, G. D.: An overview of the HYSPLIT_4 modeling system of trajectories, dispersion, and deposition., Aust. Meteor. Mag., 47, 295-308, 1998.

Duplissy, J., Gysel, M., Sjogren, S., Meyer, N., Good, N., Kammermann, L., Michaud, V., Weigel, R., Martins dos Santos, S., Gruening, C., Villani, P., Laj, P., Sellegri, K., Metzger, A., McFiggans, G. B., Wehrle, G., Richter, R., Dommen, J., Ristovski, Z., Baltensperger, U., and Weingartner, E.: Intercomparison study of six HTDMAs: results and recommendations, Atmos. Meas. Tech., 2, 363-378, 10.5194/amt-2-363-2009, 2009.

Ehn, M., Vuollekoski, H., Petaja, T., Kerminen, V. M., Vana, M., Aalto, P., de Leeuw, G., Ceburnis, D., Dupuy, R., O'Dowd, C. D., and Kulmala, M.: Growth rates during coastal and marine new particle formation in western Ireland, J. Geophys. Res.-Atmos., 115, Artn D18218, 10.1029/2010jd014292, 2010.

Granfors, A., Ahnoff, M., Mills, M. M., and Abrahamsson, K.: Organic iodine in Antarctic sea ice: A comparison between winter in the Weddell Sea and summer in the Amundsen Sea, J. Geophys. Res.-Biogeo, 119, 2014JG002727, 10.1002/2014JG002727, 2014.

Gysel, M., Crosier, J., Topping, D. O., Whitehead, J. D., Bower, K. N., Cubison, M. J., Williams, P. I., Flynn, M. J., McFiggans, G. B., and Coe, H.: Closure study between chemical composition and hygroscopic growth of aerosol particles during TORCH2, Atmos. Chem. Phys., 7, 6131–6144, 2007.

Gysel, M., McFiggans, G. B., and Coe, H.: Inversion of tandem differential mobility analyser (TDMA) measurements, J. Aerosol. Sci., 40, 134-151, DOI 10.1016/j.jaerosci.2008.07.013, 2009.

Haywood, J., and Boucher, O.: Estimates of the direct and indirect radiative forcing due to tropospheric aerosols: A review, Rev. Geophys., 38, 513-543, 10.1029/1999RG000078, 2000.

Hill, V. L., and Manley, S. L.: Release of reactive bromine and iodine from diatoms and its possible role in halogen transfer in polar and tropical oceans, Limnol Oceanogr, 54, 812-822, DOI 10.4319/lo.2009.54.3.0812, 2009.

Hodson, D. R., Keeley, S. E., West, A., Ridley, J., Hawkins, E., and Hewitt, H.: Identifying uncertainties in Arctic climate change projections, Clim Dynam, 40, 2849-2865, 10.1007/s00382-012-1512-z, 2013.

Huang, R. J., Thorenz, U. R., Kundel, M., Venables, D. S., Ceburnis, D., Ho, K. F., Chen, J., Vogel, A. L., Kupper, F. C., Smyth, P. P. A., Nitschke, U., Stengel, D. B., Berresheim, H., O'Dowd, C. D., and Hoffmann, T.: The seaweeds Fucus vesiculosus and Ascophyllum nodosum are significant contributors to coastal iodine emissions, Atmos. Chem. Phys., 13, 5255-5264, DOI 10.5194/acp-13-5255-2013, 2013.

Jayne, J. T., Leard, D. C., Zhang, X. F., Davidovits, P., Smith, K. A., Kolb, C. E., and Worsnop, D. R.: Development of an aerosol mass spectrometer for size and composition analysis of submicron particles, Aerosol Sci. Technol., 33, 49-70, 10.1080/027868200410840, 2000.

Jimenez, J. L., Bahreini, R., Cocker, D. R., Zhuang, H., Varutbangkul, V., Flagan, R. C., Seinfeld, J. H., O'Dowd, C. D., and Hoffmann, T.: New particle formation from photooxidation of diiodomethane (CH2I2), J. Geophys. Res.-Atmos., 108, 4318, doi:10.1029/2002JD002452, 2003.

Jimenez, J. L., Canagaratna, M. R., Donahue, N. M., Prevot, A. S. H., Zhang, Q., Kroll, J. H., DeCarlo, P. F., Allan, J. D., Coe, H., Ng, N. L., Aiken, A. C., Docherty, K. S., Ulbrich, I. M., Grieshop, A. P., Robinson, A. L., Duplissy, J., Smith, J. D., Wilson, K. R., Lanz, V. A., Hueglin, C., Sun, Y. L., Tian, J., Laaksonen, A., Raatikainen, T., Rautiainen, J., Vaattovaara, P., Ehn, M., Kulmala, M., Tomlinson, J. M., Collins, D. R., Cubison, M. J., E, Dunlea, J., Huffman, J. A., Onasch, T. B., Alfarra, M. R., Williams, P. I., Bower, K., Kondo, Y., Schneider, J., Drewnick, F., Borrmann, S., Weimer, S., Demerjian, K., Salcedo, D., Cottrell, L., Griffin, R., Takami, A., Miyoshi, T., Hatakeyama, S., Shimono, A., Sun, J. Y., Zhang, Y. M., Dzepina, K., Kimmel, J. R., Sueper, D., Jayne, J. T., Herndon, S. C., Trimborn, A. M., Williams, L. R., Wood, E. C., Middlebrook, A. M., Kolb, C. E., Baltensperger, U., and Worsnop, D. R.: Evolution of Organic Aerosols in the Atmosphere, Science, 326, 1525-1529, 10.1126/science.1180353, 2009.

Jones, C. E., Andrews, S. J., Carpenter, L. J., Hogan, C., Hopkins, F. E., Laube, J. C., Robinson, A. D., Spain, T. G., Archer, S. D., Harris, N. R. P., Nightingale, P. D., O'Doherty, S. J., Oram, D. E., Pyle, J. A., Butler, J. H., and Hall, B. D.: Results from the first national UK inter-laboratory calibration for very short-lived halocarbons, Atmos. Meas. Tech., 4, 865-874, 10.5194/amt-4-865-2011, 2011.

Karl, M., Leck, C., Gross, A., and Pirjola, L.: A study of new particle formation in the marine boundary layer over the central Arctic Ocean using a flexible multicomponent aerosol dynamic model, Tellus B, 64, 17158, Doi 10.3402/Tellusb.V64i0.17158, 2012.

Karl, M., Leck, C., Coz, E., and Heintzenberg, J.: Marine nanogels as a source of atmospheric nanoparticles in the high Arctic, Geophys. Res. Lett., 40, 3738-3743, 10.1002/grl.50661, 2013.

Kirkby, J., Curtius, J., Almeida, J., Dunne, E., Duplissy, J., Ehrhart, S., Franchin, A., Gagne, S., Ickes, L., Kurten, A., Kupc, A., Metzger, A., Riccobono, F., Rondo, L., Schobesberger, S., Tsagkogeorgas, G., Wimmer, D., Amorim, A., Bianchi, F., Breitenlechner, M., David, A., Dommen, J., Downard, A., Ehn, M., Flagan, R. C., Haider, S., Hansel, A., Hauser, D., Jud, W., Junninen, H., Kreissl, F., Kvashin, A., Laaksonen, A., Lehtipalo, K., Lima, J., Lovejoy, E. R., Makhmutov, V., Mathot, S., Mikkila, J., Minginette, P., Mogo, S., Nieminen, T., Onnela, A., Pereira, P., Petaja, T., Schnitzhofer, R., Seinfeld, J. H., Sipila, M., Stozhkov, Y., Stratmann, F., Tome, A., Vanhanen, J., Viisanen, Y., Vrtala, A., Wagner, P. E., Walther, H., Weingartner, E., Wex, H., Winkler, P. M., Carslaw, K. S., Worsnop, D. R., Baltensperger, U.,

and Kulmala, M.: Role of sulphuric acid, ammonia and galactic cosmic rays in atmospheric aerosol nucleation, Nature, 476, 429-U477, Doi 10.1038/Nature10343, 2011.

Korhonen, H., Carslaw, K. S., Spracklen, D. V., Mann, G. W., and Woodhouse, M. T.: Influence of oceanic dimethyl sulfide emissions on cloud condensation nuclei concentrations and seasonality over the remote Southern Hemisphere oceans: A global model study, J. Geophys. Res.-Atmos., 113, Artn D15204, Doi 10.1029/2007jd009718, 2008.

Kulmala, M., Pirjola, U., and Mäkelä, J. M.: Stable sulphate clusters as a source of new atmospheric particles, Nature, 404, 66-69, 2000.

Kulmala, M., Vehkamaki, H., Petajda, T., Dal Maso, M., Lauri, A., Kerminen, V. M., Birmili, W., and McMurry, P. H.: Formation and growth rates of ultrafine atmospheric particles: a review of observations, J. Aerosol. Sci., 35, 143-176, 2004.

Kulmala, M., Kontkanen, J., Junninen, H., Lehtipalo, K., Manninen, H. E., Nieminen, T., Petäjä, T., Sipilä, M., Schobesberger, S., Rantala, P., Franchin, A., Jokinen, T., Järvinen, E., Äijälä, M., Kangasluoma, J., Hakala, J., Aalto, P. P., Paasonen, P., Mikkilä, J., Vanhanen, J., Aalto, J., Hakola, H., Makkonen, U., Ruuskanen, T., Mauldin, R. L., Duplissy, J., Vehkamäki, H., Bäck, J., Kortelainen, A., Riipinen, I., Kurtén, T., Johnston, M. V., Smith, J. N., Ehn, M., Mentel, T. F., Lehtinen, K. E. J., Laaksonen, A., Kerminen, V.-M., and Worsnop, D. R.: Direct Observations of Atmospheric Aerosol Nucleation, Science, 339, 943-946, 10.1126/science.1227385, 2013.

Küpper, F. C., Carpenter, L. J., McFiggans, G. B., Palmer, C. J., Waite, T. J., Boneberg, E.-M., Woitsch, S., Weiller, M., Abela, R., Grolimund, D., Potin, P., Butler, A., Luther, G. W., Kroneck, P. M. H., Meyer-Klaucke, W., and Feiters, M. C.: Iodide accumulation provides kelp with an inorganic antioxidant impacting atmospheric chemistry, Proceedings of the National Academy of Sciences, 105, 6954-6958, 10.1073/pnas.0709959105, 2008.

Laaksonen, A., Kulmala, M., O'Dowd, C. D., Joutsensaari, J., Vaattovaara, P., Mikkonen, S., Lehtinen, K. E. J., Sogacheva, L., Dal Maso, M., Aalto, P., Petaja, T., Sogachev, A., Yoon, Y. J., Lihavainen, H., Nilsson, D., Facchini, M. C., Cavalli, F., Fuzzi, S., Hoffmann, T., Arnold, F., Hanke, M., Sellegri, K., Umann, B., Junkermann, W., Coe, H., Allan, J. D., Alfarra, M. R., Worsnop, D. R., Riekkola, M. L., Hyotylainen, T., and Viisanen, Y.: The role of VOC oxidation products in continental new particle formation, Atmos. Chem. Phys., 8, 2657-2665, 2008.

Laborde, M., Schnaiter, M., Linke, C., Saathoff, H., Naumann, K. H., Möhler, O., Berlenz, S., Wagner, U., Taylor, J. W., Liu, D., Flynn, M., Allan, J. D., Coe, H., Heimerl, K., Dahlkötter, F., Weinzierl, B., Wollny, A. G., Zanatta, M., Cozic, J., Laj, P., Hitzenberger, R., Schwarz, J. P., and Gysel, M.: Single Particle Soot Photometer intercomparison at the AIDA chamber, Atmos. Meas. Tech., 5, 3077-3097, 10.5194/amt-5-3077-2012, 2012.

Laturnus, F.: Volatile halocarbons released from Arctic macroalgae, Mar. Chem., 55, 359-366, Doi 10.1016/S0304-4203(97)89401-7, 1996.

Lee, L. A., Carslaw, K. S., Pringle, K. J., and Mann, G. W.: Mapping the uncertainty in global CCN using emulation, Atmos. Chem. Phys., 12, 9739-9751, 10.5194/acp-12-9739-2012, 2012.

Lehtipalo, K., Kulmala, M., Sipila, M., Petaja, T., Vana, M., Ceburnis, D., Dupuy, R., and O'Dowd, C.: Nanoparticles in boreal forest and coastal environment: a comparison of observations and implications of the nucleation mechanism, Atmos. Chem. Phys., 10, 7009-7016, DOI 10.5194/acp-10-7009-2010, 2010.

Liu, P. S. K., Deng, R., Smith, K. A., Williams, L. R., Jayne, J. T., Canagaratna, M. R., Moore, K., Onasch, T. B., Worsnop, D. R., and Deshler, T.: Transmission Efficiency of an Aerodynamic Focusing Lens System: Comparison of Model Calculations and Laboratory Measurements for the Aerodyne Aerosol Mass Spectrometer, Aerosol Sci. Technol., 41, 721-733, 10.1080/02786820701422278, 2007.

Mahajan, A. S., Plane, J. M. C., Oetjen, H., Mendes, L., Saunders, R. W., Saiz-Lopez, A., Jones, C. E., Carpenter, L. J., and McFiggans, G. B.: Measurement and modelling of tropospheric reactive halogen species over the tropical Atlantic Ocean, Atmos. Chem. Phys., 10, 4611-4624, 10.5194/acp-10-4611-2010, 2010.

McFiggans, G., Coe, H., Burgess, R., Allan, J., Cubison, M., Alfarra, M. R., Saunders, R., Saiz-Lopez, A., Plane, J. M. C., Wevill, D. J., Carpenter, L. J., Rickard, A. R., and Monks, P. S.: Direct evidence for coastal iodine particles from Laminaria macroalgae - linkage to emissions of molecular iodine, Atmos. Chem. Phys., 4, 701-713, 2004.

McFiggans, G., Alfarra, M. R., Allan, J., Bower, K., Coe, H., Cubison, M., Topping, D., Williams, P., Decesari, S., Facchini, C., and Fuzzi, S.: Simplification of the representation of the organic component of atmospheric particulates, Faraday Discuss., 130, 341-362, Doi 10.1039/B419435g, 2005.

McFiggans, G., Bale, C. S. E., Ball, S. M., Beames, J. M., Bloss, W. J., Carpenter, L. J., Dorsey, J., Dunk, R., Flynn, M. J., Furneaux, K. L., Gallagher, M. W., Heard, D. E., Hollingsworth, A. M., Hornsby, K., Ingham, T., Jones, C. E., Jones, R. L., Kramer, L. J., Langridge, J. M., Leblanc, C., LeCrane, J. P., Lee, J. D., Leigh, R. J., Longley, I., Mahajan, A. S., Monks, P. S., Oetjen, H., Orr-Ewing, A. J., Plane, J. M. C., Potin, P., Shillings, A. J. L., Thomas, F., von Glasow, R., Wada, R., Whalley, L. K., and Whitehead, J. D.: Iodine-mediated coastal particle formation: an overview of the Reactive Halogens in the Marine Boundary Layer (RHaMBLe) Roscoff coastal study, Atmos. Chem. Phys., 10, 2975-2999, 10.5194/acp-10-2975-2010, 2010.

Merikanto, J., Spracklen, D. V., Mann, G. W., Pickering, S. J., and Carslaw, K. S.: Impact of nucleation on global CCN, Atmos. Chem. Phys., 9, 8601-8616, 10.5194/acp-9-8601-2009, 2009.

Murray, B. J., Haddrell, A. E., Peppe, S., Davies, J. F., Reid, J. P., O'Sullivan, D., Price, H. C., Kumar, R., Saunders, R. W., Plane, J. M. C., Umo, N. S., and Wilson, T. W.: Glass formation and unusual hygroscopic growth of iodic acid solution droplets with relevance for iodine mediated particle formation in the marine boundary layer, Atmos. Chem. Phys., 12, 8575-8587, 10.5194/acp-12-8575-2012, 2012.

O'Dowd, C. D., Jimenez, J. L., Bahreini, R., Flagan, R. C., Seinfeld, J. H., Hämeri, K., Pirjola, L., Kulmala, M., Jennings, S. G., and Hoffmann, T.: Marine aerosol formation from biogenic iodine emissions, Nature, 417, 632-636, 2002.

O'Driscoll, P., Lang, K., Minogue, N., and Sodeau, J.: Freezing halide ion solutions and the release of interhalogens to the atmosphere, J Phys Chem A, 110, 4615-4618, Doi 10.1021/Jp060491v, 2006.

Paatero, P., and Tapper, U.: Positive matrix factorization: A non-negative factor model with optimal utilization of error estimates of data values, Environmetrics, 5, 111-126, 10.1002/env.3170050203, 1994.

Phinney, L., Leaitch, W. R., Lohmann, U., Boudries, H., Worsnop, D. R., Jayne, J. T., Toom-Sauntry, D., Wadleigh, M., Sharma, S., and Shantz, N.: Characterization of the aerosol over the sub-arctic north east Pacific Ocean, Deep-Sea Res. Pt. II, 53, 2410-2433, 10.1016/j.dsr2.2006.05.044, 2006.

Riccobono, F., Schobesberger, S., Scott, C. E., Dommen, J., Ortega, I. K., Rondo, L., Almeida, J., Amorim, A., Bianchi, F., Breitenlechner, M., David, A., Downard, A., Dunne, E. M., Duplissy, J., Ehrhart, S., Flagan, R. C., Franchin, A., Hansel, A., Junninen, H., Kajos, M., Keskinen, H., Kupc, A., Kürten, A., Kvashin, A. N., Laaksonen, A., Lehtipalo, K., Makhmutov, V., Mathot, S., Nieminen, T., Onnela, A., Petäjä, T., Praplan, A. P., Santos, F. D., Schallhart, S., Seinfeld, J. H., Sipilä, M., Spracklen, D. V., Stozhkov, Y., Stratmann, F., Tomé, A., Tsagkogeorgas, G., Vaattovaara, P., Viisanen, Y., Vrtala, A., Wagner, P. E., Weingartner, E., Wex, H., Wimmer, D., Carslaw, K. S., Curtius, J., Donahue, N. M., Kirkby, J., Kulmala, M., Worsnop, D. R., and Baltensperger, U.: Oxidation Products of Biogenic Emissions Contribute to Nucleation of Atmospheric Particles, Science, 344, 717-721, 10.1126/science.1243527, 2014.

Saiz-Lopez, A., Plane, J. M. C., Baker, A. R., Carpenter, L. J., von Glasow, R., Martin, J. C. G., McFiggans, G., and Saunders, R. W.: Atmospheric Chemistry of Iodine, Chem. Rev., 112, 1773-1804, Doi 10.1021/Cr200029u, 2012.

Saiz-Lopez, A., Blaszczak-Boxe, C. S., and Carpenter, L. J.: A mechanism for biologically-induced iodine emissions from sea-ice, Atmos. Chem. Phys. Discuss., 15, 10257-10297, doi:10.5194/acpd-15-10257-2015, 2015.

Saunders, R. W., Kumar, R., Martin, J. C. G., Mahajan, A. S., Murray, B. J., and Plane, J. M. C.: Studies of the Formation and Growth of Aerosol from Molecular Iodine Precursor, Z Phys Chem, 224, 1095-1117, DOI 10.1524/zpch.2010.6143, 2010.

Spracklen, D. V., Carslaw, K. S., Kulmala, M., Kerminen, V. M., Mann, G. W., and Sihto, S. L.: The contribution of boundary layer nucleation events to total particle concentrations on regional and global scales, Atmos. Chem. Phys., 6, 5631-5648, 2006.

Sturges, W. T., Cota, G. F., and Buckley, P. T.: Bromoform Emission from Arctic Ice Algae, Nature, 358, 660-662, Doi 10.1038/358660a0, 1992.

Sturges, W. T., Sullivan, C. W., Schnell, R. C., Heidt, L. E., and Pollock, W. H.: Bromoalkane Production by Antarctic Ice Algae, Tellus B, 45, 120-126, DOI 10.1034/j.1600-0889.1993.t01-1-00004.x, 1993.

Topping, D. O., McFiggans, G. B., and Coe, H.: A curved multi-component aerosol hygroscopicity model framework: Part 1 - Inorganic compounds, Atmos. Chem. Phys., 5, 1205-1222, 2005.

Ulbrich, I. M., Canagaratna, M. R., Zhang, Q., Worsnop, D. R., and Jimenez, J. L.: Interpretation of organic components from positive matrix factorization of aerosol mass spectrometric data, Atmos. Chem. Phys., 9, 2891-2918, 2009.

Wang, M., Audi, G., Wapstra, A. H., Kondev, F. G., MacCormick, M., Xu, X., and Pfeiffer, B.: The Ame2012 atomic mass evaluation, Chinese Physics C, 36, Artn 1603, doi:10.1088/1674-1137/36/12/003, 2012.

Werner, A., and Kraan, S.: Review of the potential mechanisation of kelp harvesting in Ireland, Marine Environment & Health Series, No.17, Marine Institute, Galway, 2004.

Whitehead, J. D., McFiggans, G. B., Gallagher, M. W., and Flynn, M. J.: Direct linkage between tidally driven coastal ozone deposition fluxes, particle emission fluxes, and subsequent CCN formation, Geophys. Res. Lett., 36, L04806, 10.1029/2008GL035969, 2009.

Whitehead, J. D., Irwin, M., Allan, J. D., Good, N., and McFiggans, G.: A meta-analysis of particle water uptake reconciliation studies, Atmos. Chem. Phys., 14, 11833-11841, DOI 10.5194/acp-14-11833-2014, 2014.

Wiedensohler, A.: An Approximation of the Bipolar Charge-Distribution for Particles in the Sub-Micron Size Range, J. Aerosol. Sci., 19, 387-389, 1988.

Wiencke, C., and Amsler, C. D.: Seaweeds and their communities in polar regions, in: Seaweed Biology, Novel Insights into Ecophysiology, Ecology and Utilization, edited by: Wiencke, C., and Bischof, K., Ecological Studies 219, Springer, Berlin, Heidelberg, pp. 265–291, 2012.

Williams, P. I., McFiggans, G., and Gallagher, M. W.: Latitudinal aerosol size distribution variation in the Eastern Atlantic Ocean measured aboard the FS-Polarstern, Atmos. Chem. Phys., 7, 2563-2573, 2007.

Winklmayr, W., Reischl, G. P., Lindner, A. O., and Berner, A.: A New Electromobility Spectrometer for the Measurement of Aerosol Size Distributions in the Size Range from 1 to 1000 nm, J. Aerosol. Sci., 22, 289-296, 1991.

Yli-Juuti, T., Nieminen, T., Hirsikko, A., Aalto, P. P., Asmi, E., Horrak, U., Manninen, H. E., Patokoski, J., Dal Maso, M., Petaja, T., Rinne, J., Kulmala, M., and Riipinen, I.: Growth rates of nucleation mode particles in Hyytiala during 2003-2009: variation with particle size,

season, data analysis method and ambient conditions, Atmos. Chem. Phys., 11, 12865-12886, DOI 10.5194/acp-11-12865-2011, 2011.

Yoon, Y. J., O'Dowd, C. D., Jennings, S. G., and Lee, S. H.: Statistical characteristics and predictability of particle formation events at Mace Head, J. Geophys. Res.-Atmos., 111, D13204, 10.1029/2005JD006284, 2006.

Yu, F., and Luo, G.: Simulation of particle size distribution with a global aerosol model: contribution of nucleation to aerosol and CCN number concentrations, Atmos. Chem. Phys., 9, 7691-7710, 10.5194/acp-9-7691-2009, 2009.

Zhang, Q., Stanier, C. O., Canagaratna, M. R., Jayne, J. T., Worsnop, D. R., Pandis, S. N., and Jimenez, J. L.: Insights into the chemistry of new particle formation and growth events in Pittsburgh based on aerosol mass spectrometry, Environ. Sci. Technol., 38, 4797-4809, 2004a.

Zhang, X. F., Smith, K. A., Worsnop, D. R., Jimenez, J. L., Jayne, J. T., Kolb, C. E., Morris, J., and Davidovits, P.: Numerical characterization of particle beam collimation: Part II - Integrated aerodynamic-lens-nozzle system, Aerosol Sci. Technol., 38, 619-638, 10.1080/02786820490479833, 2004b.

Zorn, S. R., Drewnick, F., Schott, M., Hoffmann, T., and Borrmann, S.: Characterization of the South Atlantic marine boundary layer aerosol using an aerodyne aerosol mass spectrometer, Atmos. Chem. Phys., 8, 4711-4728, 2008.

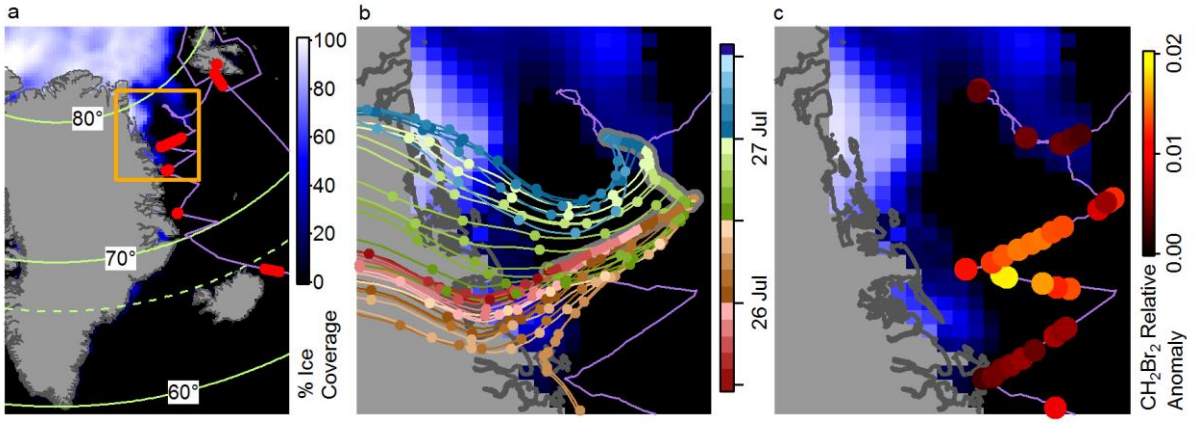

Figure 1: a) Cruise track (purple), ice coverage and locations of NPF events (red), defined by the presence of a mode of particles smaller than 10 nm not attributable to combustion or ship emissions (parts of the cruise outside of the area depicted did not show evidence of NPF). b) HYSPLIT back trajectories from cruise track corresponding to the 25-27 July case study. Markers are at 6-hourly intervals. c) Ratio of atmospheric concentrations of CH_2Br_2 (a product of ice diatom activity) to its saturation levels in seawater.

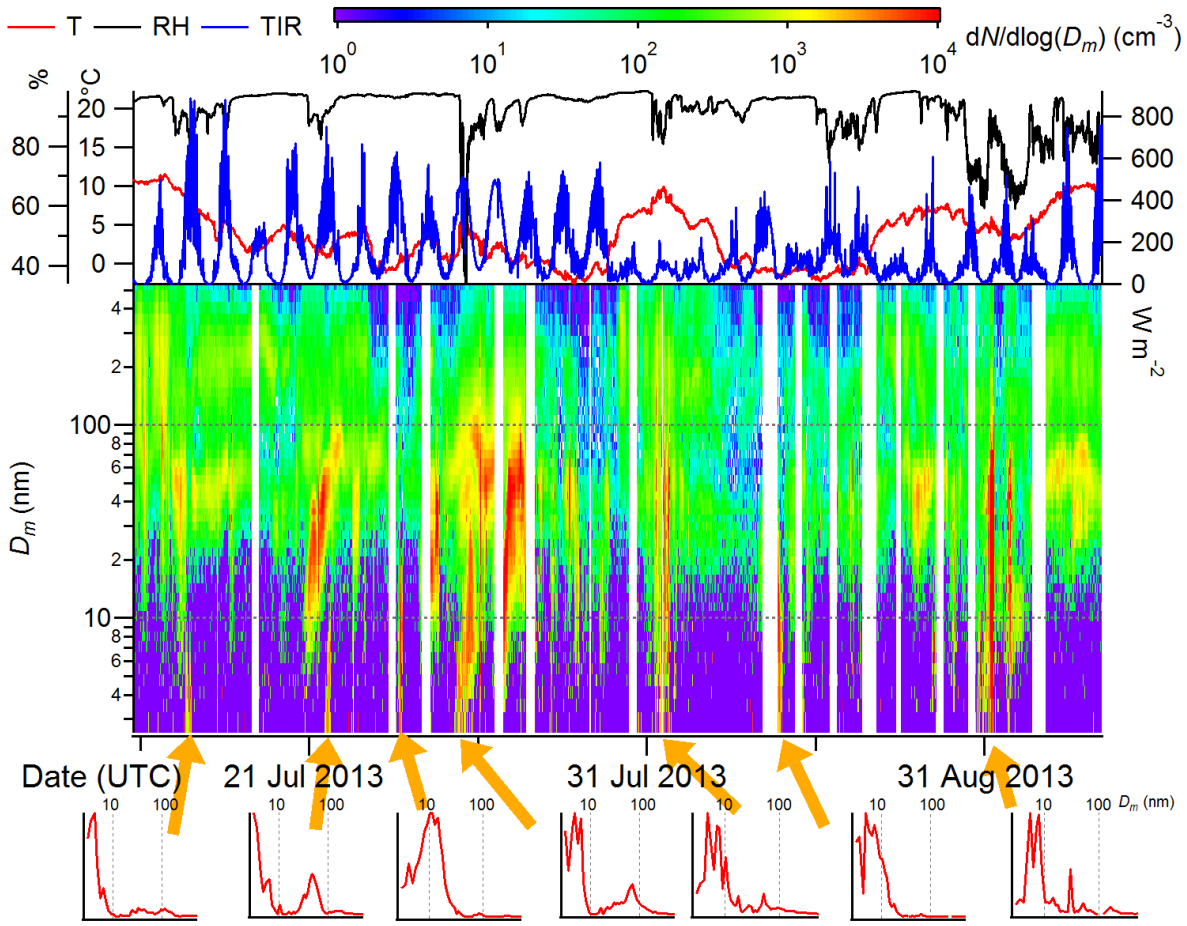

Figure 2: Temperature (T), relative humidity (RH) and total incident radiation (TIR) during the cruise, with DMPS size-resolved number concentration plotted data against electrical mobility diameter (D_m). White areas on the plot denote instrument downtime or when it was otherwise not sampling ambient air. Distributions from the seven candidate events in Fig. 1 are shown below to illustrate the shapes of the distributions during these events. Axis labels have been omitted for clarity, but are the same as the plot above, i.e. dN/dlog(D_m) (cm^{-3}) vs D_m (nm).

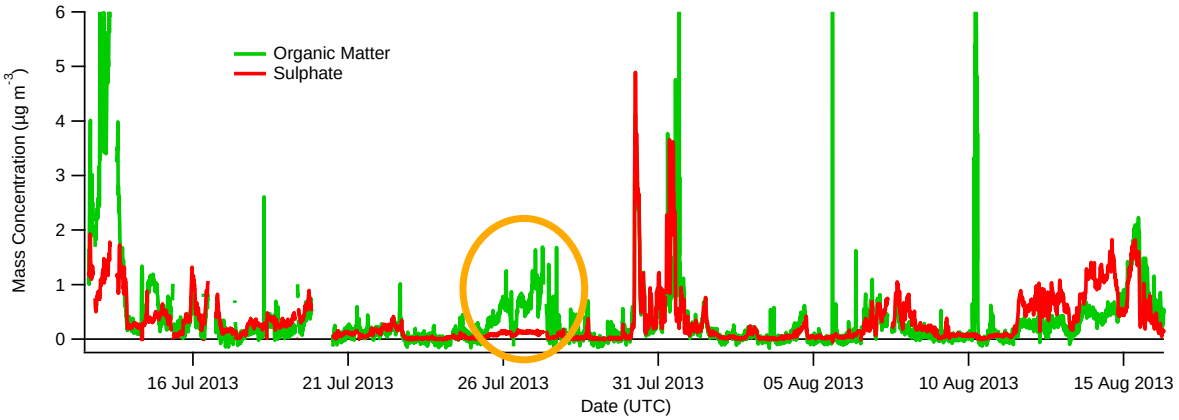

Figure 3: AMS-derived organic and sulphate mass concentrations, as calculated using the standard fragmentation tables (see section S2). Other commonly-reported species (nitrate and ammonium) were below detection limit outside of areas in close proximity to ports in the UK or Svalbard and thus considered irrelevant. The period of the main case study is highlighted in orange.

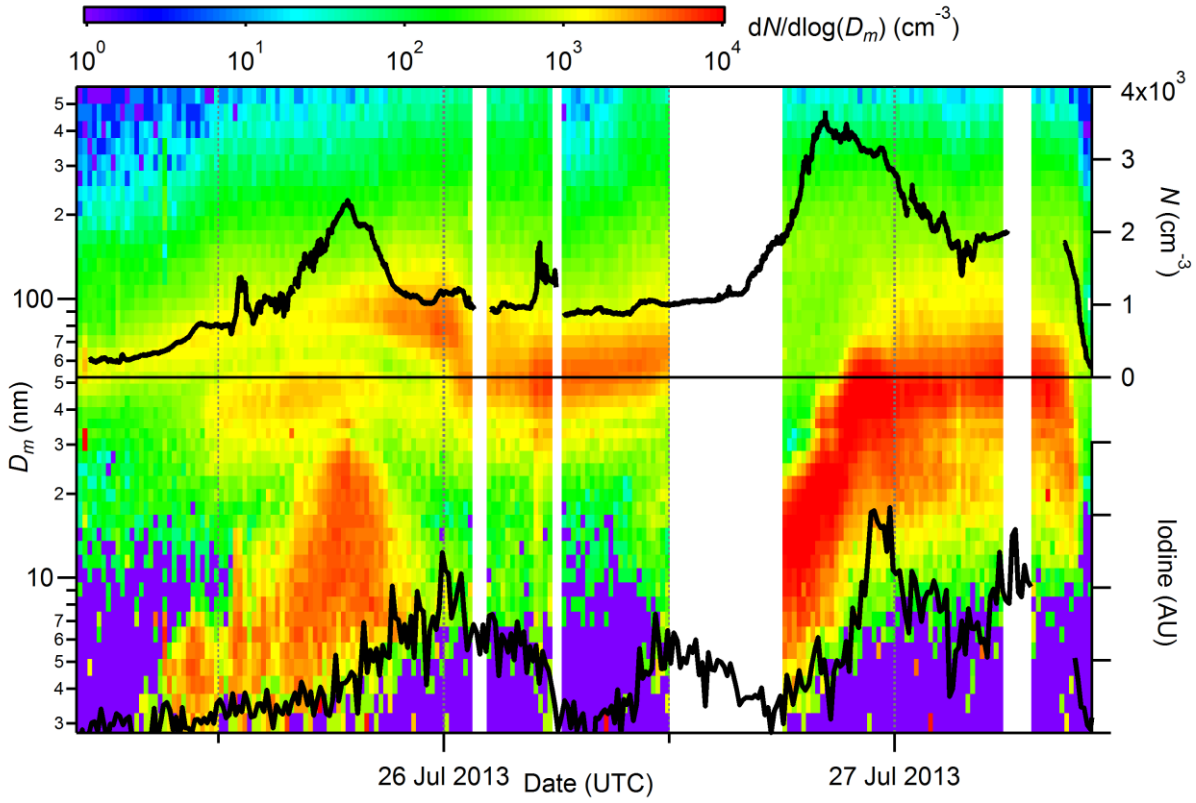

Figure 4: Size-resolved number concentrations (dN/dlog(D_m)) from a differential mobility particle sizer (DMPS) as a function of electrical mobility diameter (D_m), total number concentrations (N) from a condensation particle counter (CPC) and uncalibrated iodine ion concentrations from an Aerosol Mass Spectrometer (AMS) based on the signal at m/z=127 (I^+) during the main case study. White areas in the DMPS data show periods of ship influence or when the instrument was not sampling ambient air.

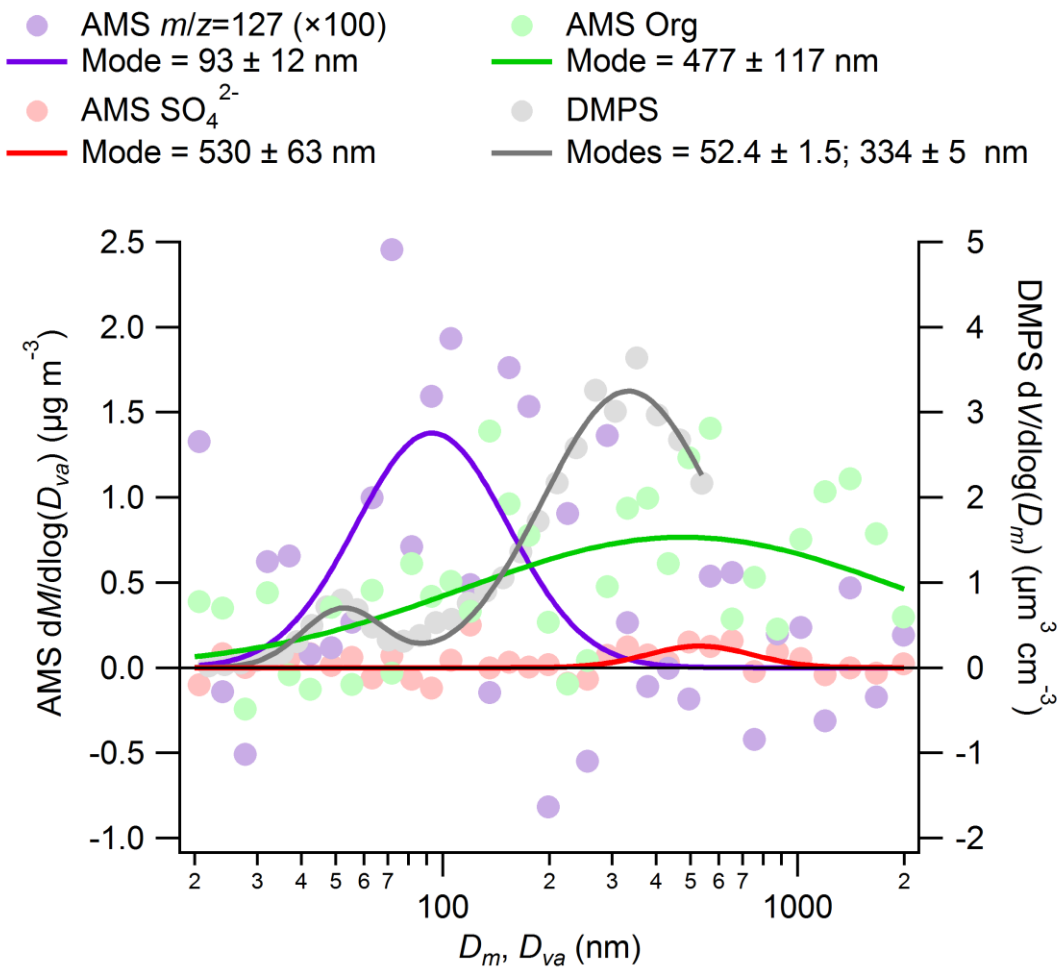

Figure 5: Size-resolved data from the DMPS and AMS, against electrical mobility and vacuum aerodynamic diameters respectively, during the period of highest iodine loading (26 July 22:50-23:45 UTC) with lognormal nonlinear least squares fits and associated standard errors, comparing DMPS volume with AMS mass at m/z=127, corresponding to I^+, and sulphate and organic matter. The low signal-to-noise ratios of the AMS data are due to the low concentrations and short averaging time. Note that the widths of the AMS distributions should not be directly compared against the DMPS, as the AMS distributions are subject to broadening introduced by the chopper wheel and variations in particle density.

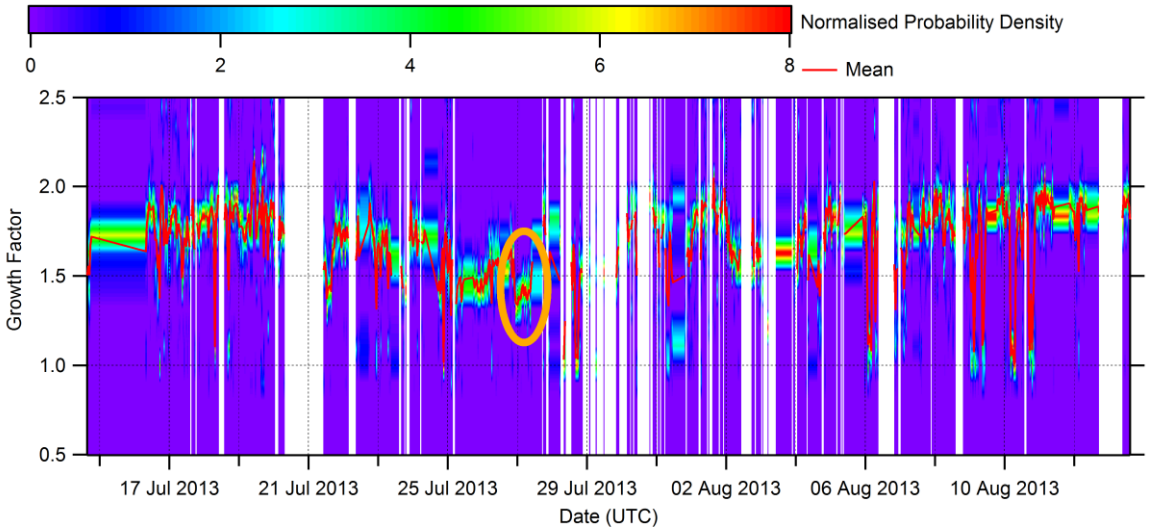

Figure 6: HTDMA-derived growth factor probability distribution functions for 50 nm dry particles at 90 % relative humidity, with associated mean growth factors. The low growth factors associated with the case study time period (26 July 22:50-23:45) are highlighted.