Thank you very much to the reviewers and editors for their time on this manuscript. The authors have reviewed the changes suggested in the technical corrections, and have highlighted the changes here. A tracked changes version of the manuscript is included.

Reviewer 1

Line numbers corresponding to the document still including the changes.

Line 93: …annual flux....

Changed

Line 396: ‘t’ needs to be in italics.

Changed

Line 397: ...as well as a response to the mesocosm wall cleaning which took place on t16...this part of the sentence does not fit with the beginning of the sentence. Needs to be reworded.

The section about wall cleaning has been put into a second sentence. Now reads ‘These higher DMS concentrations were likely connected to a peak in dissolved organic carbon (DOC) on t15, as well as increasing bacterial abundance during Phase II (Hornick et al., 2016). It is also likely that DMS concentrations increased as a response to the mesocosm wall cleaning which took place on t16.’

Line 441: ...vary...Typo

changed

Line 544: ...coastal environment. However, ...

changed

Line 599: ...t17 or t17 as before and just one line below?

CO2 did increase between t16 and t17, but the largest increase was seen after t17. However, as the first increase was seen after t16, and for ease of discussion, this has been changed to t16, as it corresponds with the change in DMS.

Line 651: ...hard... I don’t think that ‘hard’ is the appropriate word to use here.

Suggestion: ...therefore these upwelling events cannot be considered as natural high CO2 analogues. But the beginning of this sentence needs to be reworded also.
The section has been reworded to ‘The upwelling event occurring mid-way through our experiment allowed comparison of the mesocosm findings with a natural analogue of the system, as well as showing the extent to which the system perturbation can occur (up to 800 μatm). This event was a fortuitous occurrence during this mesocosm experiment, but as the scale and timing of these upwelling events is difficult to determine, and therefore these upwelling events are extremely challenging to study as natural high CO₂ analogues.’
Reviewer 2

The data in this manuscript are important information. The results show a lack of response of gas concentrations to the experimental design and no linkage to the external conditions due to the outside undergoing its own “experiment”, i.e., upwelling. No rates were measured, concentrations (mostly) remained the same, and the need to have rates of production, consumption, (photo/chem)-degradation or even “net” rates to include in prognostic and predictive models has been emphasized.

I recommend publishing pending changes. For me personally it would be important to have a clearer number agreement for the mean CO2 values.

Could the reviewer clarify what is meant by this, as I do not understand?

Also I think the firm and clearly stated replies to the editor comments under Point 1 and 2 would strengthen the discussion, as they nicely address the criticism that could still emerge.

The section on DMSP has been edited to include the following (TC version)

L 235 This method had been used during a previous mesocosm experiment (Bergen, Norway) and the results correlated well with those measured immediately on a similar GC-FPD system (Webb et al. 2015).

L 255 The DMSP acidification method is used worldwide as a simple and effective method of DMSP storage. The findings here, alongside those of del Valle et al. (2011) question the applicability of this method in other marine environments, and suggests significant testing prior to reliance on this method as a sole means of DMSP storage.

The section on the Baltic Sea has been amended to include comments from Section 2 of the replies to editors. Specifically (TC version):

L 578 The changes in biological parameters and trace gas concentrations are therefore discussed here separately from the concentrations measured in the mesocosms.

L 581 Given the separation of the waters within the mesocosms, and the movement of water masses within the Baltic Sea, it is expected that phytoplankton population structure could be significantly different inside the mesocosms compared to the external waters.

It could be worth to have a (short, taken from the comments) discussion section on methodological caveats/challenges and reasoning for the way the data is presented.

In terms of this, I believe this comment has been covered in the individual sections mentioned, and to include this recommended section would cause repetition within the manuscript. It is fair to say that the layout of the sections has caused a lot of discussion during the preparation of this manuscript.

L 607 In addition, the community demands of sulphur are likely to be very different in the Baltic Sea compared to the mesocosms, due to differences in community composition and sulphur availability, and therefore direct comparisons with mesocosm concentrations are inappropriate.
Macroalgal production in the Baltic Sea is likely the predominant iodocarbon source, compared to the mesocosms where macroalgae are excluded.
Effect of ocean acidification and elevated fCO₂ on trace gas production by a Baltic Sea summer phytoplankton community


[1] {Centre for Ocean and Atmospheric Sciences, School of Environmental Science, University of East Anglia, Norwich, UK, NR4 7TJ}
[2] {Groningen Institute for Evolutionary Life Sciences, University of Groningen, 9700 CC Groningen, The Netherlands}
[3] {Environmental Department, University of York, York, UK, YO10 5DD}
[4] {Plymouth Marine Laboratory, Plymouth, UK, PL1 3DH}
[5] {GEOMAR Helmholtz Centre for Ocean Research Kiel, Düsternbrooker Weg 20, 24148 Kiel, Germany.}
[6] {Centre for Coastal Biogeochemistry, School of Environment, Science and Engineering, Southern Cross University, Lismore, NSW 2480, Australia.}
[7] {Department of Biological Oceanography, NIOZ – Royal Netherlands Institute for Sea Research, PO Box 59, 1790 AB Den Burg, Texel, The Netherlands}
[8] {Aquatic Microbiology, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, P.O. Box 94248, 1090 GE, Amsterdam, The Netherlands}

Correspondence to: Alison Webb (a.l.webb@rug.nl)

Abstract

The Baltic Sea is a unique environment as the largest body of brackish water in the world. Acidification of the surface oceans due to absorption of anthropogenic CO₂ emissions is an additional stressor facing the pelagic community of the already challenging Baltic Sea. To investigate its impact on trace gas biogeochemistry, a large-scale mesocosm experiment was performed off Tvärminne Research Station, Finland in summer 2012. During the second half of the experiment, dimethylsulphide (DMS) concentrations in the highest fCO₂ mesocosms
(1075 - 1333 μatm) were 34% lower than at ambient CO$_2$ (350 μatm). However, the net production (as measured by concentration change) of seven halocarbons analysed was not significantly affected by even the highest CO$_2$ levels after 5 weeks exposure. Methyl iodide (CH$_3$I) and diiodomethane (CH$_2$I$_2$) showed 15% and 57% increases in mean mesocosm concentration (3.8 ± 0.6 pmol L$^{-1}$ increasing to 4.3 ± 0.4 pmol L$^{-1}$ and 87.4 ± 14.9 pmol L$^{-1}$ increasing to 134.4 ± 24.1 pmol L$^{-1}$ respectively) during Phase II of the experiment, which were unrelated to CO$_2$ and corresponded to 30% lower Chl-α concentrations compared to Phase I. No other iodo carbons increased or showed a peak, with mean chloriodomethane (CH$_2$ClI) concentrations measured at 5.3 (± 0.9) pmol L$^{-1}$ and iodoethane (C$_2$H$_5$I) at 0.5 (± 0.1) pmol L$^{-1}$. Of the concentrations of bromoform (CHBr$_3$; mean 88.1 ± 13.2 pmol L$^{-1}$), dibromomethane (CH$_2$Br$_2$; mean 5.3 ± 0.8 pmol L$^{-1}$) and dibromochloromethane (CHBr$_2$Cl, mean 3.0 ± 0.5 pmol L$^{-1}$), only CH$_2$Br$_2$ showed a decrease of 17% between Phases I and II, with CHBr$_3$ and CHBr$_2$Cl showing similar mean concentrations in both Phases. Outside the mesocosms, an upwelling event was responsible for bringing colder, high CO$_2$, low pH water to the surface starting on day t16 of the experiment; this variable CO$_2$ system with frequent upwelling events implies the community of the Baltic Sea is acclimated to regular significant declines in pH caused by up to 800 μatm fCO$_2$. After this upwelling, DMS concentrations declined, but halocarbon concentrations remained similar or increased compared to measurements prior to the change in conditions. Based on our findings, with future acidification of Baltic Sea waters, biogenic halocarbon emissions are likely to remain at similar values to today, however emissions of biogenic sulphur could significantly decrease from this region.

1 Introduction

Anthropogenic activity has increased the fugacity of atmospheric carbon dioxide (fCO$_2$) from 280 μatm (pre-Industrial Revolution) to over 400 μatm today (Hartmann et al., 2013). The IPCC AR5 long-term projections for atmospheric pCO$_2$ and associated changes to the climate have been established for a variety of scenarios of anthropogenic activity until the year 2300. As the largest global sink for atmospheric CO$_2$, the global ocean has absorbed an estimated 30% of excess CO$_2$ produced (Canadell et al., 2007). With atmospheric pCO$_2$ projected to possibly exceed 2000 μatm by the year 2300 (Collins et al., 2013; Cubasch et al., 2013), the ocean will take up increasing amounts of CO$_2$, with a potential lowering of surface ocean pH by over 0.8 units (Raven et al., 2005). The overall effect of acidification on the biogeochemistry of surface ocean ecosystems is
unknown and currently unquantifiable, with a wide range of potential positive and negative impacts (Doney et al., 2009; Hofmann et al., 2010; Ross et al., 2011).

A number of volatile organic compounds are produced by marine phytoplankton (Liss et al., 2014), including the climatically important trace gas dimethylsulphide (DMS, C\textsubscript{2}H\textsubscript{6}S) and a number of halogen-containing organic compounds (halocarbons) including methyl iodide (CH\textsubscript{3}I) and bromoform (CHBr\textsubscript{3}). These trace gases are a source of sulphate particles and halide radicals when oxidised in the atmosphere, and have important roles as ozone catalysts in the troposphere and stratosphere (O’Dowd et al., 2002; Solomon et al., 1994) and as cloud condensation nuclei (CCNs; Charlson et al., 1987).

DMS is found globally in surface waters originating from the algal-produced precursor dimethylsulphoniopropionate (DMSP, C\textsubscript{5}H\textsubscript{10}O\textsubscript{2}S). Both DMS and DMSP are provide the basis for major routes of sulphur and carbon flux through the marine microbial food web, and can provide up to 100% of the bacterial (Simó et al., 2009) and phytoplanktonic (Vila-Costa et al., 2006a) sulphur demand (Simó et al., 2009; Vila-Costa et al., 2006a). DMS is also a volatile compound which readily passes through the marine boundary layer to the troposphere, where oxidation results in a number of sulphur-containing particles important for atmospheric climate feedbacks (Charlson et al., 1987; Quinn and Bates, 2011); for this reason, any change in the production of DMS may have significant implications for climate regulation. Several previous acidification experiments have shown differing responses of both compounds (e.g. Avgoustidi et al., 2012; Hopkins et al., 2010; Webb et al., 2015), while others have shown delayed or more rapid responses as a direct effect of CO\textsubscript{2} (e.g. Archer et al., 2013; Vogt et al., 2008). Further, some laboratory incubations of coastal microbial communities showed increased DMS production with increased fCO\textsubscript{2} (Hopkins and Archer, 2014), but lower DMSP production. The combined picture arising from existing studies is that the response of communities to fCO\textsubscript{2} perturbation is not predictable and requires further study.

Previous studies measuring DMS in the Baltic Sea measured concentrations up to 100 nmol L\textsuperscript{-1} during the summer bloom, making the Baltic Sea a significant source of DMS (Orlikowska and Schulz-Bull, 2009).

In surface waters, halocarbons such as methyl iodide (CH\textsubscript{3}I), chloriodomethane (CH\textsubscript{2}ClI) and bromoform (CHBr\textsubscript{3}) are produced by biological and photochemical processes: many marine microbes (for example cyanobacteria; Hughes et al., 2011, diatoms; Manley and De La Cuesta, 1997 and haptophytes; Scarratt and Moore, 1998) and macroalgae (e.g. brown-algal Fucus species; Chance et al., 2009 and red algae; Leedham et al., 2013) utilise halides from seawater and emit a range of organic and inorganic halogenated compounds. This production can lead to significant
annual flux to the marine boundary layer in the order of 10 Tg iodine-containing compounds ('iodocarbons'; O’Dowd et al., 2002) and 1 Tg bromine-containing compounds ('bromocarbons'; Goodwin et al., 1997) into the atmosphere. The effect of acidification on halocarbon concentrations has received limited attention, but two acidification experiments measured lower concentrations of several iodocarbons while bromocarbons were unaffected by $f CO_2$ up to 3000 μatm (Hopkins et al., 2010; Webb, 2015), whereas an additional mesocosm study did not elicit significant differences from any compound up to 1400 μatm $f CO_2$ (Hopkins et al., 2013).

Measurements of the trace gases within the Baltic Sea are limited, with no prior study of DMSP concentrations in the region. The Baltic Sea is the largest body of brackish water in the world, and salinity ranges from 1 to 15. Furthermore, seasonal temperature variations of over 20 °C are common. A permanent halocline at 50-80 m separates $CO_2$-rich, bottom waters from fresher, lower $CO_2$ surface waters, and a summer thermocline at 20 m separates warmer surface waters from those below 4 °C (Janssen et al., 1999). Upwelling of bottom waters from below the summer thermocline is a common summer occurrence, replenishing the surface nutrients while simultaneously lowering surface temperature and pH (Brutemark et al., 2011). Baltic organisms are required to adapt to significant variations in environmental conditions. The species assemblage in the Baltic Sea is different to those studied during previous mesocosm experiments in the Arctic, North Sea and Korea (Brussaard et al., 2013; Engel et al., 2008; Kim et al., 2010), and are largely unstudied in terms of their community trace gas production during the summer bloom. Following the spring bloom (July-August), a low dissolved inorganic nitrogen (DIN) to dissolved inorganic phosphorous (DIP) ratio combines with high temperatures and light intensities to encourage the growth of heterocystous cyanobacteria, (Niemisto et al., 1989; Raateoja et al., 2011), in preference to nitrate-dependent groups.

Here we report the concentrations of DMS, DMSP and halocarbons from the 2012 summer post-bloom season mesocosm experiment aimed to assess the impact of elevated $f CO_2$ on the microbial community and trace gas production in the Baltic Sea. Our objective was to assess how changes in the microbial community driven by changes in $f CO_2$ impacted DMS and halocarbon concentrations. It is anticipated that any effect of $CO_2$ on the growth of different groups within the phytoplankton assemblage will result in an associated change in trace gas concentrations measured in the mesocosms as $f CO_2$ increases, which can potentially be used to predict future halocarbon and sulphur emissions from the Baltic Sea region.
2 Methods

2.1 Mesocosm design and deployment

Nine mesocosms were deployed on the 10th June 2012 (day \( t^{-10} \); days are numbered negative prior to \( \text{CO}_2 \) addition and positive afterward) and moored near Tvärminne Zoological Station (59° 51.5' N, 23° 15.5' E) in Tvärminne Storfjärden in the Baltic Sea. Each mesocosm comprised a thermoplastic polyurethane (TPU) enclosure of 17 m depth, containing approximately 54,000 L of seawater, supported by an 8m tall floating frame capped with a polyvinyl hood. For full technical details of the mesocosms see Czerny et al. (2013) and Riebesell et al. (2013). The mesocosm bags were filled by lowering through the stratified water column until fully submerged, with the opening at both ends covered by 3 mm mesh to exclude organisms larger than 3 mm such as fish and large zooplankton. The mesocosms were then left for 3 days (\( t^{-10} \) to \( t^{-7} \)) with the mesh in position to allow exchange with the external water masses and ensure the mesocosm contents were representative of the phytoplankton community in the Storfjärden. On \( t^{-7} \) the bottom of the mesocosm was sealed with a sediment trap and the upper opening was raised to approximately 1.5 m above the water surface. Stratification within the mesocosm bags was broken up on \( t^{-5} \) by the use of compressed air for three and a half minutes to homogenise the water column and ensure an even distribution of inorganic nutrients at all depths. Unlike in previous experiments, there was no addition of inorganic nutrients to the mesocosms at any time during the experiment; mean inorganic nitrate, inorganic phosphate and ammonium concentrations measured across all mesocosms at the start of the experiment were 37.2 (± 18.8 s.d.) nmol L\(^{-1}\), 323.9 (± 19.4 s.d.) nmol L\(^{-1}\) and 413.8 (± 319.5 s.d.) nmol L\(^{-1}\) respectively.

To obtain mesocosms with different \( f/\text{CO}_2 \), the carbonate chemistry of the mesocosms was altered by the addition of different volumes of 50 μm filtered, \( \text{CO}_2 \)-enriched Baltic Sea water (sourced from outside the mesocosms), to each mesocosm over a four-day period, with the first day of addition being defined as day \( t^0 \). Addition of the enriched \( \text{CO}_2 \) water was by the use of a bespoke dispersal apparatus (‘Spider’) lowered through the bags to ensure even distribution throughout the water column (further details are in Riebesell et al. 2013). Measurements of salinity in the mesocosms throughout the experiment determined that three of the mesocosms were not fully sealed, and had undergone unquantifiable water exchange with the surrounding waters. These three mesocosms (M2, M4 and M9) were excluded from the analysis. Two mesocosms were designated as controls (M1 and M5) and received only filtered seawater via the Spider; four mesocosms received addition of \( \text{CO}_2 \)-enriched waters, with the range of target \( f/\text{CO}_2 \) levels between 600 and 1650 μatm (M7, 600...
Mesocosms were randomly allocated a target $f_{CO_2}$; a noticeable decrease in $f_{CO_2}$ was identified in the three highest $f_{CO_2}$ mesocosms (M6, M3 and M8) over the first half of the experiment, which required the addition of more CO$_2$ enriched water on t15 to bring the $f_{CO_2}$ back up to maximum concentrations (Fig. 1a; Paul et al., 2015). A summary of the $f_{CO_2}$ in the mesocosms can be seen in Table 1. At the same time as this further CO$_2$ addition on t15, the walls of the mesocosms were cleaned using a bespoke wiper apparatus (See Riebesell et al., 2013 for more information), followed by weekly cleaning to remove aggregations on the film which would block incoming light. Light measurements showed that over 95% of the photosynthetically active radiation (PAR) was transmitted by the clean TPU and PVC materials with 100% absorbance of UV light (Riebesell et al., 2013). Samples for most parameters were collected from the mesocosms at the same time every morning from t-3, and analysed daily or every other day.

### 2.2 Trace gas extraction and analysis

#### 2.2.1 DMS and halocarbons

A depth-integrated water sampler (IWS, HYDRO-BIOS, Kiel, Germany) was used to sample the entire 17 m water column daily or alternative daily. As analysis of Chlorophyll-a (Chl-a) showed it to be predominantly produced in the first 10 m of the water column, trace gas analysis was conducted on only integrated samples collected from the surface 10 m, with all corresponding community parameter analyses with the exception of pigment analysis performed also to this depth.

Water samples for trace gas analysis were taken from the first IWS from each mesocosm to minimise the disturbance and bubble entrainment from taking multiple samples in the surface waters. As in Hughes et al. (2009), samples were collected in 250 mL amber glass bottles in a laminar flow with minimal disturbance to the water sample, using Tygon tubing from the outlet of the IWS. Bottles were rinsed twice before being carefully filled from the bottom with minimal stirring, and allowed to overflow the volume of the bottle approximately three times before sealing with a glass stopper to prevent bubble formation and atmospheric contact. Samples were stored below 10°C in the dark for 2 hours prior to analysis. Each day, a single sample was taken from each mesocosm, with two additional samples taken from one randomly selected mesocosm to evaluate the precision of the analysis (<4%, no further data shown).

On return to the laboratory, 40 mL of water was injected into a purge and cryotrap system (Chuck et al., 2005), filtered through a 25 mm Whatman glass fibre filter (GF/F; GE Healthcare Life Sciences, Little Chalfont, England) and purged with oxygen-free nitrogen (OFN) at 80 mL min$^{-1}$ for 10
minutes. Each gas sample passed through a glass wool trap to remove particles and aerosols, before a dual nafion counterflow drier (180 mL min\(^{-1}\) OFN) removed water vapour from the gas stream. The gas sample was trapped in a stainless steel loop held at -150 °C in the headspace of a liquid nitrogen-filled dewar. The sample was injected by immersion of the sample loop in boiling water into an Agilent 6890 gas chromatograph equipped with a 60 m DB-VRX capillary column (0.32 mm ID, 1.8 μm film thickness, Agilent J&W Ltd) according to the programme outlined by Hopkins et al. (2010). Analysis was performed by an Agilent 5973 quadrupole mass spectrometer operated in electron ionisation, single ion mode. Liquid standards of CH\(_3\)I, diiodomethane (CH\(_2\)I\(_2\)), CH\(_2\)ClI, iodoethane (C\(_2\)H\(_5\)I), iodopropane (C\(_3\)H\(_7\)I), dibromoethane (CHBr\(_2\)Br), dibromochloromethane (CHBrCl\(_2\)), bromiodomethane (CH\(_2\)BrI) and DMS (Standards supplied by Sigma Aldrich Ltd, UK) were gravimetrically prepared by dilution in HPLC-grade methanol (Table 2) and used for calibration. The relative standard error was expressed as a percentage of the mean for the sample analysis, calculated for each compound using triplicate analysis each day from a single mesocosm, and was <7% for all compounds. GC-MS instrument drift was corrected by the use of a surrogate analyte standard in every sample, comprising deuterated DMS (D\(_6\)-DMS), deuterated methyl iodide (CD\(_3\)I) and \(^{13}\)C dibromoethane (\(^{13}\)C\(_2\)H\(_4\)Br\(_2\)) via the method described in Hughes et al. (2006) and Martino et al. (2005). Five-point calibrations were performed weekly for each compound with the addition of the surrogate analyte, with a single standard analysed daily to check for instrument drift; linear regression from calibrations typically produced \(r^2>0.98\). All samples measured within the mesocosms were within the concentration ranges of the calibrations (Table 2).

### 2.2.2 DMSP

Samples for total DMSP (DMSP\(_T\)) were collected and stored for later analysis by the acidification method of Curran et al. (1998). A 7 mL sub-sample was collected from the amber glass bottle into an 8 mL glass sample vial (Labhut, Churcham, UK), into which 0.35 μL of 50% H\(_2\)SO\(_4\) was added, before storage at ambient temperature. Particulate DMSP (DMSP\(_P\)) samples were prepared by the gravity filtration of 20 mL of sample through a 47 mm GF/F in a glass filter unit, before careful removal and folding of the GF/F into a 7 mL sample vial filled with 7 mL of Milli-Q water and 0.35 μL of H\(_2\)SO\(_4\) before storage at ambient temperature. Samples were stored for approximately 8 weeks prior to analysis. DMSP samples (total and particulate) were analysed on a PTFE purge and cryotrap system using 2 mL of the sample purged with 1 mL of 10M NaOH for 5 minutes at 80 mL min\(^{-1}\). The sample gas stream passed through a glass wool trap and Nafion counterflow (Permapure) drier before being trapped in a PTFE sample loop kept at -150 °C by suspension in the headspace of a liquid nitrogen-filled dewar and controlled by feedback from a thermocouple. Immersion in
boiling water rapidly re-volatilised the sample for injection into a Shimadzu GC2010 gas chromatograph with a Varian Chrompack CP-Sil-5CB column (30 m, 0.53 mm ID) and flame photometric detector (FPD). The GC oven was operated isothermally at 60 °C which resulted in DMS eluting at 2.1 minutes. Liquid DMSP standards were prepared and purged in the same manner as the sample to provide weekly calibrations of the entire analytical system. Involvement in the 2013 AQA 12-23 international DMS analysis proficiency test (National Measurement Institute of Australia, 2013) in February 2013 demonstrated excellent agreement between our method of DMS analysis and the mean from thirteen laboratories measuring DMS using different methods, with a measurement error of 5%.

DMSP was not detected in any of the samples (total or particulate) collected and stored during the experiment, and it was considered likely that this was due to an unresolved issue regarding acidifying the Baltic Sea samples for later DMSP analysis. This method had been used during a previous mesocosm experiment (Bergen, Norway) and the results correlated well with those measured immediately on a similar GC-FPD system (Webb et al. 2015). It was considered unlikely that rates of bacterial DMSP turnover through demethylation rather than through cleavage to produce DMS (Curson et al., 2011) were sufficiently high in the Baltic Sea to remove all detectable DMSP, yet still produce measurable DMS concentrations. Also, rapid turnover of dissolved DMSP in surface waters being the cause of low DMSP concentrations does not explain the lack of intracellular particulate-phase DMSP. Although production of DMS is possible from alternate sources, it is highly unlikely that there was a total absence of DMSP-producing phytoplankton within the mesocosms or Baltic Sea surface waters around Tvärminne; DMSP has been measured in surface waters of the Southern Baltic Sea at 22.2 nmol L⁻¹ in 2012, indicating that DMSP-producing species are present within the Baltic Sea (Cathleen Zindler, GEOMAR, Pers. Comm.).

A previous study by del Valle et al. (2011) highlighted up to 94% loss of DMSP from acidified samples of colonial *Phaeocystis globosa* culture, and field samples dominated by colonial *Phaeocystis antarctica*. Despite filamentous, colonial cyanobacteria in the samples from Tvärminne mesocosms potentially undergoing the same process, these species did not dominate the community at only 6.6% of the total Chl-α, implying that the acidification method for DMSP fixation also failed for unicellular phytoplankton species. The findings of this mesocosm study suggest that the acidification method is unreliable in the Baltic Sea, and should be considered inadequate as the sole method of DMSP fixation in future experiments in the region. The DMSP acidification method is used worldwide as a simple and effective method of DMSP storage. The findings here, alongside those of del Valle et al. (2011) The question of the applicability of this method in other marine
waters environments, and suggests significant testing prior to reliance on this method as a sole means of DMSP storage also needs further investigation.

2.3 Measurement of carbonate chemistry and community dynamics

Water samples were collected from the 106 m and 17 m IWS on a daily basis and analysed for carbonate chemistry, fluorometric Chl-α, phytoplankton pigments (17 m IWS only) and cell abundance to analyse the community structure and dynamics during the experiment. The carbonate system was analysed through a suite of measurements (Paul et al., 2015), including potentiometric titration for total alkalinity (TA), infrared absorption for dissolved inorganic carbon (DIC) and spectrophotometric determination for pH. For Chl-α analysis and pigment determination, 500 mL sub-samples were filtered through a GF/F and stored frozen (-20 °C for two hours for Chl-α and -80 °C for up to 6 months for pigments), before homogenisation in 90 % acetone with glass beads. After centrifuging (10 minutes at 800 x g at 4 °C) the Chl-α concentrations were determined using a Turner AU-10 fluorometer by the methods of Welschmeyer (1994), and the phytoplankton pigment concentrations by reverse phase high performance liquid chromatography (WATERS HPLC with a Varian Microsorb-MV 100-3 C8 column) as described by Barlow et al. (1997). Phytoplankton community composition was determined by the use of the CHEMTAX algorithm to convert the concentrations of marker pigments to Chl-α equivalents (Mackey et al., 1996; Schulz et al., 2013). Microbes were enumerated using a Becton Dickinson FACSCalibur flow cytometer (FCM) equipped with a 488 nm argon laser (Crawford et al., 2016) and counts of phytoplankton cells >20 µm were made on concentrated (50 mL) sample water, fixed with acidic Lugol’s iodine solution with an inverted microscope. Filamentous cyanobacteria were counted in 50 µm length units.

2.4 Statistical Analysis

All statistical analysis was performed using Minitab V16. In analysis of the measurements between mesocosms, one-way ANOVA was used with Tukey’s post-hoc analysis test to determine the effect of different fCO2 on concentrations measured in the mesocosms and the Baltic Sea (H0 assumes no significant difference in the mean concentrations of trace gases measured through the duration of the experiment). Spearman’s Rank Correlation Coefficients were calculated to compare the relationships between trace gas concentrations, fCO2, and a number of biological parameters, and the resulting p-values for each correlation are given in Supplementary table S1 for the mesocosms and S2 for the Baltic Sea data.
3 Results and Discussion

3.1 Biogeochemical changes within the mesocosms

The mesocosm experiment was split into three phases based on the temporal variation in Chl-α (Fig. 2; Paul et al., 2015) evaluated after the experiment was completed:

- Phase 0 (days $t-5$ to $t0$) – pre-CO$_2$ addition
- Phase I (days $t1$ to $t16$) – ‘productive phase’
- Phase II (days $t17$ to $t30$) – temperature induced autotrophic decline.

3.1.1 Physical Parameters

fCO$_2$ decreased over Phase I in the three highest fCO$_2$ mesocosms, mainly through air-sea gas exchange and carbon fixation by phytoplankton (Fig. 1a). All mesocosms still showed distinct differences in fCO$_2$ levels throughout the experiment (Table 1), and there was no overlap of mesocosm fCO$_2$ values on any given day, save for the two controls (M1 and M5). The control mesocosm fCO$_2$ increased through Phase I of the experiment, likely as a result of undersaturation of the water column encouraging dissolution of atmospheric CO$_2$ (Paul et al., 2015). Salinity in the mesocosms remained constant throughout the experiment at $5.70 \pm 0.004$, and showed no variation with depth (data not shown but available in Paul et al., 2015). It remained similar to salinity in the Baltic Sea surrounding the mesocosms, which was $5.74 \pm 0.14$. Water temperature varied from a low of $8.6 \pm 0.4$ °C during Phase 0 to a high of $15.9 \pm 2.2$ °C measured on day $t16$, before decreasing once again (Fig. 1b).

Summertime upwelling events are common and well described (Gidhagen, 1987; Lehmann and Myrberg, 2008), and induce a significant temperature decrease in surface waters; such an event appears to have commenced around $t16$, as indicated by significantly decreasing temperatures inside and out of the mesocosms (Fig. 1b) and increased salinity in the Baltic Sea from 5.5 to 6.1 over the following 15 days to the end of the experiment. Due to the enclosed nature of the mesocosms, the upwelling affected only the temperature and not pH, fCO$_2$ or the microbial community. However, the temperature decrease after $t16$ was likely to have had a significant effect on phytoplankton growth (and biogenic gas production), explaining the lower Chl-α in Phase II.
3.1.2 Community Dynamics

Mixing of the mesocosms and redistribution of the nutrients throughout the water column after closure (prior to t-3) did not trigger a notable increase in total Chl-α in Phase 0 as was identified in previous mesocosm experiments; in previous mesocosm experiments, mixing redistributed nutrients from the deeper stratified layers throughout the water column. During Phase I, light availability, combined with increasing water temperatures favoured the growth of phytoplankton in all mesocosms (Paul et al. 2015), and was unlikely to be a direct result of the CO₂ enrichment, as no difference was identified between enriched mesocosms and controls. Mean Chl-α during Phase I was 1.98 (± 0.29) μg L⁻¹ from all mesocosms, decreasing to 1.44 (± 0.46) μg L⁻¹ in Phase II: this decrease was attributed to a temperature induced decreased in phytoplankton growth rates and higher grazing rates as a result of higher zooplankton reproduction rates during Phase I (Lischka et al., 2015; Paul et al., 2015). Mesocosm Chl-α decreased until the end of the experiment on t31.

The largest contributors to Chl-α in the mesocosms during the summer of 2012 were the chlorophytes and cryptophytes, with up to 40% and 21% contributions to the Chl-α respectively (Table 3; Paul et al., 2015). Significant long-term differences in abundance between mesocosms developed as a result of elevated fCO₂ in only two groups: picoeukaryotes I showed higher abundance at high fCO₂ (F=8.2, p<0.01; Crawfurd et al., 2016 and Supplementary Fig. S2), as seen in previous mesocosm experiments (Brussaard et al., 2013; Newbold et al., 2012) and picoeukaryotes III the opposite trend (F=19.6, p<0.01; (Crawfurd et al., 2016)) Temporal variation in phytoplankton abundance was similar between all mesocosms (Supplementary Fig. S1 and S2).

Diazotrophic, filamentous cyanobacterial blooms in the Baltic Sea are an annual event in summer (Finni et al., 2001), and single-celled cyanobacteria have been found to comprise as much as 80% of the cyanobacterial biomass and 50% of the total primary production during the summer in the Baltic Sea (Stal et al., 2003). However, CHEMTAX analysis identified cyanobacteria as contributing less than 10% of the total Chl-α in the mesocosms (Crawfurd et al., 2016; Paul et al., 2015). These observations were backed up by satellite observations showing reduced cyanobacterial abundance throughout the Baltic Sea in 2012 compared to previous and later years (Oberg, 2013). It was proposed that environmental conditions of limited light availability and lower surface water temperatures during the summer of 2012 were sub-optimal for triggering a filamentous cyanobacteria bloom (Wasmund, 1997).
3.2 DMS and DMSP

3.2.1 Mesocosm DMS

A significant 34% reduction in DMS concentrations was detected in the high fCO$_2$ treatments during Phase II compared to the ambient fCO$_2$ mesocosms (F=31.7, p<0.01). Mean DMS concentrations of 5.0 (± 0.8; range 3.5 – 6.8) nmol L$^{-1}$ in the ambient treatments compared to 3.3 (± 0.3; range 2.9 – 3.9) nmol L$^{-1}$ in the 1333 and 1075 μatm mesocosms (Fig. 23a). The primary differences identified were apparent from the start of Phase II on t17, after which maximum concentrations were observed in the ambient mesocosms on t21. The relationship between DMS and increasing fCO$_2$ during Phase II was found to be linear (Fig. 32b), a finding also identified in previous mesocosm experiments (Archer et al., 2013; Webb et al., 2015). Furthermore, increases in DMS concentrations under high fCO$_2$ were delayed by three days relative to the ambient and medium fCO$_2$ treatments, a situation which has been observed in a previous mesocosm experiment. This was attributed to small-scale shifts in community composition and succession which could not be identified with only a once-daily measurement regime (Vogt et al., 2008). DMS measured in all mesocosms fell within the range 2.7 to 6.8 nmol L$^{-1}$ across the course of the experiment. During Phase I, no difference was identified in DMS concentrations between fCO$_2$ treatments with the mean of all mesocosms 3.1 (± 0.2) nmol L$^{-1}$. Concentrations in all mesocosms gradually declined from t21 until the end of DMS measurements on t31. DMS concentrations measured in the mesocosms and Baltic Sea were comparable to those measured in temperate coastal conditions in the North Sea (Turner et al., 1988), the Mauritanian upwelling (Franklin et al., 2009; Zindler et al., 2012) and South Pacific (Lee et al., 2010).

Although the majority of DMS production is presumed to be from DMSP. However, an alternative production route for DMS is available through the methylation of methanethiol (Drotar et al., 1987; Kiene and Hines, 1995; Stets et al., 2004) predominantly identified in anaerobic environments such as freshwater lake sediments (Lomans et al., 1997), saltmarsh sediments (Kiene and Visscher, 1987) and microbial mats (Visscher et al., 2003; Zinder et al., 1977). However, recent studies have also identified this pathway of DMS production from Pseudomonas deceptionensis in an aerobic environment (Carrión et al., 2015), where P. deceptionensis was unable to synthesise or catabolise DMSP, but was able to enzymatically mediate DMS production from methanethiol (MeSH). The same enzyme has also been identified in a wide range of other bacterial taxa, including the cyanobacterial Pseudanabaena, which was identified in the Baltic Sea during this and previous investigations (Stuhr, pers. comm.; Kangro et al., 2007; Nausch et al., 2009). Correlations...
between DMS and the cyanobacterial equivalent Chl-ɑ \((\rho=0.42, p<0.01; \text{Supplementary Figure S1})\) and DMS and single-celled cyanobacteria \((\rho=0.58, p<0.01; \text{Supplementary Figure S2a})\) indicate suggest that the methylation pathway may be a potential source of DMS within the Baltic Sea community. In addition to the methylation pathway, DMS production has been identified from S-methylmethionine (Bentley and Chasteen, 2004), as well as from the reduction of dimethylsulphoxide (DMSO) in both surface and deep waters by bacterial metabolism (Hatton et al., 2004). As these compounds were not measured in the mesocosms, it is impossible to determine if they were significant sources of DMS.

3.2.2 DMS and Community Interactions

Throughout Phase I, DMS showed no correlation with any measured variables of biological activity or cell abundance, and was unaffected by elevated \(f\text{CO}_2\), indicating measured DMS net production concentrations were not directly related to the perturbation of the system and associated cellular stress (Sunda et al., 2002). Of the studied phytoplankton groupings, neither the cryptophyes or chlorophyes as the largest contributors of Chl-ɑ were identified as significant producers of DMSP. During Phase II, DMS was negatively correlated with Chl-ɑ in the ambient and medium \(f\text{CO}_2\) mesocosms \((\rho=-0.60, p<0.01)\). During Phase II, a significant correlation was seen between DMS and single-celled cyanobacteria identified predominantly as Synechococcus \((\rho=0.53, p<0.01; \text{Crawfurd et al. 2016 and supplementary table S1})\) and picoeukaryotes III \((\rho=0.75, p<0.01)\). The peak in DMS concentrations on \(t=21\) is unlikely to be a delayed response to the increased Chl-ɑ on \(t=16\) due to the time lag of 7 days. These higher DMS concentrations were likely connected to a peak in dissolved organic carbon (DOC) on \(t=15\), as well as increasing bacterial abundance during Phase II (Hornick et al., 2016). It is also likely that DMS concentrations increased as a response to the mesocosm wall cleaning which took place on \(t=16\). The variation in inorganic nutrient concentrations between mesocosms at the start of the experiment did not have an effect on DMS concentrations during Phase I, and by the start of Phase II the variation between mesocosms had decreased.

In previous mesocosm experiments (Archer et al., 2013; Hopkins et al., 2010; Webb et al., 2015), DMS has shown poor correlations with many of the indicators of primary production and phytoplankton abundance, as well as showing the same trend of decreased concentrations in high \(f\text{CO}_2\) mesocosms compared to ambient. DMS production is often uncoupled from measurements of primary production in open waters (Lana et al., 2012), and also often from production of its
precursor DMSP (Archer et al., 2009). DMS and DMSP are important sources of sulphur and carbon in the microbial food web for both bacteria and algae (Simó et al., 2002, 2009), and since microbial turnover of DMSP and DMS play a significant role in net DMS production, it is unsurprising that DMS concentrations have shown poor correlation with DMSP-producing phytoplankton groups in past experiments and open waters.

DMS concentrations have been reported lower under conditions of elevated fCO$_2$ compared to ambient controls, in both mesocosm experiments (Table 4) and phytoplankton monocultures (Arnold et al., 2013; Avgoustidi et al., 2012). However, the varying response of the community within each experiment or experiments limit our ability to generalise the response of algal production of DMS and DMSP in all situations due to the characteristic community dynamics of each experiment in specific geographical areas and temporal periods. Previous experiments in the temperate Raunefjord of Bergen, Norway, showed lower abundance of DMSP-producing algal species, and subsequently DMSP-dependent DMS concentrations (Avgoustidi et al., 2012; Hopkins et al., 2010; Vogt et al., 2008; Webb et al., 2015). In contrast mesocosm experiments in the Arctic and Korea have shown increased abundance of DMSP producers (Archer et al., 2013; Kim et al., 2010) but lower DMS concentrations, while incubation experiments by Hopkins and Archer (2014) showed lower DMSP production but higher DMS concentrations at high fCO$_2$. However, in all previous experiments with DMSP as the primary precursor of DMS, elevated fCO$_2$ had a less marked effect on measured DMSP concentrations than on measured DMS concentrations. Hopkins et al. (2010) suggested that ‘the perturbation of the system has a greater effect on the processes that control the conversion of DMSP to DMS rather than the initial production of DMSP itself’. This is relevant even for the current experiment, where DMSP was not identified, since processes controlling DMS concentrations were likely more affected by the change in fCO$_2$ than the production of precursors.

Previous mesocosm experiments have suggested significant links between increased bacterial production through greater availability of organic substrates at high fCO$_2$ (Engel et al., 2013; Piontek et al., 2013). Further, Endres et al. (2014) identified significant enhanced enzymatic hydrolysis of organic matter with increasing fCO$_2$, with higher bacterial abundance. Higher bacterial abundance will likely result in greater bacterial demand for sulphur, and therefore greater consumption of DMS and conversion to DMSO. This was suggested as a significant sink for DMS in a previous experiment (Webb et al., 2015), but during the present experiment, both bacterial abundance and bacterial production were lower at high fCO$_2$ (Hornick et al., 2016). However, as it has been proposed that only specialist bacterial groups are DMS consumers (Vila-Costa et al.,
2006b), and there is no determination of the DMS consumption characteristics of the bacterial community in the Baltic Sea, it is not known if this loss pathway is stimulated at this is still a potential stimulated DMS loss pathway at high f\textsubscript{CO}_2. As microbial DMS yields can vary between 5-40% depending on the sulphur and carbon demand (Kiene and Linn, 2000), a change in the bacterial sulphur requirements could change DMS turnover despite lower abundance. *Synechococcus* has been identified as a DMS consumer in the open ocean, but abundance of this group was negatively correlated with f\textsubscript{CO}_2, implying that DMS consumption by this group would have been lower as f\textsubscript{CO}_2 increased.

### 3.3 Iodocarbons in the mesocosms and relationships with community composition

Elevated f\textsubscript{CO}_2 did not affect the concentration of iodocarbons in the mesocosms significantly at any time during the experiment, which is in agreement with the findings of Hopkins *et al.* (2013) in the Arctic, but in contrast to Hopkins *et al.* (2010) and Webb (2015), where iodocarbons were measured significantly lower under elevated f\textsubscript{CO}_2 (Table 4). Concentrations of all iodocarbons measured in the mesocosms and the Baltic Sea fall within the range of those measured previously in the region (Table 5). Mesocosm concentrations of CH\textsubscript{3}I (Fig. 34a) and C\textsubscript{2}H\textsubscript{5}I (Fig. 34b) showed concentration ranges of 2.91 to 6.25 and 0.23 to 0.76 pmol L\textsuperscript{-1} respectively. CH\textsubscript{3}I showed a slight increase in all mesocosms during Phase I, peaking on t16 which corresponded with higher Chl-\textalpha concentrations, and correlated throughout the entire experiment with picoeukaryote groups II (\textrho=0.59, p<0.01) and III (\textrho=0.23, p<0.01; Crawfurd *et al.*, [this issue]2016) and nanoeukaryotes I (\textrho=0.37, p<0.01). Significant differences identified between mesocosms for CH\textsubscript{3}I were unrelated to elevated f\textsubscript{CO}_2 (F=3.1, p<0.05), but concentrations were on average 15% higher in Phase II than Phase I. C\textsubscript{2}H\textsubscript{5}I decreased slightly during Phases I and II, although concentrations of this halocarbon were close to its detection limit (0.2 pmol L\textsuperscript{-1}), remaining below 1 pmol L\textsuperscript{-1} at all times. As this compound showed no significant effect of elevated f\textsubscript{CO}_2, and was identified by Orlikowska and Schulz-Bull (2009) as having extremely low concentrations in the Baltic Sea (Table 5), it will not be discussed further.

No correlation was found between CH\textsubscript{3}I and Chl-\textalpha at any phase, and the only correlation of any phytoplankton grouping was with nanoeukaryotes II (\textrho=0.88, p<0.01; Crawfurd *et al.*, 2015\textsuperscript{b}). These CH\textsubscript{3}I concentrations compare well to the 7.5 pmol L\textsuperscript{-1} measured by Karlsson *et al.* (2008) during a cyanobacterial bloom in the Baltic Sea (Table 5), and the summer maximum of 16 pmol L\textsuperscript{-1} identified by Orlikowska and Schulz-Bull (2009).
Karlsson et al. (2008) showed Baltic Sea halocarbon production occurring predominately during daylight hours, with concentrations at night decreasing by 70% compared to late afternoon. Light dependent production of CH$_3$I has been shown to take place through abiotic processes, including radical recombination of CH$_3$ and I (Moore and Zafiriou, 1994). However, since samples were integrated over the surface 10m of the water column, it was impossible to determine if photochemistry was affecting iodocarbon concentrations near the surface where some UV light was able to pass between the top of the mesocosm film material and the cover. For the same reason, photodegradation of halocarbons (Zika et al., 1984) within the mesocosms was also likely to have been significantly restricted. Thus, as photochemical production was expected to be minimal, biogenic production was likely to have been the dominant source of these compounds. Karlsson et al. (2008) identified Pseudanabaena as a key producer of CH$_3$I in the Baltic Sea. However, the abundance of Pseudanabaena was highest during Phase I of the experiment (A. Stuhr, Pers. Comm.) when CH$_3$I concentrations were lower, and as discussed previously, the abundance of these species constituted only a very small proportion of the community. Previous investigations in the laboratory have identified diatoms as significant producers of CH$_3$I (Hughes et al., 2013; Manley and De La Cuesta, 1997), and the low, steady-state abundance of the diatom populations in the mesocosms could have produced the same relatively steady-state trends in the iodocarbon concentrations.

Measured in the range 57.2 – 202.2 pmol L$^{-1}$ in the mesocosms, CH$_3$I$_2$ (Fig. 34c) showed the clearest increase in concentration during Phase II, when it peaked on t21 in all mesocosms, with a maximum of 202.2 pmol L$^{-1}$ in M5 (348 μatm). During Phase II, concentrations of CH$_3$I$_2$ were 57% higher than Phase I, and were therefore negatively correlated with Chl-α. The peak on t21 corresponds with the peak identified in DMS on t21, and concentrations through all three phases correlate with picoeukaryotes II ($\rho=0.62$, p<0.01) and III ($\rho=0.47$, p<0.01) and nanoeukaryotes I ($\rho=0.88$, p<0.01; Crawfurd et al., 2015). CH$_2$I (Fig. 34d) showed no peaks during either Phase I or Phase II, remaining within the range 3.81 to 8.03 pmol L$^{-1}$, and again correlated with picoeukaryotes groups II ($\rho=0.34$, p<0.01) and III ($\rho=0.38$, p<0.01). These results may suggest that these groups possessed halo-peroxidase enzymes able to oxidise I, most likely as an anti-oxidant mechanism within the cell to remove H$_2$O$_2$ (Butler and Carter-Franklin, 2004; Pedersen et al., 1996; Theiler et al., 1978). However, given the lack of response of these compounds to elevated fCO$_2$ ($F=1.7$, p<0.01), it is unlikely that production was increased in relation to elevated fCO$_2$. Production of all iodocarbons increased during Phase II when total Chl-α decreased, particularly after the walls of the mesocosms were cleaned for the first time, releasing significant volumes of organic
aggregates into the water column. Aggregates have been suggested as a source of CH$_2$I and C$_2$H$_5$I (Hughes et al., 2008), likely through the alkylation of inorganic iodide (Urhahn and Ballschmiter, 1998) or through the breakdown of organic matter by microbial activity to supply the precursors required for iodocarbon production (Smith et al., 1992). Hughes et al. (2008) did not identify this route as a pathway for CH$_2$I$_2$ or CH$_2$ClI production, but Carpenter et al. (2005) suggested a production pathway for these compounds through the reaction of HOI with aggregated organic materials.

3.4 Bromocarbons in the mesocosms and the relationships with community composition

No effect of elevated fCO$_2$ was identified for any of the three bromocarbons, which compared with the findings from previous mesocosms where bromocarbons were studied (Hopkins et al., 2010, 2013; Webb, 2015; Table 4). Measured concentrations were comparable to those of Orlikowska and Schulz-Bull (2009) and Karlsson et al. (2008) measured in the Southern part of the Baltic Sea (Table 3). The concentrations of CHBr$_3$, CH$_2$Br$_2$ and CHBr$_2$Cl showed no major peaks of production in the mesocosms. CHBr$_3$ (Fig. 4a) decreased rapidly in all mesocosms over Phase 0 from a maximum measured concentration of 147.5 pmol L$^{-1}$ in M1 (mean of 138.3 pmol L$^{-1}$ in all mesocosms) to a mean of 85.7 ($\pm$ 8.2 s.d.) pmol L$^{-1}$ in all mesocosms for the period t0 to t31 (Phases I and II). The steady-state CHBr$_3$ concentrations indicated a production source, however there was no clear correlation with any measured algal groups. CH$_2$Br$_2$ concentrations (Fig. 5b) decreased steadily in all mesocosms from t-3 through to t31, over the range 4.0 to 7.7 pmol L$^{-1}$, and CHBr$_2$Cl followed a similar trend in the range 1.7 to 4.7 pmol L$^{-1}$ (Fig. 5c). Of the three bromocarbons, only CH$_2$Br$_2$ showed correlation with total Chl-a ($\rho$=0.52, p<0.01), and with cryptophyte ($\rho$=0.86, p<0.01) and dinoflagellate ($\rho$=0.65, p<0.01) derived Chl-a. Concentrations of CH$_2$BrI were below detection limit for the entire experiment.

CH$_2$Br$_2$ showed positive correlation with Chl-a ($\rho$=0.52, p<0.01), nanoeukaryotes II ($\rho$=0.34, p<0.01) and cryptophytes ($\rho$=0.86, p<0.01; see supplementary material), whereas CHBr$_3$ and CHBr$_2$Cl showed very weak or no correlation with any indicators of algal biomass or primary production. Schall et al. (1997) have proposed that CHBr$_2$Cl is produced in seawater by the nucleophilic substitution of bromide by chloride in CHBr$_3$, which given the steady-state concentrations of CHBr$_3$ would explain the similar distribution of CHBr$_2$Cl concentrations. Production of all three bromocarbons was identified from large-size cyanobacteria such as *Aphanizomenon flos-aquae* by Karlsson et al. (2008), and in addition, significant correlations were
found in the Arabian Sea between the abundance of the cyanobacterium *Trichodesmium* and several bromocarbons (Roy et al., 2011), and the low abundance of such bacteria in the mesocosms would explain the low variation in bromocarbon concentrations through the experiment.

Halocarbon loss processes such as nucleophilic substitution (Moore, 2006), hydrolysis (Elliott and Rowland, 1995), sea-air exchange and microbial degradation are suggested as of greater importance than production of these compounds by specific algal groups, particularly given the relatively low growth rates and low net increase in total Chl-a. Hughes et al. (2013) identified bacterial inhibition of CHBr3 production in laboratory cultures of *Thalassiosira* diatoms, but that it was not subject to bacterial breakdown; which could explain the relative steady state of CHBr3 concentrations in the mesocosms. In contrast, significant bacterial degradation of CH2Br2 in the same experiments could explain the steady decrease in CH2Br2 concentrations seen in the mesocosms. Bacterial oxidation was also identified by Goodwin et al. (1998) as a significant sink for CH2Br2. As discussed for the iodocarbons, photolysis was unlikely due to the UV absorption of the mesocosm film, and limited UV exposure of the surface waters within the mesocosm due to the mesocosm cover. The ratio of CH2Br2 to CHBr3 was also unaffected by increased fCO2, staying within the range 0.04 to 0.08. This range in ratios is consistent with that calculated by Hughes et al. (2009) in the surface waters of an Antarctic depth profile, and attributed to higher sea-air flux of CHBr3 than CH2Br2 due to a greater concentrations gradient, despite the similar transfer velocities of the two compounds (Quack et al., 2007). Using cluster analysis in a time-series in the Baltic Sea, Orlikowska and Schulz-Bull (2009) identified both these compounds as originating from different sources and different pathways of production.

Macroalgal production would not have influenced the mesocosm concentrations after the bags were sealed due to the isolation from the coastal environment. However, macroalgal production into the water column prior to mesocosm installation, the higher bromocarbon concentrations identified in the mesocosms during Phase 0 may have originated from macroalgal sources (Klick, 1992; Leedham et al., 2013; Moore and Tokarczyk, 1993) prior to mesocosm closure, could account for the high initial concentrations with concentrations decreasing through the duration of the experiment via turnover and transfer to the atmosphere.
3.5 Natural variations in Baltic Sea fCO$_2$ and the effect on biogenic trace gases

3.5.1 Physical variation and community dynamics

Baltic Sea deep waters have high fCO$_2$ and subsequently lower pH (Schneider et al., 2002), and the influx to the surface waters surrounding the mesocosms resulted in fCO$_2$ increasing to 725 μatm on t31, close to the average fCO$_2$ of the third highest mesocosm (M6: 868 μatm). The input of upwelled water into the region mid-way through the experiment significantly altered the biogeochemical properties of the waters surrounding the mesocosms, and as a result it is inappropriate to directly compare the community structure and trace gas production of the Baltic Sea and the mesocosms. These conditions imply that pelagic communities in the Baltic Sea are regularly exposed to rapid changes in fCO$_2$ and the associated pH, as well as having communities associated with the elevated fCO$_2$ conditions. The changes in biological parameters and trace gas concentrations are therefore discussed here separately from the concentrations measured in the mesocosms.

Given the separation of the waters within the mesocosms, and the movement of water masses within the Baltic Sea, it is expected that phytoplankton population structure could be significantly different inside the mesocosms compared to the external waters. Chl-a followed the pattern of the mesocosms until t4, after which concentrations were significantly higher than any mesocosm, peaking at 6.48 μg L$^{-1}$ on t16, corresponding to the maximum Chl-a peak in the mesocosms and the maximum peak of temperature. As upwelled water intruded into the surface waters, the surface Chl-a was diluted with low Chl-a deep water: Chl-a in the surface 10m decreased from around t16 at the start of the upwelling until t31 when concentrations were once again equivalent to those found in the mesocosms at 1.30 μg L$^{-1}$. In addition, there was potential introduction of different algal groups to the surface, but chlorophytes and cryptophytes were the major contributors to the Chl-a in the Baltic Sea, as in the mesocosms. Cyanobacteria contributed less than 2% of the total Chl-a in the Baltic Sea (Crawfurd et al., 2016; Paul et al., 2015).

Temporal community dynamics in the Baltic Sea were very different to that in the mesocosms across the experiment, with euglenophytes, chlorophytes, diatoms and prasinophytes all showing distinct peaks at the start of Phase II, with these same peaks identified in the nanoeukaryotes I and II, and picoeukaryotes II (Crawfurd et al., 2016; Paul et al., 2015; Supplementary Figs. S1 and S2). The decrease in abundance of many groups during Phase II was attributed to the decrease in temperature and dilution with low-abundance deep waters.
3.5.2 DMS in the Baltic Sea

The Baltic Sea samples gave a mean DMS concentration of 4.6 ± 2.6 nmol L\(^{-1}\), but peaked at 11.2 nmol L\(^{-1}\) on t16, and were within the range of previous measurements for the region (Table 5). Strong correlations were seen between DMS and Chl-\(\alpha\) (\(\rho=0.84\), \(p<0.01\)), with the ratio of DMS: Chl-\(\alpha\) at 1.6 (± 0.3) nmol \(\mu\)g\(^{-1}\). Other strong correlations were seen with euglenophytes (\(\rho=0.89\), \(p<0.01\)), dinoflagellates (\(\rho=0.61\), \(p<0.05\)) and nanoeukaryotes II (\(\rho=0.88\), \(p<0.01\)), but no correlation was found between DMS and cyanobacterial abundance, or with picoeukaryotes III which was identified in the mesocosms, suggesting that DMS had a different origin in the Baltic Sea community than in the mesocosms. In addition, the community demands of sulphur are likely to be very different in the Baltic Sea compared to the mesocosms, due to differences in community composition and sulphur availability, and therefore direct comparisons with mesocosm concentrations are inappropriate. Once again, there was no DMSP detected in the samples.

As CO\(_2\) levels increased after t16 during Phase II, the DMS concentration measured in the Baltic Sea decreased, from the peak on t16 to the lowest recorded sample of the entire experiment at 1.85 nmol L\(^{-1}\) on t31. As with Chl-\(\alpha\), DMS concentrations in the surface of the Baltic Sea may have been diluted with low-DMS deep water, however, the inverse relationship of DMS with CO\(_2\)-shown in the mesocosms may suggest that this decrease in DMS is attributed to the increase in CO\(_2\)-levels. Bacterial abundance was similar in the Baltic Sea as in the mesocosms (Hornick et al., 2015), however the injection of high CO\(_2\)-water may have stimulated bacterial consumption of DMS during the upwelling, which combined with the dilution of DMS-rich surface water could have resulted in the rapid decrease in DMS concentrations. As no discernible decrease in total bacterial abundance was identified during the upwelling, it is also possible that the upwelled water contained a different microbial community, and may potentially have introduced a higher abundance of DMS-consuming microbes. No breakdown of bacterial distributions was available with which to test this hypothesis.

3.5.3 Halocarbon concentrations in the Baltic Sea

Outside the mesocosms in the Baltic Sea, CH\(_3\)I was measured at a maximum concentration of 8.65 pmol L\(^{-1}\), during Phase II, and showed limited effect of the upwelling event. Both CH\(_2\)I\(_2\) and CH\(_2\)ClI showed higher concentrations in the Baltic Sea samples than the mesocosms (CH\(_2\)I\(_2\): 373.9 pmol L\(^{-1}\) and CH\(_2\)ClI: 18.1 pmol L\(^{-1}\)), and were correlated with the euglenophytes (CH\(_2\)I\(_2\): \(\rho=0.63\), \(p<0.05\) and CH\(_2\)ClI: \(\rho=0.68\), \(p<0.01\)) and nanoeukaryotes II (CH\(_2\)I\(_2\): \(\rho=0.53\), \(p<0.01\) and CH\(_2\)ClI: \(\rho=0.58\), \(p<0.01\)), but no correlation with Chl-\(\alpha\). Both polyhalogenated compounds showed
correlation with picoeukaryote groups II and III, indicating that production was probably not limited to a single source. These concentrations of CH$_2$I$_2$ and CH$_2$ClII compared well to those measured over a macroalgal bed in the higher saline waters of the Kattegat by Klick and Abrahamsson (1992), suggesting that macroalgae were a significant iodocarbon source in the Baltic Sea. **Macroalgal production in the Baltic Sea is likely the predominant iodocarbon source, compared to the mesocosms where macroalgae are excluded.**

As with the iodocarbons, the Baltic Sea showed significantly higher concentrations of CHBr$_3$ (F=28.1, p<0.01), CH$_2$Br$_2$ (F=208.8, p<0.01) and CHBr$_2$Cl (F=23.5, p<0.01) than the mesocosms, with maximum concentrations 191.6 pmol L$^{-1}$, 10.0 pmol L$^{-1}$ and 5.0 pmol L$^{-1}$ respectively. In the Baltic Sea, only CHBr$_3$ was correlated with Chl-α ($\rho$=0.65, p<0.05), cyanobacteria ($\rho$=0.61, p<0.01; Paul et al., 2015) and nanoeukaryotes II ($\rho$=0.56, p<0.01; Crawfurd et al., 2015), with the other two bromocarbons showing little to no correlations with any parameter of community activity. Production of bromocarbons from macroalgal sources (Laturnus et al., 2000; Leedham et al., 2013; Manley et al., 1992) was likely a significant contributor to the concentrations detected in the Baltic Sea; over the macroalgal beds in the Kattegat, Klick (1992) measured concentrations an order of magnitude higher than seen in this experiment for CH$_2$Br$_2$ and CHBr$_2$Cl. **There was only a slight increase in bromocarbon concentrations as a result of the upwelling, indicating that the upwelled water had similar concentrations to the surface waters.** These data from the Baltic Sea are presented as an important time-series of halocarbon measurements during the summer of 2012, which are expected to add to existing Baltic Sea trace gas datasets.

4 **The Baltic Sea as a natural analogue to future ocean acidification?**

Mesocosm experiments are a highly valuable tool in assessing the potential impacts of elevated CO$_2$ on complex marine communities, however they are limited in that the rapid change in fCO$_2$ experienced by the community may not be representative of changes in the future ocean (Passow and Riebesell, 2005). This inherent problem with mesocosm experiments can be overcome through using naturally low pH/ high CO$_2$ areas such as upwelling regions or vent sites (Hall-Spencer et al., 2008), which can give an insight into populations already living and adapted/acclimated to high CO$_2$ regimes by exposure over timescales measured in years. This mesocosm experiment was performed at such a location with a relatively low-high fCO$_2$ excursion, however still low compared to some sites (800 μatm compared to >2000 μatm; Hall-Spencer et al., 2008), and it was clear through the minimal variation in Chl-α between all mesocosms that the community was relatively
unaffected by elevated $f$CO$_2$, although variation could be identified in some phytoplankton groups and some shifts in community composition. The upwelling event occurring mid-way through our experiment allowed comparison of the mesocosm findings with a natural analogue of the system, as well as showing the extent to which the system perturbation can occur (up to 800 μatm). This event was a fortuitous occurrence during this mesocosm experiment, but as the scale and timing of these upwelling events is difficult to determine, however, it is very difficult to determine where and when an upwelling will occur, and therefore these upwelling events are extremely challenging to study as natural high CO$_2$ analogues. Hard to utilise these events as natural high CO$_2$ analogues.

In this paper, we described the temporal changes in concentrations of DMS and halocarbons in natural Baltic phytoplankton communities exposed to elevated $f$CO$_2$ treatments. In contrast to the halocarbons, concentrations of DMS were significantly lower in the highest $f$CO$_2$ treatments compared to the control. Despite very different physicochemical and biological characteristics of the Baltic Sea (e.g. salinity, community composition and nutrient concentrations), this is a very similar outcome to that seen in several other high $f$CO$_2$ experiments. The Baltic Sea trace gas samples give a good record of trace gas production cycling during the injection of high $f$CO$_2$ deep water into the surface community during upwelling events. For the concentrations of halocarbons, no response the measured concentrations did not change during was shown to the upwelling event in the Baltic Sea, which may indicate that emissions of organic iodine and bromine are unlikely to change with future acidification of the Baltic Sea without significant alteration to the meteorological conditions. Further studies of these compounds are important to determine rates of production and consumption to include in prognostic and predictive models. However, net production of organic sulphur within the Baltic Sea region is likely to decrease with an acidified future ocean scenario, despite the possible acclimation of the microbial community to elevated $f$CO$_2$. This will potentially impact the flux of DMS to the atmosphere over Northern Europe, and could have significant impacts on the local climate through the reduction of atmospheric sulphur aerosols. Data from a previous mesocosm experiment has been used to estimate future global changes in DMS production, and predicted that global warming would be amplified (Six et al., 2013); utilising the data from this experiment combined with those of other mesocosm, field and laboratory experiments and associated modelling provide the basis for a better understanding of the future changes in global DMS production and their climatic impacts.
Acknowledgements

The Tvärminne 2012 mesocosm experiment was part of the SOPRAN II (Surface Ocean Processes in the Anthropocene) Programme (FKZ 03F0611) and BIOACID II (Biological Impacts of Ocean Acidification) project (FKZ 03F06550), funded by the German Ministry for Education and Research (BMBF) and led by the GEOMAR Helmholtz Centre for Ocean Research Kiel, Germany. The authors thank all participants in the SOPRAN Tvärminne experiment for their assistance, including A. Ludwig for logistical support, the diving team, and the staff of Tvärminne Zoological Research Station for hosting the experiment. We also acknowledge the captain and crew of RV ALKOR (AL394 and AL397) for their work transporting, deploying and recovering the mesocosms.

This work was funded by a UK Natural Environment Research Council Directed Research Studentship (NE/H025588/1) through the UK Ocean Acidification Research Programme, with CASE funding from Plymouth Marine Laboratory. Additional funding was supplied by the EU Seventh Framework Program (FP7/2007-2013) MESOAQUA (EC Contract No. 228224).


25


Table 1. Summary of \( f^2 \text{CO}_2 \) and pH\( _T \) (total scale) during phases 0, 1 and 2 of the mesocosm experiment.

<table>
<thead>
<tr>
<th>Mesocosm*</th>
<th>Target ( f^2 \text{CO}_2 ) (µatm)</th>
<th>Mean ( f^2 \text{CO}_2 ) (µatm)</th>
<th>Mean pH( _T )</th>
<th>Mean ( f^2 \text{CO}_2 ) (µatm)</th>
<th>Mean pH( _T )</th>
<th>Mean ( f^2 \text{CO}_2 ) (µatm)</th>
<th>Mean pH( _T )</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>Control</td>
<td>331</td>
<td>7.91</td>
<td>231</td>
<td>8.00</td>
<td>328</td>
<td>7.95</td>
</tr>
<tr>
<td>M5</td>
<td>Control</td>
<td>334</td>
<td>7.91</td>
<td>244</td>
<td>7.98</td>
<td>329</td>
<td>7.94</td>
</tr>
<tr>
<td>M7</td>
<td>390</td>
<td>458</td>
<td>7.80</td>
<td>239</td>
<td>7.99</td>
<td>494</td>
<td>7.81</td>
</tr>
<tr>
<td>M6</td>
<td>840</td>
<td>773</td>
<td>7.63</td>
<td>236</td>
<td>7.99</td>
<td>932</td>
<td>7.59</td>
</tr>
<tr>
<td>M3</td>
<td>1120</td>
<td>950</td>
<td>7.56</td>
<td>243</td>
<td>7.98</td>
<td>1176</td>
<td>7.51</td>
</tr>
<tr>
<td>M8</td>
<td>1400</td>
<td>1166</td>
<td>7.49</td>
<td>232</td>
<td>8.00</td>
<td>1481</td>
<td>7.43</td>
</tr>
<tr>
<td>Baltic Sea</td>
<td>380</td>
<td>350</td>
<td>7.91</td>
<td>298</td>
<td>7.91</td>
<td>277</td>
<td>7.98</td>
</tr>
</tbody>
</table>

a listed in order of increasing \( f^2 \text{CO}_2 \)
Table 2. Calibration ranges and calculated percentage mean relative standard error for the trace gases measured in the mesocosms.

<table>
<thead>
<tr>
<th>Compound</th>
<th>Calibration range (pmol L(^{-1}))</th>
<th>% Mean relative standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>DMS</td>
<td>600 – 29300*</td>
<td>6.33</td>
</tr>
<tr>
<td>DMSP</td>
<td>2030 – 405900*</td>
<td></td>
</tr>
<tr>
<td>CH(_3)I</td>
<td>0.11 – 11.2</td>
<td>4.62</td>
</tr>
<tr>
<td>CH(_2)I</td>
<td>5.61 – 561.0</td>
<td>4.98</td>
</tr>
<tr>
<td>C(_2)H(_2)I</td>
<td>0.10 – 4.91</td>
<td>5.61</td>
</tr>
<tr>
<td>CH(_2)Cl</td>
<td>1.98 – 99.0</td>
<td>3.64</td>
</tr>
<tr>
<td>CHBr(_2)</td>
<td>8.61 – 816.0</td>
<td>4.03</td>
</tr>
<tr>
<td>CHBr(_2)Cl</td>
<td>0.21 – 20.9</td>
<td>5.30</td>
</tr>
</tbody>
</table>

* throughout the rest of this paper, these measurements are given in nmol L\(^{-1}\).

32
Table 3. Abundance and contributions of different phytoplankton groups to the total phytoplankton community assemblage, showing the range of measurements from total Chl-α (Paul et al., 2015), CHEM_TAX analysis of derived Chl-α (Paul et al., 2015) and phytoplankton abundance (Crawford et al., 2016). Data are split into the range of all the mesocosm measurements and those from the Baltic Sea.

<table>
<thead>
<tr>
<th>Phytoplankton Taxonomy (Equivalent Chlorophyll µg L⁻¹)</th>
<th>Mesocosm Integrated 10 m</th>
<th>Mesocosm Integrated 17 m</th>
<th>% Contribution to Chl-α</th>
<th>Baltic Sea Integrated 10 m</th>
<th>Baltic Sea Integrated 17 m</th>
<th>% Contribution to Chl-α</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chl-α</td>
<td>0.9 – 2.9</td>
<td>0.9 – 2.6</td>
<td>100</td>
<td>1.3 – 6.5</td>
<td>1.12 – 5.5</td>
<td>100</td>
</tr>
<tr>
<td>Cyanobacteria</td>
<td>0.01 – 0.4</td>
<td>8</td>
<td>0.0 – 0.1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prasinophytes</td>
<td>0.04 – 0.3</td>
<td>7</td>
<td>0.01 – 0.3</td>
<td>4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Euglenophytes</td>
<td>0.0 – 1.6</td>
<td>15</td>
<td>0.0 – 2.6</td>
<td>21</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dinoflagellates</td>
<td>0.0 – 0.3</td>
<td>3</td>
<td>0.04 – 0.6</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Diatoms</td>
<td>0.1 – 0.3</td>
<td>7</td>
<td>0.04 – 0.9</td>
<td>9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Chlorophytes</td>
<td>0.3 – 2.0</td>
<td>40</td>
<td>0.28 – 3.1</td>
<td>41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cryptophytes</td>
<td>0.1 – 1.4</td>
<td>21</td>
<td>0.1 – 1.0</td>
<td>15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Small Phytoplankton (&lt;10 µm) abundance (cells mL⁻¹)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cyanobacteria</td>
<td>55000 – 380000</td>
<td>65000 – 470000</td>
<td>30000 – 180000</td>
<td>30000 – 250000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Picoeukaryotes I</td>
<td>15000 – 100000</td>
<td>17000 – 110000</td>
<td>5000 – 70000</td>
<td>6100 – 78000</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Picoeukaryotes II</td>
<td>700 – 4000</td>
<td>600 – 4000</td>
<td>400 – 3000</td>
<td>460 – 3700</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Picoeukaryotes III</td>
<td>1000 - 9000</td>
<td>1100 – 8500</td>
<td>1000 – 6900</td>
<td>950 – 7500</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nanoeukaryotes I</td>
<td>400 – 1400</td>
<td>270 – 1500</td>
<td>200 – 4000</td>
<td>210 – 4100</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nanoeukaryotes II</td>
<td>0 – 400</td>
<td>4 – 400</td>
<td>100 – 1100</td>
<td>60 – 1300</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4. Concentration ranges of trace gases measured in the mesocosms compared to other open water ocean acidification experiments, showing the range of concentrations for each gas and the percentage change between the control and the highest fCO₂ treatment.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Range fCO₂ (μatm)</th>
<th>DMS (nmol L⁻¹)</th>
<th>CH₃I</th>
<th>CH₂I₂</th>
<th>CH₂Cl₂</th>
<th>CHBr₃</th>
<th>CH₂Br₂</th>
<th>CH₂Br₂Cl₃</th>
</tr>
</thead>
<tbody>
<tr>
<td>SOPRAN Tvärmme Mesocosm (this study)</td>
<td>346 – 1333</td>
<td>2.7-6.8</td>
<td>2.9-6.4</td>
<td>57-202</td>
<td>3.8-8.0</td>
<td>69-148</td>
<td>4.0-7.7</td>
<td>1.7-3.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>% change</td>
<td>-34</td>
<td>-0.3</td>
<td>1.3</td>
<td>-11</td>
<td>-9</td>
<td>-3</td>
</tr>
<tr>
<td>SOPRAN Bergen 2011 (Webb et al., 2015)</td>
<td>280 – 3000</td>
<td>0.1-4.9</td>
<td>4.9-32</td>
<td>5.8-321</td>
<td>9.0-123</td>
<td>64-306</td>
<td>6.3-30.8</td>
<td>3.9-14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>% change</td>
<td>-60</td>
<td>-37</td>
<td>-48</td>
<td>-27</td>
<td>-2</td>
<td>-4</td>
</tr>
<tr>
<td>NERC Microbial Metagenomics Experiment, Bergen 2006 (Hopkins et al., 2010)</td>
<td>300 - 750</td>
<td>ND-50</td>
<td>2.0-25</td>
<td>ND-750</td>
<td>ND-700</td>
<td>5.0-80</td>
<td>ND-5.5</td>
<td>0.2-1.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>% change</td>
<td>-57</td>
<td>-41</td>
<td>-33</td>
<td>-28</td>
<td>13</td>
<td>8</td>
</tr>
<tr>
<td>EPOCA Svalbard 2010 (Archer et al., 2013; Hopkins et al., 2013)</td>
<td>180 - 1420</td>
<td>ND-14</td>
<td>0.04-10</td>
<td>0.01-2.5</td>
<td>0.3-1.6</td>
<td>35-151</td>
<td>6.3-33.3</td>
<td>1.6-4.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>% change</td>
<td>-60</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
<td>NS</td>
</tr>
<tr>
<td>UKOA European Shelf 2011 (Hopkins and Archer, 2014)</td>
<td>340 - 1000</td>
<td>0.5-12</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>% change</td>
<td>225</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Korean Mesocosm Experiment 2012 (Park et al., 2014)</td>
<td>160 - 830</td>
<td>1.0-100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>% change</td>
<td>-82</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 5. Concentration ranges of trace gases measured in the Baltic Sea compared to concentrations measured in the literature. ND – Not Detected.

<table>
<thead>
<tr>
<th>Study</th>
<th>DMS concentration range (nmol L⁻¹)</th>
<th>Halocarbon concentration range (pmol L⁻¹)</th>
<th>Halocarbon concentration range (pmol L⁻¹)</th>
<th>Halocarbon concentration range (pmol L⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CH₃I</td>
<td>CH₂I₂</td>
<td>C₂H₃I</td>
<td>CH₃Cl</td>
</tr>
<tr>
<td>SOPRAN Tvärminne Baltic Sea (This Study)</td>
<td>1.9-11</td>
<td>4.3-8.6</td>
<td>66.9-374</td>
<td>0.6 – 1.0</td>
</tr>
<tr>
<td>Orlikowska and Schulz-Bull (2009)</td>
<td>0.3-120</td>
<td>1-16</td>
<td>0.4 – 1.2</td>
<td>5-50</td>
</tr>
<tr>
<td>Karlsson et al. (2008)</td>
<td>3.0-7.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klick and Abrahamsson (1992)</td>
<td>15-709</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Klick (1992)</td>
<td>ND-243</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leck and Rodhe (1991)</td>
<td>0.4-2.8</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leck et al. (1990)</td>
<td>ND-3.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Figure 1. Daily measurements of (a) $f$CO$_2$, (b) mean temperature and (c) total Chlorophyll-$\alpha$ in the mesocosms and surrounding Baltic Sea waters. Dashed lines represent the three Phases of the experiment, based on the Chl-$\alpha$ data.
Figure 2. (a) Mean DMS concentrations measured daily in the mesocosms and Baltic Sea from an integrated water sample of the surface 10 m integrated from the surface 10 m. Dashed lines show the Phases of the experiment as given in Fig. 1. fCO$_2$ shown in the legend are mean fCO$_2$ across the duration of the experiment. (b) Mean DMS concentrations from each mesocosm during Phase I (crosses) and Phase II (diamonds), for ambient (blue), medium (grey) and high fCO$_2$ (red), with error bars showing the range of both the DMS and fCO$_2$. 

37
Figure 3. Mean concentrations (pmol L⁻¹) of (a) CH₃I, (b) C₂H₅I, (c) CH₂I₂ and (d) CH₂ClI taken from a water sample integrated from the surface 10m. Dashed lines indicate the Phases of the experiment, as given in Fig. 2. fCO₂ shown in the legend are mean fCO₂ across the duration of the experiment.
Figure 5. Mean concentrations (pmol L$^{-1}$) of (a) CHBr$_3$, (b) CH$_2$Br$_2$ and (c) CHBr$_2$Cl taken from a water sample integrated from the surface 10m. Dashed lines indicate the phases of the experiment as defined in Fig. 2, fCO$_2$ shown in the legend are mean fCO$_2$ across the duration of the experiment.