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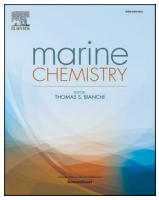

Oxidation of iodide to iodate by cultures of marine ammonia-oxidising bacteria

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A B S T R A C T

Reaction with iodide (I^-) at the sea surface is an important sink for atmospheric ozone, and causes sea-air emission of reactive iodine which in turn drives further ozone destruction. To incorporate this process into chemical transport models, improved understanding of the factors controlling marine iodine speciation, and especially sea-surface iodide concentrations, is needed. The oxidation of I^- to iodate (IO_3^-) is the main sink for oceanic I^-, but the mechanism for this remains unknown. We demonstrate for the first time that marine nitrifying bacteria mediate I^- oxidation to IO_3^-. A significant increase in IO_3^- concentrations compared to media-only controls was observed in cultures of the ammonia-oxidising bacteria *Nitrosomonas* sp. (Nm51) and *Nitrosoccocus oceani* (Nc10) supplied with 9–10 mM I^-, indicating I^- oxidation to IO_3^-. Cell-normalised production rates were 15.69 (±4.71) fmol IO_3^- cell^{-1} d^{-1} for *Nitrosomonas* sp., and 11.96 (±6.96) fmol IO_3^- cell^{-1} d^{-1} for *Nitrosococcus oceani*, and molar ratios of iodate-to-nitrite production were 9.2 ± 4.1 and 1.88 ± 0.91 respectively. Preliminary experiments on nitrite-oxidising bacteria showed no evidence of I^- to IO_3^- oxidation. If the link between ammonia and I^- oxidation observed here is representative, our ocean iodine cycling model predicts that future changes in marine nitrification could alter global sea surface I^- fields with potential implications for atmospheric chemistry and air quality.

1. Introduction

Iodine plays an important role in catalytic ozone destruction and new particle formation in the troposphere, thereby impacting the oxidative capacity of the atmosphere (Sherwen et al., 2016) and the Earth's radiation balance (O'Dowd et al., 2002). Sea-to-air iodine transfer is known to be the main source of iodine to the atmosphere (Carpenter, 2003; Sherwen et al., 2016). Reactive inorganic iodine (I_2, HOI) emissions resulting from the reaction of gas-phase ozone with sea surface iodide (I^-) is now thought to be the dominant mechanism mediating sea-air iodine emissions (Carpenter et al., 2013). The strength of the surface reactive iodine flux is related to sea surface I^- concentrations (Carpenter et al., 2013) so knowledge of ocean I^- distributions is required in order to estimate the significance of this process. Furthermore, a detailed understanding of the processes controlling inorganic iodine speciation is needed to allow us to develop predictive capacity regarding sea surface I^-, ozone-deposition rates and sea-air emission of reactive iodine.

Total inorganic iodine is found at 400–500 nM in seawater and predominantly exists as iodate (IO_3^-) and I^- (Chance et al., 2014) with inter-conversion between these two species alongside physical mixing being the main causes of spatial and temporal variability in sea surface I^-. Iodate is the thermodynamically stable form and the dominant form in the deep ocean. The existence of relatively higher levels of I^- in the euphotic zone (reviewed by Chance et al., 2014) has led to the suggestion that IO_3^- reduction to I^- is linked to primary productivity. This theory has been supported by observations of I^- production in cultures of a wide range of marine phytoplankton (e.g. Chance et al., 2007; Bluhm et al., 2010; Hepach et al., 2020) and some field studies (Chance et al., 2010). The mechanism of biogenic iodate reduction to iodide is not yet known, but may be related to senescence processes (Bluhm et al., 2010; Hepach et al., 2020; Carrano et al., 2020). Reduction of IO_3^- to I^- by phytoplankton nitrate reductase enzymes (Hung et al., 2005), or

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macroalgal cell surface reductases (Carrano et al., 2020), has also been suggested but neither has been confirmed as a significant route of conversion.

Oxidation of I^- back to IO_3^- is the dominant sink for I-, but is a relatively slow reaction with rate estimates ranging from ~4 to 670 nM yr^{-1} (Chance et al., 2014; Hardisty et al., 2020). The rates and processes involved in I^- to IO_3^- oxidation are associated with large uncertainty (Truesdale et al., 2001; Amachi, 2008), and the mechanisms involved remain undefined. This uncertainty has been suggested to be one of the factors hindering the development of mathematical models of iodine transformations in the global oceans (Truesdale et al., 2001). Abiotic oxidation of I^- back to IO_3^- in the ocean (e.g. by oxygen, hydroxyl radicals, hydrogen peroxide and ozone) is thought to occur so slowly as to be insignificant (e.g. Wong, 1991), and so I^- oxidation to IO_3^- is also thought to be associated with marine microbiological activity. I^- oxidation to I_2 has been observed in bacterial isolates obtained from a range of environments including seawater aquaria (Gozlan, 1968), natural gas brines (Iino et al., 2016) and seawater/marine mud (Fuse et al., 2003). Additionally, based on field observations, a number of studies (Truesdale et al., 2001; Zic et al., 2013) have proposed that I^- oxidation to IO_3^- is linked to nitrification in marine systems. Nitrification is the two-stage biological transformation of ammonia (NH_3) to nitrate (NO_3^-) (Eqs. 1 and 2; Koops and Pommerening-Röser, 2001) mediated by chemoautotrophic ammonia-oxidising bacteria (AOB), and nitrite-oxidising bacteria (NOB). Previously thought to only occur outside of the euphotic zone, nitrification is now known to occur throughout the oceanic water-column (reviewed by Yool et al., 2007).

$$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O \quad (1)$$

$$2NO_2^- + O_2 \rightarrow 2NO_3^- \quad (2)$$

A link between I^- oxidation/ IO_3^- production and nitrification is yet to be confirmed but, if established, would suggest that I^- oxidation to IO_3^- is widespread throughout the world's oceans (Yool et al., 2007).

The primary aim of this study was to establish whether I^- oxidation to IO_3^- is associated with marine nitrification. Our objectives were to determine if IO_3^- production occurs in cultures of marine ammonia- and nitrite-oxidising bacteria supplied with I^-, determine the relative rates of IO_3^- production and nitrification and explore the possible implications of the findings.

2. Methods

2.1. Cultures

Stock bacterial cultures were taken from the existing culture collections of the authors. Two marine AOB cultures, *Nitrosomonas* sp. Nm51 (C-15) and *Nitrosococcus oceani* Nc10 (C-107, ATCC 19707) were investigated for IO_3^- production in the presence of I^- as the only iodine source. These strains were originally isolated from seawater in the south Pacific and the north Atlantic respectively (Watson and Mandel, 1971). Cultures were grown in the dark in a water bath at 25 °C in autoclaved ESAW artificial seawater mixture (Berges et al., 2001) made up using distilled water. The ESAW media was supplemented with 7–8 mM ammonium chloride and potassium phosphate. We also conducted preliminary tests on three active marine NOB: *Nitrospira marina* Nb-295 (isolated from Gulf of Maine, Watson et al., 1986); *Nitrospina gracilis* 3/211 (isolated from the south Atlantic, Watson and Waterbury, 1971); *Nitrococcus mobilis* Nb-231 (ATCC 25380, isolated from Galapagos seawater, Watson and Waterbury, 1971). However we saw no evidence of IO_3^- production in any of the NOB cultures studied and these results are not discussed further. Handling of cultures was done at all times in a biosafety cabinet using sterile equipment.

2.2. Experimental set up

For the AOB experiments triplicate cultures were incubated alongside triplicate media-only controls for periods of 8–12 days. The experiments were kept as short as possible to avoid significant changes in pH in the bulk media which would impact inorganic iodine speciation. Hence experiments were only run until an increase in nitrite across two time-points was observed. Samples were taken at regular intervals of between 1 and 6 days for pH measurement, cell counts and determination of NO_2^-, IO_3^-, I^- and NH_4^+/NH_3 concentrations. In all cases, I^- (Aristar) was added to be at similar concentrations with the NH_4^+ required in the growth media. The levels of I^- are much higher than those encountered in the oceans (global ocean median = 77 nM I^- [interquartile range 28–140 nM], Chance et al., 2014) but were chosen to be similar to the levels of NH_4^+. This is because in the marine environment nitrifiers would be exposed to similar ratio of NH_4^+ and I^-. For example, Rees et al. (2006) show that NH_4^+/NH_3 occurs at concentrations ranging from 60 to 300 nM in the Atlantic between 60°N to 50°S.

2.3. pH

A spectrophotometric method using a Lambda 25 UV/Vis spectrophotometer (Perkin-Elmer) and m-cresol purple dye (Dickson et al., 2007) with measurements at 730, 578 and 434 nm was used to determine pH in the cultures and media-only controls. Salinity, needed for the pH calculation, was calculated from conductivity measured using a calibrated Hanna Instruments hand-held probe.

2.4. Cell counts

Immediately after sampling, 4 mL of the culture was fixed with 15 μL of 50% glutaraldehyde (Alfa Aesar), flash frozen in liquid nitrogen and placed in a − 80 °C freezer for later determination of cell density. Cell counts were made using a Beckman Coulter Cytoflex S flow cytometer (flow rate of 10 μL min^{-1}) within 2 months of collection. DAPI (Sigma; 2 μg mL^{-1}) stained samples were excited by a laser at 405 nm and the emitted fluorescence detected using an avalanche photodiode detector with a reflective band pass filter 450/45. The flow cytometer thresholds were set using the 405 nm laser side scatter and the DAPI fluorescence signals.

2.5. Nitrite concentration

NO_2^- was measured in 0.45 μm (Millex) filtered samples using a spectrophotometric method (Lambda 25 UV/Vis spectrophotometer, Perkin-Elmer) developed by Norwitz and Keliher (1984). The method involves diazotizing nitrite with sulfanilamide (Fisher, analytical reagent grade) and coupling with N-1-naphthylethylenediamine dihydrochloride (Fisher, analytical reagent grade) to form a coloured azo dye which is measured spectrophotometrically at 540 nm. The method was calibrated using $NaNO_2$ standards (Fisher, analytical reagent grade) prepared in the ESAW-based media.

2.6. Iodate concentration

IO_3^- concentrations were measured in 0.45 μm (Millex) filtered samples using a manual version of the spectrophotometric (Lambda 25 UV/Vis spectrophotometer) method detailed in Truesdale and Spencer, 1974 and Jickells et al., 1988. Absorbance was measured at 350 nm. Strictly, this method determines all oxidised (0 to +5 oxidation state) forms of inorganic iodine, but in seawater derived media this is predominantly IO_3^-, and so will be referred to as IO_3^- iodate hereafter. The method was calibrated using potassium iodate (Aristar) standard solutions made up in ESAW.

Some validation and modification to the method was required due to the nature of our experimental set-up. Chapman and Liss (1977) show

that NO_2^- can interfere with spectrophotometric IO_3^- measurements (using sulfamic acid) at ambient seawater concentrations with a 15% error. Clearly significant interference would be an issue for our experiments where NO_2^- was being produced so we ran tests. We found that the presence of NO_2^- up to 10 μM had negligible impact on IO_3^- measurements (between 0.1 and 50 μM). We did however identify that the high starting concentration of I^- (~10 μM) in the culture media was problematic. The iodate analysis method comprises two steps: the first involves an initial absorbance reading after the addition of sulfamic acid; the second involves the addition of excess I^-. Under acidic conditions I^- reacts with IO_3^- to form I_2 (Eq. 3a) which reacts with excess I^- to form the coloured ion I_3^- (eq. 3b) that can be measured spectrophotometrically.

$$IO_3^- + 5I^- + 6H^+ \rightarrow 3I_2 + 3H_20 \quad (3a)$$

$$I_2 + I^- \rightarrow I_3^- \quad (3b)$$

The difference between the first and second absorbance readings is then used to calibrate the method. In the case of our experiments the media already contained excess I^- so the formation of I_2 and I_3^- was initiated as soon as the acid was added in the first step. Hence we calibrated the method based on a single absorbance reading obtained after acid and then additional I^- was added. Calibrations and standard checks revealed this approach did not have any impact on the quality of the data.

2.7. Ammonium concentration

NH_4^+ concentrations were measured in 0.45 μm (Millex) filtered samples with a Seal Analytical Autoanalyser 3 according to method G-109-93 rev. 10 (Seal Analytical) using sodium salicylate, dichloroisocyanuric acid and citrate buffer. The method was calibrated using standards ranging from 0 to 2 mg/L prepared from dilutions of a 1000 mg/L ammonium standard solution (Merck).

2.8. Iodide concentration

I^- concentrations were determined using a Dionex ICS-2000 ion chromatograph equipped with an EGC III KOH elugen cartridge, AG18 (2 × 50 mm) guard column, AS18 (2 × 250 mm) analytical column, ASRS 300 (2 mm) suppressor, DS6 heated conductivity cell and AS40 autosampler. Samples were diluted 100-fold with 18 MΩ deionised water for analysis and 5 μL was injected onto the ion chromatograph. Aqueous potassium hydroxide was used as the eluent at a flow rate of 0.25 mL min^{-1} with a gradient program starting from an initial concentration of 2 mM hydroxide (hold 1 min) to 20 mM at 18 min then to 41 mM at 19 min (hold 2 min) before returning to 2 mM. The I^- retention time was 19 min. The instrument was calibrated with matrix-matched standards ranging from 0 to 100 nM (I^-), prepared from dilutions of a 1000 mg/L iodide standard solution (Fisher Scientific) with 18 MΩ deionised water and containing a final concentration of 1% ESAW.

2.9. Data analysis

As in Guerrero and Jones (1996), the NH_4^+ oxidation rate is defined here as the rate of increase in NO_2^-. Similarly, we define the rate of I^- oxidation as the rate of increase in IO_3^-. This is appropriate as no other iodine species were supplied to the cultures and conversion between I^- and IO_3^- is known to be the main cause of variability in inorganic iodine speciation (Bluhm et al., 2010; Chance et al., 2014). Average NO_2^- and IO_3^- production rates were calculated for each replicate culture using Eq. 4.

$$\text{Production Rate (nM day} - 1) = \frac{(C_{end} - C_0)}{t} \quad (4)$$

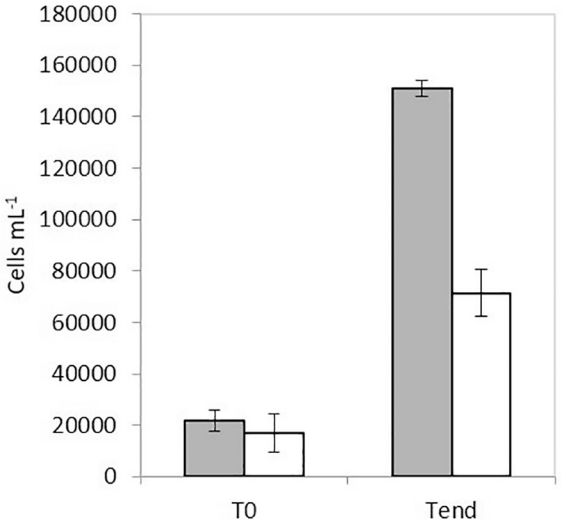

Fig. 1. Average cell number in the *Nitrosomonas* sp. (grey bars) and *Nitrosococcus oceani* (white bars) cultures used in this study at the start (T_0) and end (T_{end}; 8 days for *Nitrosomonas* sp. and 12 days for *Nitrosococcus oceani*) of each experiment. Error bars are standard deviations from three replicate cultures.

where C_0 and C_{end} are the NO_2^- or IO_3^- concentrations observed at the start and end of the experiment and t is the experimental duration in days. Cell-normalised rates were calculated by dividing these rates by the final cell density observed in each AOB culture and are hence likely to be minimum values.

3. Results

3.1. Cell counts and pH

Increases in cell density were observed in all replicates of *Nitrosomonas* sp. and *Nitrosococcus oceani* between the start and end of the experiment indicating growth (Fig. 1). Average initial cell density in the *Nitrosomonas* sp. cultures was 21,767 (±4046) cells mL^{-1} and this increased to 150,983 (±7585) cells mL^{-1} by the end of the experiment (8 days). For *Nitrosococcus oceani* start and end (12 days) cell densities were 16,947 (± 3098) and 71,430 (±9062) cells mL^{-1}, respectively. Average pH levels in the culture experiments calculated from measurements at each time point (data not shown) were 7.69 (±0.07) for *Nitrosomonas* sp. and 7.41 (±0.12) for *Nitrosococcus* sp. These pH levels are consistent with those found in the media-only controls (7.64 ± 0.07 for *Nitrosomonas* sp.; 7.64 ± 0.15 for *Nitrosococcus oceani*).

3.2. Iodine and nitrogen speciation

Fig. 2 shows that significant increases in the concentrations of IO_3^- (compared to media-only controls) were observed alongside NO_2^- production in both AOB cultures studied. In *Nitrosomonas* sp. (Fig. 2ai and bi) there was a steady increase in IO_3^- concentrations throughout the experiment reaching a maximum of 19,921 (±4754) nM by the end of the experiment (day 8). In contrast NO_2^- concentrations reached a maximum of 2360 (±386) nM by day 6 and remained at around that level until the end of the experiment. In *Nitrosococcus oceani* (Fig. 2aii and bii) IO_3^- concentrations increased rapidly during the initial stages of the experiment reaching 23, 943 (±8568) nM by day 6. IO_3^- concentrations at the end of the experiment (day 12) were 16,365 (±7603) nM. NO_2^- concentrations increased gradually throughout the experiment reaching 5547 (±1251) nM by day 12. There was larger variability in IO_3^- concentrations between replicates for *Nitrosococcus oceani* but despite this a clear increase in all replicates was observed.

Average production rates of IO_3^- and NO_2^- are presented in Table 1. In

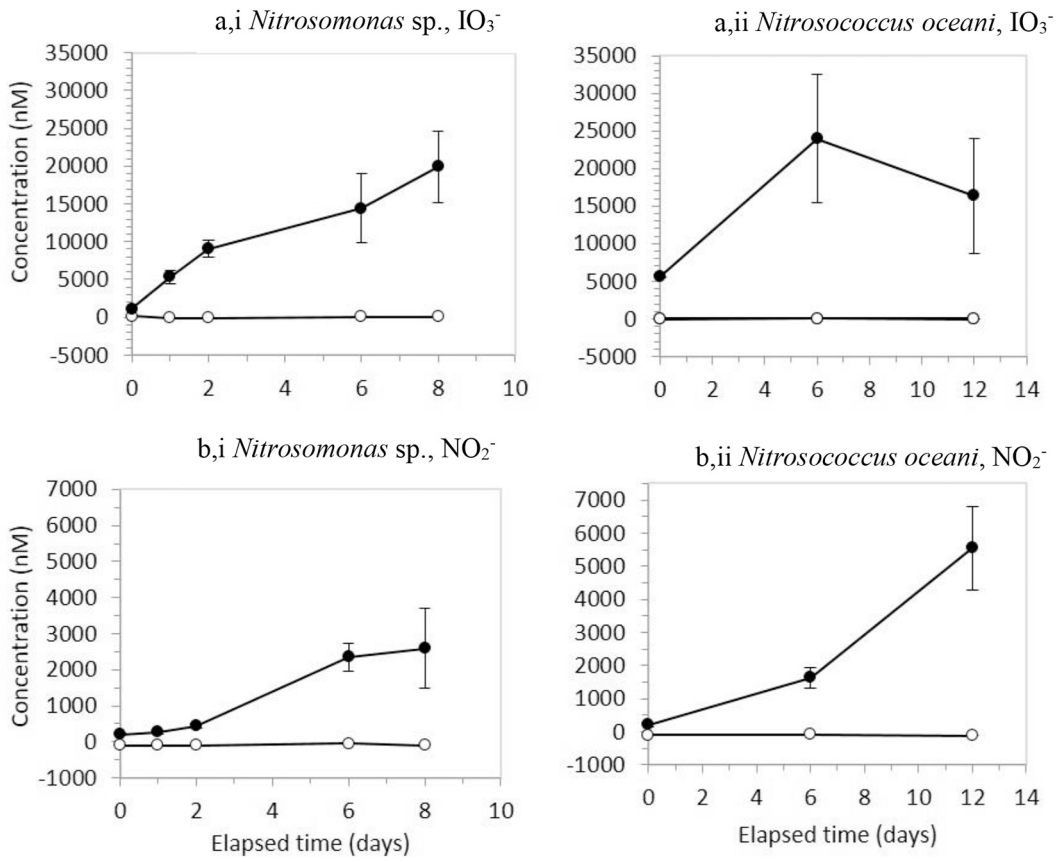

Fig. 2. Changes in iodate (a) and nitrite (b) concentrations in cultures (closed symbols) and media-only controls (open symbols) for two cultures of ammonia-oxidising bacteria: i) *Nitrosomonas* sp.; and, ii) *Nitrosococcus oceani* supplied with 9–10 mM iodide and 7–8 mM NH_4^+. Error bars show the standard deviation of three replicate cultures.

Table 1
Nitrite and iodate production rates (± standard deviations) observed in cultures of the ammonia-oxidising bacteria *Nitrosomonas* sp. and *Nitrosococcus oceani*. Cell-normalised values are a minimum as they are calculated using maximum cell densities.

	Nitrite		Iodate	
Culture	nM day^{-1}	fmol $cell^{-1}$ day^{-1}	nM day^{-1}	fmol $cell^{-1}$ day^{-1}
Nitrosomonas sp.	298 (±141)	1.96 (±0.88)	2348 (±593)	15.69 (±4.71)
Nitrosococcus oceani	445 (±99)	6.19 (±0.56)	897 (±640)	11.96 (±6.96)

Nitrosomonas sp. average rates (±standard deviation) were 2348 (±593) nM IO_3^- day^{-1} and 298 (±141) nM NO_2^- day^{-1}. In *Nitrosococcus oceani* averages rates were 897 (±640) nM IO_3^- day^{-1} and 445 (±99) nM NO_2^- day^{-1}. Minimum cell-normalised rates (based on the final cell density observed in each culture) were 15.69 (±4.71) fmol IO_3^- $cell^{-1}$ day^{-1} and 1.96 (±0.88) fmol NO_2^- $cell^{-1}$ day^{-1} for *Nitrosomonas* sp., and 11.96 (±6.96) fmol IO_3^- $cell^{-1}$ day^{-1} and 6.19 (±0.56) fmol NO_2^- $cell^{-1}$ day^{-1} for *Nitrosococcus oceani*. Molar ratios of iodate-to-nitrite production were 9.2 ± 4.0 for *Nitrosomonas* sp. and 1.88 ± 0.91 for *Nitrosococcus oceani*.

Fig. 3 shows that, within error, a decline in I^- or NH_4^+ concentrations was not observed during either of the AOB experiments. Average starting I^- or NH_4^+ concentrations in *Nitrosomonas* sp. were 9.8 (±0.2) mM and 7.6 (±0.1) mM respectively. At the end of the experiment these values were 10.2 (±0.3) mM I^- and 7.7 (±0.1) mM NH_4^+. For *Nitrosococcus oceani* the start and end concentrations were 9.8 (±0.3) and 9.4 (±0.1) mM for I^- and 7.8 (±0.1) and 7.7 (±0.1) mM for NH_4^+. This result was expected as the average standard deviations associated with the observed concentrations of I^- or NH_4^+ (i.e. 0.1 to 0.3 mM) are at least an order of magnitude higher than the maximum levels of IO_3^- and NO_2^- observed in the culture experiments, i.e. very little of the initial stock of NO_2^- or NH_4^+ was oxidised during the experiments.

4. Discussion

4.1. Iodate production by ammonia-oxidising bacteria

Our results confirm that IO_3^- production occurs in cultures of the ammonia-oxidising bacteria *Nitrosomonas* sp. and *Nitrosococcus oceani* supplied with I^-, but not in cultures of nitrite oxidising bacteria. Coincident increases in NO_2^- (Fig. 2) show that both cultures were actively oxidising ammonia throughout the experiments at rates of 1.96 ± 0.0.88 fmol NO_2^- $cell^{-1}$ day^{-1} for *Nitrosomonas* sp. and 6.19 ± 0.56 fmol NO_2^- $cell^{-1}$ day^{-1} for *Nitrosococcus oceani*. Whilst these cell-normalised oxidation rates are of the same order as those reported in the literature (e.g. 6–20 fmol NO_2^- $cell^{-1}$ day^{-1}; Ward, 1987; Ward et al., 1989) they are at the lower end. This is consistent with the approach taken here to calculate the rates by normalising to the final (highest) cell densities. It is also worth noting that the cultures were at an early stage of growth and had relatively low cell densities during the experiment. This was done to avoid significant changes in pH in the bulk media which would impact inorganic iodine speciation (Section 3.2). The observation of an increase in IO_3^- concentrations alongside active biological ammonia oxidation supports previous studies (e.g. Truesdale et al., 2001; Zic et al., 2013) which have shown that high aqueous concentrations of IO_3^- are found in regions of enhanced nitrification, and provides the first

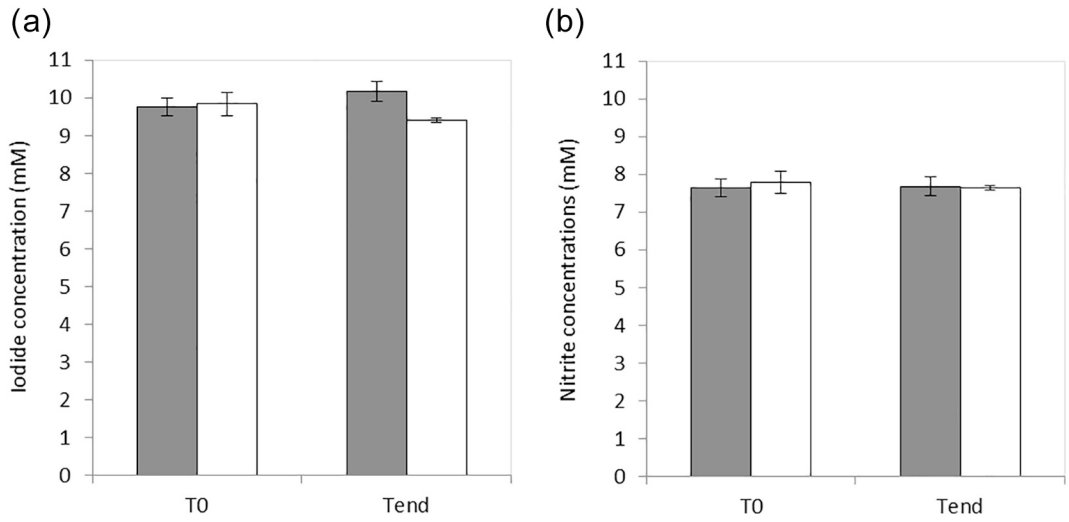

Fig. 3. Start and end concentrations of a) iodide and b) ammonia in cultures of *Nitrosomonas* sp. (grey bars) and *Nitrosococcus oceani* (white bars). Error bars show the standard deviation of three replicate cultures.

direct confirmation of a biological basis for at least one mechanism of iodide oxidation.

Whilst we did not set out to establish the mechanism for I^- to IO_3^- oxidation by marine nitrifiers, some speculations can be made. As I^- oxidation to IO_3^- requires the transfer of six electrons, it may occur in a series of one- or two- electron transfer steps. Initially, I^- may be oxidised to molecular iodine ($I^- \rightarrow I_2$), a reaction which is thermodynamically unfavourable at the pH of seawater (Luther et al., 1995). Further oxidation to IO_3^- by disproportionation ($I_2 \rightarrow HOI \rightarrow IO_3^-$) can occur spontaneously, but in seawater is subject to competition with reduction of I_2 by organic matter (Truesdale and Moore, 1992; Truesdale and Luther, 1995). It is not known whether the ammonia-oxidisers mediate just the first stage of I^- oxidation, with the observed IO_3^- production due to subsequent spontaneous reactions in the culture media, or if they are involved in driving the complete conversion of I^- to IO_3^-. However, bacteria which just oxidise I^- to I_2 have been isolated from seawater aquaria (Gozlan, 1968), I^--rich natural gas brine waters (Amachi et al., 2005) and marine environmental samples (Fuse et al., 2003; Amachi et al., 2005).

The observed IO_3^- production is either linked to the nitrification process itself or associated with other metabolic activities of the AOB studied. Truesdale et al. (2001) has proposed that I^- oxidation to IO_3^- would be energetically advantageous for chemoautotrophic AOB. In that case the key enzymes used to obtain energy during the oxidation of NH_4^+ to NO_2^- (ammonia monooxygenase [AMO] and hydroxylamine oxidoreductase [HAO]) could also have the potential to use I^- as a substrate. The observed IO_3^--to-NO_2^- molar production rates (9.2 ± 4.0 for *Nitrosomonas* sp. and 2.3 ± 1.1 for *Nitrosococcus oceani*) are intriguing. If AMO/HAO are involved, this suggests that the enzymes have higher affinities for I^- than NH_4^+/NH_2OH given the similar concentrations of I^- and NH_4^+ used in the experiments. Other enzymes that have been implicated in I^- oxidation include the chloroperoxidases (Thomas and Hager, 1968) but we do not know if they occur in AOB. The exact metabolic pathway driving the observed IO_3^- production and its controls (i.e. substrate concentrations, light intensity) will need to be determined in future work. To establish if such further experimentation is warranted we need to explore whether the link between nitrification and I^- oxidation is likely to be an important part of inorganic iodine cycling in seawater.

4.2. Implications for inorganic iodine speciation in the oceans

Our culture studies suggest that the molar rate of I^- oxidation (IO_3^- production) is ~2–9 times higher than that for ammonia oxidation (nitrification). Note that although ammonium and iodide concentrations were much higher in the experimental media than in the oceans, the concentration ratio of these species was comparable to that found naturally. Ammonia oxidation rates in seawater range from below detection to 10^2 nM day^{-1} (Table 2). Literature estimates of the rate of I^- oxidation in the marine environment range from ~4 to 670 nM $year^{-1}$ or 0.01 to 1.84 nM day^{-1} (reviewed in Chance et al., 2014). If the oxidation molar ratios observed in this study (~2–9) are representative, predicted rates of I^- oxidation are in-line (i.e. 2–9 times higher) with the lower end of observed ammonia oxidation rates (Table 2).

Table 2
Ammonia-oxidation rates measured in a range of ocean regions.

Study	Location	Rate (nM day^{-1})
Newell et al. (2011)	Arabian Sea, Indian Ocean	undetected to 21.6
Smith et al. (2016)	Northeast Pacific	< 0.01 to 90
Peng et al. (2015)	Eastern tropical north Pacific	< 1 to 8.6
Newell et al. (2013)	Subtropical Atlantic, Sargasso Sea (BATS)	< 2
Lam et al. (2007)	Black Sea	7–24
Beman et al. (2012)	Gulf of California, eastern tropical north Pacific	0–348

Truesdale et al. (2001) derive likely I^- oxidation (or IO_3^- production) rates for the near surface Black Sea using an iodine budget and this allows us to examine the potential importance of the link between nitrification and I^- oxidation on a local scale. They predict a minimum I^- oxidation flux of 3.89×10^{-4} mol I m^{-2} $year^{-1}$ which is an average of 0.02 nM day^{-1} at a mixed-layer depth (MLD) of 50 m or 0.11 nM day^{-1} at an MLD of 10 m. Lam et al. (2007) report an AOB abundance of ≤1400 cells mL^{-1} in the Black Sea. If we apply a cell density of 1400 AOB cells mL^{-1} to the average cell-normalised rates of IO_3^- production observed in this study (Table 1) we derive I^- oxidation rates of ~20 nM d^{-1}. This is clearly much higher than the rates suggested in Truesdale et al. (2001). This discrepancy could be explained in a number of ways. Firstly, Lam et al. (2007) state that net nitrification only takes place within a narrow depth range of the Black Sea water column (i.e. between 71 and 81 m) and, the I^- oxidation values derived in Truesdale et al. (2001) are minimum values. It is also possible that the AOB studied here have a higher capacity for I^- oxidation (per unit ammonia-oxidised) than other ammonia-oxidisers or that our culture conditions (e.g. substrate

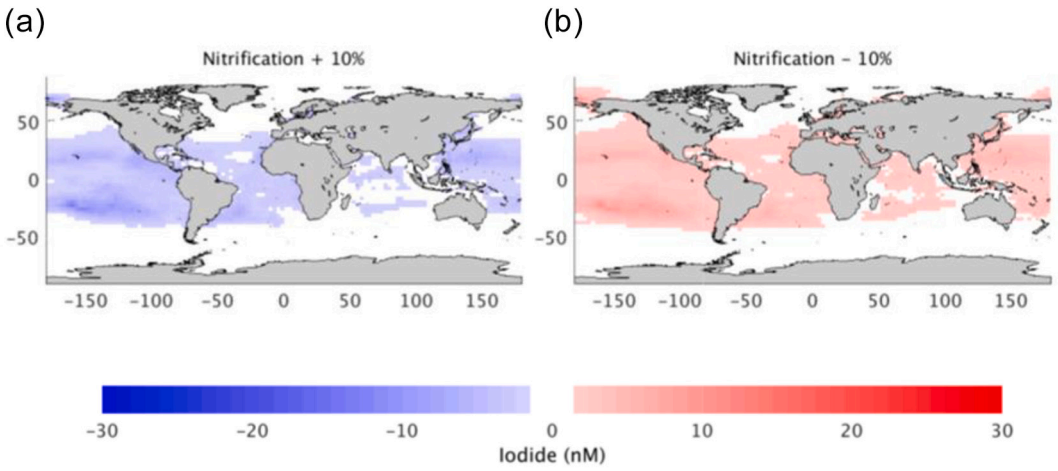

Fig. 4. Modelled changes in surface I^- concentration (nM) resulting from a) +10%, b) -10%, changes in the rates of nitrification. Negative percent values indicate a decline in the rate of nitrification and vice-versa. Negative values on the scale bar indicate a decrease in I^- concentrations and vice versa.

availability) promoted higher I^- oxidation rates than would be observed in marine systems. For example, ammonia-oxidising Archaea (AOA), which can outnumber known bacterial ammonia oxidisers by orders of magnitudes in environments such as the marine water-column (reviewed by Schleper and Nicol, 2010), may have a very different capacity for I^- oxidation compared to the AOB studied here. Further studies are needed to establish the relationship between ammonia- and I^- oxidation in the marine environment.

4.3. Potential implications for future oceanic inorganic iodine distributions

Environmental factors which are known to be currently undergoing change in the oceans (e.g. oxygen, light, pH, temperature) have all been found to impact rates and patterns of marine nitrification (reviewed by Pajores and Ramos, 2019). Whilst there remains some uncertainty about the future magnitude and, in some cases, sign of the response, some of the expected future changes in marine nitrification are large. For example, whilst some studies have seen no impact on specific marine nitrifiers (e.g. Qin et al., 2014), Beman et al. (2011) suggest that expected rates of acidification could cause a decline in ammonia oxidation by up to 44% within the next few decades. It is hence worth exploring how possible future changes in marine nitrification could impact ocean iodine cycling.

In order to explore the possible impact of future changes in marine nitrification rates on sea surface iodine fields we used the ocean cycling model described in Wadley et al. (2020). Within the model iodide production is driven by primary productivity, and I^- oxidation to IO_3^- linked to nitrification in the mixed layer. Nitrogen fluxes and the spatial distribution of mixed layer ammonia oxidation are derived from a global biogeochemical cycling model (Yool et al., 2007). I^- is oxidised to IO_3^- in association with the ammonia oxidation, with the same I:N:C ratio as associated with iodide production (Truesdale et al., 2001; Long et al., 2015). The model does not use any of the rates derived in the current study as these are based on results from only 2 AOB species cultured at high substrate concentrations. Model outputs (Fig. 4) show that even with small (+/−10%) changes in ammonia oxidation there is a clear alteration to sea surface I^- fields. Sea surface I^- concentrations increase as ammonium oxidation rates decrease and vice-versa. For example, the ocean cycling model suggests there could be an average global increase of 0.13 nM I^- per 1% decrease in nitrification. The outputs suggest that the change in the iodine fields is spatially variable and will increase as the perturbation to ammonia oxidation increases. For example, at the 44% decline in nitrification predicted by Beman et al. (2011) the model predicts there will be a 25% increase (+30 nM) in sea surface I^- in the sub-tropical gyres. Carpenter et al. (2013) show that I_2 emissions due to ozone deposition increase near linearly with I^- concentration. Hence, the predicted changes to sea surface I^- fields under future ocean acidification could have a major impact on ozone deposition to the sea surface, atmospheric chemistry and resulting sea-air iodine emissions.

5. Conclusions

This study has shown that I^- oxidation to IO_3^- occurs in cultures of ammonia oxidising (nitrifying) bacteria, but not nitrite oxidising bacteria. Our calculations suggest that I^- oxidation by AOB could be an important control on inorganic iodine speciation in seawater, but to confirm this further study is needed on a wider range of ammonia-oxidisers including ammonia oxidising archaea (AOA). Simulations from our iodine cycling model suggest that changes in nitrification rate, such as those predicted to occur under acidification (Beman et al., 2011), could have an important impact on sea surface I^- fields. A future change in marine nitrification could alter sea surface I^- fields. In turn, this could lead to a change in ozone deposition to the sea surface and sea-air iodine emissions with potentially major implications for atmospheric chemistry and air quality.

Data statement

The data presented in this manuscript is available from the British Oceanographic Data Centre (BODC), doi:https://doi.org/10.5285/aaa4dab8-7c9d-0cca-e053-6c86abc00b1d

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Declaration of Competing Interest

The authors have no financial conflicts of interest with the research in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marchem.2021.104000.

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