Reviews and syntheses: Marine biogenic aerosols and the ecophysiology of coral reefs

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Abstract. Coral reefs are being threatened by global climate change, with ocean warming and acidification, compounded by declining water quality in many coastal systems, adversely affecting coral health and cover. This is of great concern as coral reefs provide numerous ecosystem, economic and social services. Corals are also recognized as being amongst the strongest individual sources of natural atmospheric sulfur, through stress-induced emissions of dimethylsulfide (DMS). In the clean marine boundary layer, biogenic sulfates contribute to new aerosol formation and the growth of existing particles, with important implications for the radiative balance. Evidence suggests that DMS is not only directly involved in the coral stress response, alleviating oxidative stress, but may create an "ocean thermostat" which suppresses sea surface temperature (SST) through changes to aerosol and cloud properties. This review provides a summary of the current major threats facing coral reefs and describes the role of dimethylated sulfur compounds in coral physiology and climate. The role of coral reefs as a source of climatically important compounds is an emerging topic of research however, the window of opportunity to understand the complex biogeophysical processes involved is closing with ongoing degradation of the world's coral reefs. The greatest uncertainty in our estimates of radiative forcing and climate change are derived from natural aerosol sources, such as marine DMS, which constitutes the largest flux of oceanic reduced sulfur to the atmosphere. Gaining a better understanding of the role of coral reef DMS emissions is crucial to predicting the future climate of our planet.

1. Introduction

Tropical corals grow in warm, oligotrophic waters from approximately 30° N to 30° S (Fig. 1). This geographical restriction is due to the physiological requirements of reef-building Scleractinian corals which have relatively narrow thermal, light and salinity tolerance ranges (Bourne et al., 2016; Lesser, 2010; Hughes et al., 2018). The term coral holobiont refers to the

5   symbiosis of the coral host with multiple endosymbiotic microorganisms including cyanobacteria, which aid in nitrogen fixation (Lesser et al., 2004) and photosynthetic dinoflagellates of the genus *Symbiodinium* (Muscatine and Porter, 1977). Several clades of *Symbiodinium* may exist within the coral host depending on species and thermo-tolerance and are collectively termed zooxanthellae. These are acquired via phagocytosis and reside within membrane enclosed compartments (the symbiosome) within the coral gastrodermis (Tresguerres et al., 2017). Zooxanthellae provide corals with their vibrant colours

10 (e.g. Fig. 2) and 95% of their metabolic requirements via translocation of photosynthetically fixed carbon and in return, depend upon the coral host to obtain inorganic carbon (Falkowski et al., 1984; Dubinsky and Falkowski, 2011). This symbiosis is essential for coral survival (Bourne et al., 2016).

Shallow-water coral reefs cover only 0.1% (~600,000 km^2) of the marine environment (Spalding et al., 2001), yet provide

15 numerous essential ecosystem, economic and social services (Barbier et al., 2011; Hoegh-Guldberg et al., 2007; Jones, 2015), with an estimated value of US$9.9 trillion annually (Costanza et al., 2014). Approximately one third of all described marine species obtain food and habitat from coral reefs (Reaka-Kudla, 1997). The biodiversity of coral reefs makes them hotspots for global tourism, providing approximately US$36 billion annually (Spalding et al., 2017) and for the discovery of new medically important biochemical compounds (Kumar, 2006). Their high productivity also provides a valuable source of income for

20 global fisheries, estimated at US$5.7 billion per year (Cesar et al., 2003). Fringing and barrier reefs are also highly effective at mitigating coastal erosion by reducing wave energy by up to 97% (Ferrario et al., 2014). Coral reefs provide many other services including nutrient cycling (Barbier et al., 2011; Gattuso et al., 1998; Bourne et al., 2016) and potentially climate regulation through stress-induced emissions of volatile sulfur compounds (Cropp et al., 2018; Fischer and Jones, 2012; Jones, 2015; Fiddes et al., 2018).

When corals experience physiological stress from high sea surface temperature (SST), light, hyposalinity or exposure to air at low tide, they increase production of dimethylsulfoniopropionate (DMSP), which acts as an antioxidant for the coral holobiont (Deschaseaux et al., 2014a; Hopkins et al., 2016; Gardner et al., 2016). Depending on the degree of coral stress, a portion of DMSP is enzymatically cleaved to form the volatile gas dimethylsulfide (DMS) (Raina et al., 2009; Bullock et al., 2017). Upon

30 ventilation to the atmosphere DMS is oxidised to form aerosol precursors (Andreae and Crutzen, 1997), which can affect aerosol formation and growth (Sanchez et al., 2018; Charlson et al., 1987). DMS emissions from coral reefs may therefore exert a significant influence on local climate.

The role of coral reefs in climate has only recently begun to be appreciated, despite zooxanthellate corals being amongst the largest sources of natural sulfur in the marine environment (Burdett et al., 2015; Broadbent and Jones, 2004; Haydon et al., 2018; Swan et al., 2017; Van Alstyne et al., 2009). However, our understanding of the biogeochemical and ocean-atmosphere interactions involved in the coral reef DMS cycle is not yet complete (Jones, 2015), contributing to the large uncertainty in the

5   role of natural aerosols in our estimates of radiative forcing (Carslaw et al., 2013). The ongoing degradation of the world's coral reefs provides an urgency to gaining a better understanding of these processes. A primary concern is whether a decline in emissions of DMS - derived aerosol will alter the local radiative balance and accelerate warming in coral reefs, impeding the ability of corals to cope with future rises in SST. In this review we examine the role of DMS in coral ecophysiology and the emerging topic of coral reefs as a source of marine biogenic aerosol (MBA). The implications of coral bleaching and

10   ongoing coral reef degradation will also be discussed to highlight the importance of a multi-disciplinary approach to coral reef management. In the face of rapid climate change, non-traditional means of conservation and management may be required.

2. The role of dimethylated sulfur compounds in coral reefs

2.1 The coral reef sulfur cycle

Scleractinian corals are recognized as being a significant source of DMS/P, with reported concentrations as high as 54,381 nM

15   DMSP and 18,665 nM DMS in coral mucous ropes (Broadbent and Jones, 2004), 409 nmol DMSP cm^{-2} of coral surface (Frade et al., 2016), and 45.9 nmol m^{-3} atmospheric DMS (DMS_a) above an aerially exposed coral reef (Swan et al., 2017). Zooxanthellate soft corals such as Octocorals, are also reported to contain high amounts of DMSP, with concentrations up to 4710 nmol mg^{-1} protein (Haydon et al., 2018). These concentrations are higher than those reported for lone dinoflagellate cells and benthic algae (Broadbent et al., 2002).

Figure 3 provides a simplified overview of the coral reef sulfur cycle and the role of dimethylated sulfur compounds in the DMS - SST feedback.

DMSP is a zwitterion and will not passively diffuse across cell membranes. Particulate DMSP ($DMSP_p$) may be released to

25   surrounding reef waters via zooxanthellae expulsion, which can occur at a rate of 0.2 - 0.4% *Symbiodinium* cells day^{-1} in response to elevated irradiance or temperature (Jones et al., 2007), zooplankton grazing on phytoplankton (Dacey and Wakeham, 1986), or in the form of DMS or dimethyl sulfoxide (DMSO) released in coral mucous and *Symbiodinium* exudates (Broadbent and Jones, 2006; Raina et al., 2009). DMS and acrylate are produced via the cleavage of DMSP by enzymes collectively termed DMSP-lyases (Bullock et al., 2017), present in zooxanthellae (Caruana and Malin, 2014) and coral-

30   associated bacteria (Raina et al., 2009). The amount of DMS ultimately released to surrounding reef waters is dependent upon the ratio of DMSP breakdown to DMS and DMS/P photo-oxidation to DMSO by reactive oxygen produced by the coral holobiont under stress (Fig. 4). Although oxidation to DMSO is a sink of DMS/P, DMSO may also be reduced back to DMS

and therefore also acts as a DMS source in coral reef waters (Fischer and Jones, 2012; Gardner et al., 2016; Deschaseaux et al., 2014b). The physiological requirements of microbial communities within the coral host and in coral reef waters also plays an important role in the cycling of DMSP, switching between the DMSP catabolism and demethylation pathways (Fig. 4). The microbial catabolism pathway yields DMS and acrylate, both of which serve as an important carbon source (Bourne et al., 2016; Sun et al., 2016; Bullock et al., 2017).

Dissolved DMS (DMS_w) is then ventilated to the atmosphere where it has a residence time of approximately one day (Khan et al., 2016), before atmospheric reaction mechanisms such as oxidation to sulfur dioxide (SO_2) occur (Fig. 3) (Andreae and Crutzen, 1997; Barnes et al., 2006). When pre-existing aerosol concentrations and cloud cover are high, for example when high wind speeds enhance sea-spray aerosol (SSA) emission, heterogenous oxidation of SO_2 in cloud droplets occurs rapidly, contributing to the growth of existing particles rather than the formation of new particles (Woodhouse et al., 2013; Hoffmann et al., 2016). Conversely, during calm, clear conditions, SO_2 may undergo further oxidation to sulfuric acid (H_2SO_4), followed by gaseous phase nucleation to form new non-sea salt sulfate (nss-SO_4) particles (Fig. 3). Nucleation of H_2SO_4 may occur within the marine boundary layer (MBL) or in the free troposphere where conditions are more favourable, with entrainment providing an important source of new sulfate particles to the MBL (Sanchez et al., 2018). These secondary aerosols can be efficient cloud condensation nuclei (CCN) and may affect cloud albedo over oceans (Charlson et al., 1987).

2.2 Mechanisms of biosynthesis

The biochemical pathways involved in DMSP biosynthesis in corals are complex (Bullock et al., 2017). Until recently, it was thought that biosynthesis was limited to photosynthetic endosymbionts. However, recent findings show that coral hosts themselves are substantial sources of DMSP (Raina et al., 2013). In phytoplankton, DMSP is produced via a series of four enzymes (Gage et al., 1997) which assimilate sulfur into cysteine and methionine and subsequently into the stable, soluble form DMSP (Bourne et al., 2016; Stefels, 2000). *Acropora spp.* contain orthologues of genes responsible for the expression of two of these enzymes, which encode NADPH-reductase and Ado-Met-dependent methyltransferase enzymes involved in the second and third steps of the DMSP biosynthesis pathway, respectively (Raina et al., 2013). The methyltransferase enzyme is particularly specific to this pathway and is highly expressed in *Acropora* juveniles which have not yet assimilated endosymbiotic *Symbiodinium*. Expression declines with adult development likely due to coral association with zooxanthellae (Raina et al., 2013). Additionally, high levels of intracellular DMSP are reported in *Acropora spp.*, with *A. tenuis* and *A. millepora* juveniles exhibiting 65% and 76% increases in DMSP concentration in response to thermal stress (Raina et al., 2013). Similar responses were observed in adult corals after exposure to temperatures of 32º C for 10 days. Despite a decline in *Symbiodinium* density of 84% (where the remaining 16% were severely structurally compromised and not producing DMSP) DMSP concentration increased by 68%, suggesting that the coral polyp was the source of biosynthesis (Raina et al., 2013).

There are a number of hypotheses as to why corals synthesize DMSP. Sulfur is an essential nutrient for all lifeforms, involved in amino acid and protein synthesis. Carbon is also an essential component of life, providing an energy source for respiration. DMSP provides an abundant organic source of both sulfur and carbon in coral reefs and biosynthesis is thought to play a role in the structuring of the coral microbiome (Bourne et al., 2016; Raina et al., 2010; Raina et al., 2009). These endosymbionts

5 provide a number of services to the coral host, including carbon and nitrogen fixation (Falkowski et al., 1984; Dubinsky and Falkowski, 2011) and disease prevention via production of antimicrobial compounds such as tropodithietic acid (TDA), derived from microbial DMSP catabolism (Raina et al., 2016). DMSP is also involved in alleviating oxidative stress in Scleractinian corals (Hopkins et al., 2016; Gardner et al., 2016; Deschaseaux et al., 2014b).

2.3 The coral antioxidant response

10 Empirical evidence shows that DMSP biosynthesis in Scleractinian corals is upregulated during periods of elevated SST, irradiance, aerial exposure at low tide and hyposalinity associated with rainfall or fluvial discharges from adjacent river systems (Swan et al., 2017; Broadbent and Jones, 2006; Jones et al., 2007; Gardner et al., 2016; Hopkins et al., 2016; Raina et al., 2013). Corals and the endosymbiotic relationship they depend upon, have a relatively narrow thermal, light and salinity tolerance range (Lesser, 2010; Nielsen et al., 2018). Enhanced production of dimethylated sulfur compounds when these

15 tolerance ranges are approached, suggests DMSP may play a key role in the coral stress response. Field measurements show that DMSP and DMS are positively correlated with SST (Jones et al., 2007) and tide height (Jones and Trevena, 2005) throughout the Great Barrier Reef (GBR), Australia. This relationship has also been demonstrated in chamber experiments (Raina et al., 2013; Hopkins et al., 2016). For example, *A. intermedia* sampled from Heron Island in the southern GBR increased intracellular DMSP production by 45% in response to a 2° C rise in ambient SST (Jones et al., 2014).

Elevated irradiance and/or SST can impair zooxanthellae photosystems, destabilizing the photosynthetic electron-transport chain and increasing the production of harmful reactive oxygen species (ROS) (Lesser et al., 1990; Jones et al., 2002; Yakovleva et al., 2009; Downs et al., 2002). These ROS can diffuse from the algal symbiont into coral cytoplasm where antioxidant defences may prevent oxidative damage when ROS levels are below the tolerance threshold of the coral holobiont.

25 In phytoplankton, superoxide dismutase (SOD) and glutathione interactions form an antioxidant pathway, whereby SOD converts superoxide anions to hydrogen peroxide (H_2O_2) and oxygen (O_2) while the glutathione pathway regenerates the enzyme ascorbate peroxidase, responsible for scavenging H_2O_2 (Lesser, 2006). DMSP, DMS and acrylate are also capable of scavenging ROS (Sunda et al., 2002) and may therefore form a similar antioxidant system in corals (summarised in Fig. 4).

30 The role of DMSP in the coral antioxidant response is supported by several studies which show that when stress exceeds coral physiological limits (e.g. SST > 30° C or salinity < 24 psu), DMSP and DMS concentrations decline as the rate of oxidation to DMSO increases (Hopkins et al., 2016; Gardner et al., 2016; Deschaseaux et al., 2014b). For example, when *Acropora* spp. were exposed to SST two degrees above the climatological summer maximum for a period of 36 hours, chamber headspace

DMS concentrations declined by 93% as the ratio of dissolved DMSO:DMSP increased (Fischer and Jones, 2012). Similarly, increases in DMS_a occur when corals are exposed to air at low tide, due to direct atmospheric exchange (Swan et al., 2017). DMS_a declines with time as oxidation to DMSO increases. When corals are resubmerged, a second spike in DMS_a occurs as the dissolution of DMS-rich coral mucous increases sea surface concentration and ventilation to the atmosphere. Atmospheric

5   and dissolved DMS levels then decline again as DMSO concentrations increase (Hopkins et al., 2016; Swan et al., 2016). This trend is also observed when corals are exposed to low salinity (~16 psu) (Gardner et al., 2016), as occurs on inshore continental reefs during the wet season when fluvial discharge is high. The decline in intracellular DMSP and DMS emissions with extreme stress reflects enhanced photochemical oxidation to DMSO, suggesting DMS/P is a sensitive indicator of coral stress and an important antioxidant in the coral holobiont. Interestingly, unlike Scleractinian corals, emissions of DMS from zooxanthellate

10   soft corals do not vary seasonally, perhaps indicating an alternative ecological role possibly involving holobiont community structuring (Haydon et al., 2018).

3. Environmental stressors and their impact on DMSP cycling

A key question is how the DMS/P antioxidant system in corals will respond to a changing climate, and whether a change in DMS/P synthesis facilitates or hinders corals ability to adapt to rapid environmental change. Bourne et al. (2016) review the

15   cumulative impacts of coral reef stressors, and claim that when temperature, ocean acidification, water quality and other stressors such as overfishing accumulate, the diversity and resilience of the coral microbiome and coral reef ecosystem declines. Reduced diversity may lead to a higher risk of coral disease and mortality and wide-scale ecosystem shifts before a new stable state is achieved (Bourne et al., 2016). Figure 5 summarises the impacts of climate change and modification of land-use on coral reefs and the predicted impact on DMS emissions.

20   ### 3.1 Ocean warming

Ocean warming is considered to be one of the greatest threats to coral reefs (Baker et al., 2008; Heron et al., 2016; Hughes et al., 2018; Skirving et al., 2019). More than 90% of the heat energy accumulated in the Earth's climate system, largely a result of anthropogenic greenhouse gas (GHG) emissions, is stored in the ocean. Consequently, global mean SST has risen by 0.5° C over the last 40 years (IPCC, 2014). The stability of the coral system is dependent upon the range of temperature and

25   irradiance experienced by the coral host and their endosymbionts (Dubinsky and Falkowski, 2011; Lesser, 2010). If thermal and/or light stress induces the production of excess ROS (Lesser, 2010), corals may change the composition of zooxanthellae clades (symbiont switching or shuffling) in an attempt to reduce oxidative stress (Bay et al., 2016), or expel their zooxanthellae resulting in coral bleaching (Gates et al., 1992; Nielsen et al., 2018; Lesser et al., 1990). The severity of coral bleaching and subsequent mortality is dependent on the duration and magnitude of stress during conditions preceding the event (Ainsworth

30   et al., 2016). For example, high SST or irradiance may not independently result in coral bleaching, however, may do so synergistically.

As many Scleractinian corals now reside in regions with SST close to their upper physiological limits, a 0.5º C rise in SST above the local summer maximum for a period of several weeks is sufficient to cause coral bleaching and mortality (Berkelmans, 2009). SST greater than ~2º C above the summertime maximum can result in coral bleaching over much shorter time-scales (Bainbridge, 2017). If stress levels subside quickly, corals may regain their zooxanthellae and recover, although

5   surviving corals can have reduced growth, calcification and reproductive rates and a higher incidence of disease and competitive susceptibility (Baker et al., 2008; Ward et al., 2002; Chaves-Fonnegra et al., 2018). Recent work found an 89% decline in larval recruitment during the 2018 spawning event in the GBR after consecutive mass bleaching events adversely affected populations of adult spawning corals (Hughes et al., 2019). If current GHG emissions continue, it is estimated that 50% of coral reefs will experience annual severe coral bleaching by 2030, and more than 95% by 2050 (Burke et al., 2011),

10 assuming corals cannot adapt or acclimate to the changing climate.

Empirical evidence has demonstrated that DMS/P biosynthesis is upregulated during thermal stress, followed by oxidation to DMSO in temperature sensitive species (e.g. Deschaseaux et al., 2014a). Therefore, warmer oceans will likely cause an upregulation of DMSP biosynthesis and oxidation to DMSO in coral reefs (Fig. 5). However, variation among coral species

15 and zooxanthellae type and their interactions with marine macro and microalgae will govern changes to the coral reef sulfur cycle. When corals experience thermal stress, *Acropora spp.* in the GBR have been found to expel thermo-sensitive Clade C *Symbiodinium*, instead taking up the more tolerant Clade D variety (Bay et al., 2016). Symbiont switching and/or shuffling may occur rapidly over time-scales of several days to weeks or may occur gradually over several months in response to changes in environmental conditions. This can assist corals in coping with physiological stress, as thermo-tolerant *Symbiodinium*

20 photosystems are not producing excess amount of ROS. For example, symbiont shuffling to favour type D symbiont dominance in *A. millepora* increased thermo-tolerance by ~1.5°C (Berkelmans and Van Oppen, 2006). Interestingly, some temperature-tolerant zooxanthellae clades (e.g. clade D) are weaker producers of DMSP compared to the temperature sensitive clades (Deschaseaux et al., 2014b; Bay et al., 2016). This may change if future SST rises establish new baseline temperatures above the tolerance threshold of these more tolerant clades, increasing oxidative stress and DMSP biosynthesis. However, tolerance

25 thresholds within *Symbiodinium* clades is highly variable (Klueter et al., 2017) and does not always predict DMSP biosynthesis (Steinke et al. 2011).

Marine micro- and macroalgae compete with corals for light, nutrients and space. When coral reefs are degraded by coral bleaching, fleshy macroalgae such as *Polysiphonia spp.* and *Ulva spp.* which also synthesize DMSP (Van Alstyne and Puglisi,

30 2007), may dominate (De'ath and Fabricius, 2010; Bell, 1992; McClanahan et al., 2011; McCook and Diaz-Pulido, 2002). Phytoplankton blooms, which are additional sources of DMSP in coral reefs, have been positively correlated with aerosol concentration in the Southern Ocean, reflecting an enhanced biogenic particle source from DMS and other organic emissions (Korhonen et al., 2008; McCoy et al., 2015). This additional source of biogenic sulfur may counteract any decline in coralline emissions (Fig. 5). Algal blooms may also increase light attenuation at the surface, alleviating coral light stress however, these

organisms also promote heat absorption at the ocean surface, converting ~60% of absorbed photons to heat (Lin et al., 2016). Increasingly algal dominated coral reef communities may exacerbate the warming effects of GHGs in coral reefs.

3.2 Ocean acidification

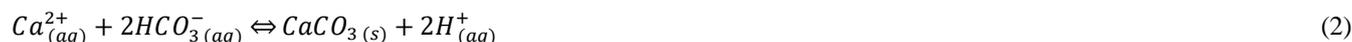
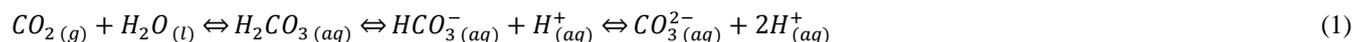
Ocean acidification (OA) affects coral reefs by enhancing dissolution and limiting pH sensitive coral calcification rates

5 (Tresguerres et al., 2017; Albright et al., 2018; Steiner et al., 2018). Anthropogenic carbon dioxide (CO_2) emissions are 10.1 ± 0.5 Gt C year $^{-1}$ (Le Quéré et al., 2018), of which approximately 30% is absorbed by the oceans and affects seawater chemistry (IPCC, 2014; Orr, 2011). Increased CO_2 levels increase the formation of carbonic acid (H_2CO_3) which readily dissociates into bicarbonate ions (HCO_3^-) and protons (H^+) as per Eq. (1). These protons react with carbonate (CO_3^{2-}) to produce more HCO_3^- ions, which in turn, decrease the bioavailability of CO_3^{2-} for marine calcification (Orr, 2011). The current

10 concentration of CO_3^{2-} ions in the ocean is 200 µmol kg^{-1} of seawater (Zeebe and Tyrrell, 2019), around 40 µmol kg^{-1} less than the minimum over the past 420,000 years (Hoegh-Guldberg et al., 2007). OA also favours erosion of calcareous structures (Eq. (2)), with massive *Porites* corals in the northern GBR already displaying annual declines in linear extension rates and skeletal density of 1.02% and 0.36% respectively (Cooper et al., 2008). If current GHG emissions persist, it is estimated that less than 15% of the world's coral reefs will be in regions with carbonate saturation sufficient for coral growth by 2050 (Burke

15 et al., 2011).

$$CO_{2\,(g)} + H_2O_{\,(l)} \Leftrightarrow H_2CO_{3\,(aq)} \Leftrightarrow HCO_{3\,(aq)}^- + H_{(aq)}^+ \Leftrightarrow CO_{3\,(aq)}^{2-} + 2H_{(aq)}^+ \tag{1}$$

$$Ca_{(aq)}^{2+} + 2HCO_{3\,(aq)}^- \Leftrightarrow CaCO_{3\,(s)} + 2H_{(aq)}^+ \tag{2}$$

It is unclear how DMSP cycling will be influenced by OA and this is particularly true of coral reefs. In remote oceans such as the Arctic, biosynthesis of DMSP is predicted to increase due to enhanced phytoplankton biomass and availability of inorganic carbon (Archer et al., 2013). Other studies predict that the flux of DMS to the atmosphere will decrease due to a decline in the abundance of DMSP-producers such as phytoplankton (Schwinger et al., 2017; Archer et al., 2018). Regardless,

25 acidification appears to be adversely affecting coral calcification and health (Cooper et al., 2008; Hoegh-Guldberg et al., 2007; Orr, 2011; Albright et al., 2018). If this continues, a decline in coral cover may result in a decline in DMS emissions from coral reefs (Fig. 5). Again, opportunistic growth of algae is predicted to dominate degraded coral reef systems (De'ath and Fabricius, 2010; Brodie et al., 2011; McCook and Diaz-Pulido, 2002). It is possible that increased DMS emissions from this algal source may counteract the decline in coralline source-strength (Fig. 5). However, recent evidence from the southern GBR

30 demonstrated that the combined effects of ocean warming and acidification under RCP8.5 conditions also impaired calcification in the macroalga *Halimeda heteromorpha* (Brown et al., 2019), highlighting the complexity inherent in coral-algae interactions.

3.3 Water quality and eutrophication

Declining water quality is another cause of coral reef degradation. Although inner-shelf coral reefs exposed to reduced water quality are more resistant to coral bleaching, resilience is low due to increased susceptibility to disease and predation (MacNeil et al., 2019). Eutrophication arises when enhanced loading of the limiting macro-nutrients nitrogen (N) and/or phosphorous

5 (P) induce excessive growth of marine algae (Howarth et al., 2011; Diaz and Rosenberg, 2008; McEwan et al., 1998), which impede coral growth and reduce the opportunity for new corals to establish (De'ath and Fabricius, 2010; Bell, 1992; McClanahan et al., 2011). This is often caused by catchment runoff and soil erosion from land clearing, agriculture and urbanization (Brodie et al., 2011; McKergow et al., 2005). Resulting algal blooms can reduce water clarity, deplete dissolved oxygen and release toxins (Osborne et al., 2001), all of which adversely affect coral health and grazing fish populations.

10 Depletion of grazing fish populations further favours algal growth by removing top-down control (McClanahan et al., 2011). Eutrophication leading to an increase in phytoplankton standing stock also contributes to outbreaks of *Acanthaster planci* (Crown of Thorns Seastar), an invasive predator of corals and a significant threat to the GBR (Fabricius et al., 2010; De'ath et al., 2012; Wooldridge and Brodie, 2015). These impacts are compounded by enhanced sedimentation from riverine discharge and dredging, which cause benthic smothering, increased turbidity and reduced light penetration, all of which adversely affect

15 photosynthesising organisms including coral zooxanthellae (Erftemeijer et al., 2012). Sea-level rise and changes to large-scale oceanic circulation in response to global warming is exacerbating coastal erosion and declining water quality and has caused an increase in storm surges which further degrade coral reefs (Mellin et al., 2019). Measurements of dissolved DMS/P have been found to decline along a gradient of relatively pristine to human-impacted coral reefs in the central GBR (Jones et al., 2007). However, it is unclear whether poor water quality will result in a net decline in DMS flux from coral reefs in future, as

20 an enhanced algal source may counteract declining emissions from corals themselves (Fig. 5).

4. Marine biogenic aerosols

4.1 The CLAW hypothesis

The CLAW hypothesis (1987) proposed that marine DMS emissions increase the formation of low-level, high albedo cloud cover, establishing a biologically-derived negative feedback on the warming effects of GHG (Charlson et al., 1987; Shaw,

25 1983). Despite decades of research, our knowledge of the biological, chemical and atmospheric processes involved in the biosynthesis, flux and climatic influences of DMS remains incomplete. Some suggest that the original hypothesis is an over-simplification (Green et al., 2014) or no longer relevant (Quinn and Bates, 2011) with anthropogenic perturbation of the atmosphere throughout much of the globe (Spracklen and Rap, 2013). However, others remain steadfastly positive about the role of DMS in global climate (Grandey and Wang, 2015).

30 ### 4.2 DMS sea-to-air flux

The global sea-air flux of DMS is estimated to be 17.6 - 34.4 Tg S year^{-1} (Kettle and Andreae, 2000; Lana et al., 2011; Land et al., 2014), accounting for approximately 50% of the natural global atmospheric sulfate burden (Bates et al., 1992; Simó, 2001; Barnes et al., 2006). The large DMS flux range reflects the uncertainty in under sampled ocean regions where newly collected data is improving the estimate (Webb et al., 2019). Emissions are highly variable in both space and time and are

5   primarily governed by ocean biology in the mid-low latitude oceans (Broadbent and Jones, 2006; Jones et al., 2007; Korhonen et al., 2008) and sea-ice dynamics in polar regions (Gabric et al., 2018). The sea-to-air flux of DMS depends on its surface ocean concentration (Lana et al., 2011), SST (Yang et al., 2011), wind speed (Ho and Wanninkhof, 2016) and water depth or tide height (Swan et al., 2017), all of which reduce the thermal capacity of the sea surface, causing enhanced heating and reduced diffusivity resistance.

In the Arctic, DMS flux is estimated to increase by 86% to 300% under modelled scenarios of three to four-times present-day CO$_2$ concentrations. This predicted increase is due to a combination of enhanced biological activity and changes to sea-ice dynamics (Gabric et al., 2005; Qu et al., 2017). On a global scale, atmospheric DMS concentrations are predicted to increase by 41% with a tripling of atmospheric CO$_2$, increasing mean aerosol optical depth (AOD) by 3.5% and cooling the northern

15   and southern hemisphere by 0.4 K and 0.8 K respectively (Gabric et al., 2013). Other studies, such as Kloster et al. (2007), simulate a global reduction of the DMS flux by 10% by the late 21st century. Overall, studies from the last few decades of global biogeochemical modeling provide both negative and positive changes in DMS flux under future climate conditions. However, other factors affecting regional ocean biogeochemistry will also be important, such as natural variability in carbonate chemistry and the buffering capacity of the ocean surface (Hopkins et al., 2018).

The total contribution of coral reefs to the global sulfur budget is not yet clear, however, the GBR and lagoon waters (347,000 km^2) are estimated to emit 0.02 Tg S year^{-1} (Jones et al., 2018). It is noted that coral cover in the GBR is ~20,000 km^2 and consequently, DMS flux from the surrounding lagoon was far higher than estimates from the coral reef. However, it is likely that most of the dissolved DMS in the lagoon was produced by corals. Therefore, the total DMS flux can be considered an

25   estimate of coral DMS emissions. This is the first estimate of DMS flux from the entire GBR, however it is based on a limited number of field observations and does not account for occasional large pulses of DMS emitted by corals during aerial exposure at low tide (Swan et al., 2017). When these events are considered, DMS sea-air flux from coral reefs would periodically increase. Hopkins et al. (2016) provided an estimate of DMS flux per unit area of the GBR, based on laboratory measurements taken from *A. horrida* periodically exposed to air. As *Acropora* are the dominant genus throughout the Indo-Pacific and are

30   amongst the strongest producers of DMS/P, it was estimated that corals in the GBR release 3 - 11 mmol S m^{-2} day^{-1}. According to this estimate the GBR releases 0.01 - 0.04 Tg S yr^{-1}, consistent with the estimate provided by Jones et al. (2018). Assuming that DMS flux is constant across coral reefs and lagoon waters, tropical coral reefs (~600,000 km^2) emit 0.02 - 0.08 Tg S yr^{-1}. Although this represents < 1% of global or tropical average DMS sea-air flux estimates (Lana et al., 2011), it is a substantial amount of sulfur released from only 0.2% of the ocean surface, with the potential to influence local climate in coral reefs.

4.3 Complexity of the DMS cycle

Once ventilated to the atmosphere, the influence of DMS on climate is dependent on the efficiency of DMS oxidation to SO_2 and secondarily to H_2SO_4 (Barnes et al., 2006), which ranges from 0.14 to 0.95 in the MBL due to spatiotemporal variation in pre-existing atmospheric properties (Glasow and Crutzen, 2004). The annual mean contribution of DMS to CCN is estimated

5   to be only 3.3% in the northern hemisphere and 9.9% in the southern hemisphere (Woodhouse et al., 2010). Consequently, the sensitivity of CCN to DMS emissions at a global scale is low, with a 1% increase in global DMS flux resulting in only a 0.1% increase in mean CCN (Woodhouse et al., 2010). Although the response of CCN to DMS is low on a global scale, spatial and seasonal estimates vary, with higher responses evident in pristine regions of high biological activity (Woodhouse et al., 2013; Lana et al., 2012; Zavarsky et al., 2018). Further, models may be underestimating DMS emissions in some parts of the ocean

10   due to sparsity in global observations, resulting in large uncertainties in interpolated flux estimates (Mulcahy et al., 2018).

In the remote MBL, biogenic aerosols such as DMS-derived sulfates have been shown to be influential on regional or local climate, suggesting that DMS may be important in smaller-scale climate regulation in pristine marine environments. In the North Atlantic, new sulfate particles formed via the nucleation of DMS-derived H_2SO_4 in the free troposphere accounted for

15   33% of CCN at 0.1% supersaturation, largely due to enhanced phytoplankton biomass in spring (Sanchez et al., 2018). In the Southern Ocean, seasonal variability in cloud droplet number is primarily driven by changes in sea-spray, organic matter and biogenic sulfates, with seasonal maxima during spring and summer, coinciding with enhanced biological activity and DMS emissions. DMS-derived nss-SO_4 particles account for 7-20% of mean CCN in winter and 43-65% in summer (Korhonen et al., 2008), increasing the Southern Ocean summertime mean reflectivity by more than 10 W m^{-2} (McCoy et al., 2015).

20   Similarly, complete removal of DMS results in a modelled top of atmosphere radiative forcing of +1.7 W m^{-2} (Fiddes et al., 2018).

5. Do coral reefs affect the climate?

The GBR provides a valuable study location for the analysis of biogenic aerosols. Given its large spatial extent (2,300 km in length and 60 - 250 km in width) and southern hemisphere location, the atmosphere over the GBR is considered to be relatively

25   unpolluted. The region also experiences predominant east to south-easterly trade winds year-round, which carry clean, marine air to the GBR and advect biogenic compounds northward over downwind coral reefs. Consequently, the majority of research examining the role of coral reefs in MBA production has focused on the GBR region.

5.1 Influence on particle formation and growth

The ability of corals to influence local atmospheric properties has only recently begun to be appreciated. Bigg and Turvey

30   (1978) measured total atmospheric particle concentration along the north-east Queensland (QLD) coastline from 1974 to 1977 and found that concentrations were up to seven-times higher in maritime air directly over the GBR compared to the seaward

side. Three decades later, Leck and Bigg (2008) observed fluctuations in particle concentration at Lizard Island in the northern GBR during September 1998 and July 2005. Nucleation events forming particles with a diameter greater than > 0.01 μm, were observed on all study days with concentrations reaching 40,000 cm^{-3} during the warmer September period and up to 4,300 cm^{-3} in July (Leck and Bigg, 2008). The large seasonal difference in particle concentration implies a temperature or irradiance-

5   dependent biological influence. Similarly, Modini et al. (2009) observed nucleation events at Agnes Water in the southern GBR, in which corals were concluded to be the most likely source of precursor compounds. These events occurred in clean, easterly air masses originating in the MBL, when solar irradiance at the sea surface was high (~1,000 W m^{-2}). Particles consisted of 40% organics and 60% sulfate. In the strongest nucleation event, Aitken mode (< 0.1 μm in diameter) concentration was measured at 3,200 cm^{-3}. This event occurred during a NNE wind, accumulating particles of marine origin

10   from upwind coral reefs. The authors concluded that Aitken mode concentration was too low to have been derived from coagulation alone, thus new particles were largely derived from the condensation of low volatility vapours such as DMS-derived H_2SO_4 (Modini et al., 2009). Swan et al. (2016) also measured high particle concentration over Heron Island in the southern GBR, which coincided with a peak in DMS emissions from the coral reef flat during calm conditions after an extremely low tide, again suggesting the coral reef to be a source of MBA precursor compounds.

The ability of corals to influence the atmosphere above them has also been investigated using remote-sensing approaches. Lana et al. (2012) found that sulfate aerosols positively correlated with CCN and negatively with cloud droplet radius throughout the mid to high latitude oceans and in some tropical latitudes, where a high density of coral reefs exists. Observations of satellite-derived fine-mode aerosol over parts of the GBR show concentrations to be positively correlated with

20   conditions that are empirically shown to cause a stress response in corals and thus, enhance DMS emissions (Cropp et al., 2018; Jackson et al., 2018). Correlation strength between aerosol and coral light stress (a function of PAR, tide height and water clarity) improved with decreasing wind speed at Heron Island, suggestive of a substantial local MBA source over the southern GBR (Cropp et al., 2018).

25   There is strong seasonality in both DMS (Jones et al., 2018; Swan et al., 2017) and aerosol loading in the GBR (Cropp et al., 2018; Jackson et al., 2018). Figure 6 shows the seasonal variation in daily mean (2001 - 2017) total AOD (869 nm) over the GBR. This data was acquired at 4 km resolution from the Moderate Resolution Imaging Spectroradiometer (MODIS) on board the Terra and Aqua satellites (https://oceancolor.gsfc.nasa.gov/). Observations over the Australian continent were excluded, thus Fig. 6b shows only AOD for the GBR and adjacent Coral Sea (Fig 6a). In the northern half of the GBR, AOD is highest

30   during the winter dry season (May - October). Conversely, the southern half of the GBR displays a marked increase in AOD during the warmer months (November - April) and a decrease in winter (Fig. 6b). It is not clear what is driving this latitudinal variability, however emissions of DMS and other volatile organic compounds (VOCs) cannot be excluded as a potential driver of seasonal variability. Existing research has linked seasonal variability in aerosol and CCN formation to enhanced biological activity in other remote ocean regions (Gabric et al., 2018; Korhonen et al., 2008). The increase in AOD during summer in the

southern GBR is also suggestive of a temperature or light-dependent biogenic influence, potentially from the high biomass of coral reefs below.

5.2 Influence on low-level clouds, sea surface temperature and surface solar radiation

The Western Pacific Warm Pool (WPWP) is a coral reef dense region located to the north-east of Australia, where SST reaches
5   an upper limit of ~30° C due to regular pulses of low-level cloud (LLC) cover which closely follow the tidal lunar cycle (Kleypas et al., 2008; Takahashi et al., 2010; Ramanathan and Collins, 1991). It has been posited that coral reef DMS emissions contribute to the formation of this "ocean thermostat", acting to suppress ocean temperatures below coral thermal tolerance thresholds, resulting in few coral bleaching events over the past 25 years (Kleypas et al., 2008; Takahashi et al., 2010). Similarly, although an overall warming trend is apparent along the NE coast of Australia, SST in the far northern GBR is
10   warming at a slower rate compared to southern regions (Lough, 2008; Heron et al., 2016). As in the WPWP, this is potentially due to enhanced LLC which is estimated to account for approximately 30% of the variance in SST over the GBR (Leahy et al., 2013). Figure 7 shows LLC closely aligned over the Swains Reefs in the southern GBR, captured by MODIS Terra on 31st May 2018. Back trajectories computed by the National Oceanic and Atmospheric Administration (NOAA) Air Resources Laboratory HYSPLIT Model show dominant south-westerly winds on this day (Stein et al., 2015; Rolph et al., 2017),
15   potentially explaining the north-eastward migration of LLC in Fig. 7.

Reduced SST and irradiance due to enhanced LLC have also been observed to mitigate mass coral bleaching events. For example, extreme SST in the summer of 1998 resulted in widespread coral bleaching throughout the tropics (Wilkinson et al., 1999). This event caused severe bleaching and subsequent mortality of 99% of *Pocillopora* corals in the Tuamotu Archipelago,
20   French Polynesia (Mumby et al., 2001a). However, high LLC cover significantly reduced the amount of surface solar radiation at coral reefs in the nearby Society Islands where bleaching did not occur (Mumby et al., 2001b). Similarly, high SST (> 31° C) in 1994 caused coral bleaching at Nelly Bay (Magnetic Island) in the central GBR (Jones et al., 1997) however, no bleaching was observed ~60 km away at Pioneer Bay (Orpheus Island) (Jones et al., 2007). Jones et al. (2017) examined DMS$_a$ before, during and after this bleaching event at both locations. At the unbleached reef, regular pulses of LLC often coincided with
25   pulses of DMS (14-20 µmol m^{-2} day^{-1}). Conversely, at the bleached reef LLC cover and DMS emissions were low when SST exceeded 30° C (Jones et al., 2007) and coincided with extreme solar irradiance (Jones et al., 2017). Together these findings suggest that stress-induced emissions of DMS from coral reefs may influence local LLC cover to mitigate stress and prevent coral bleaching. However, spatial variation in this phenomenon is apparent, possibly due to existing meteorological conditions or other factors affecting coral reef health as discussed in section 2.

30   ## 5.3 Influence on precipitation

Coral reef-derived aerosol emissions have also been proposed to affect precipitation patterns. Jones (2015) discusses extreme rainfall in regions lying in the path of SE trade winds travelling over the GBR, implying that emissions of DMS and other

organic compounds from the coral reef contributed to cloud droplet formation. Conversely, Fiddes et al. (2018) found that DMS-derived sulfate particles enhanced LLC cover and lifetime and consequently suppressed rainfall in parts of the tropics. When high concentrations of fine particles rapidly grow to CCN activation sizes, cloud droplet size decreases, cloud lifetime increases, and rainfall is suppressed (Rosenfeld et al., 2007; Dave et al., 2019; Singh et al., 2018). However, when CCN

5   minimum size is not met, water vapour remains in the atmosphere, suppressing local rainfall yet enhancing rainfall downwind when conditions for particle growth are more favourable (Andreae and Rosenfeld, 2008; Fan et al., 2018; Grandey and Wang, 2015; Lin et al., 2018; Guo et al., 2016). Changes to the source strength of ultra-fine and fine aerosols may therefore affect climate by either increasing or suppressing rainfall. The latter poses a concerning question for the sustainability of rainfall sensitive agriculture in NE Australia with ongoing degradation of the GBR and highlights the need for an improved

10   understanding of the relationship between MBA emissions and their impact on cloud micro-physics.

5.4 Other biogenic volatile organic compounds

Although DMSP and its derivatives are the most abundant compounds in the coral reef sulfur cycle (~95% of sulfur compounds), other VOCs such as isoprene, dimethyl disulfide (DMDS), carbon disulfide (CS_2) and the recently discovered DMSP variant, dimethylsulfoxonium propionate (DMSOP) are also produced in coral reefs (Swan et al., 2016; Thume et al.,

15   2018). Isoprene is the most abundant biogenic VOC in the atmosphere, largely derived from terrestrial vegetation however, oceanic emissions are also reported from marine algae including *Symbiodinium* (Exton et al., 2013). Swan et al. (2016) recorded large quantities of isoprene in *A. aspera* mucous, likely produced by expelled coral *Symbiodinium*. This compound may be oxidised in the atmosphere or condense onto existing particles, thus also contributing to aerosol formation over coral reefs with the potential to affect local climate (Fan and Zhang, 2004; Kroll et al., 2006; Surratt et al., 2007). Photochemistry

20   at the ocean surface is also an important abiotic source of organic vapours, with VOC emission estimates ranging from 23.2 - 91.9 Tg C yr^{-1}, contributing approximately 60% of organic aerosol mass in the remote MBL (Brüggemann et al., 2018).

6. Outlook and the implications for coral bleaching

The response of corals to increasing light and/or temperature stress is nonlinear. As these environmental factors increase beyond optimal levels, DMS emissions initially increase, but when thermal and/or light stress becomes too great, DMS

25   emissions from corals essentially shut-down (Jones et al., 2007; Fischer and Jones, 2012). This means that there are less aerosol precursor compounds and potentially fewer secondary aerosols forming over the coral reef. Recent work examined anomalies in fine-mode AOD over the GBR during four mass coral bleaching events which occurred primarily due to marine heatwaves (Jackson et al., 2018). Prior to each bleaching event, when SST was rising and corals were likely emitting more DMS, above average AOD was observed. However, just prior to and during the bleaching events, when corals were likely experiencing

30   extreme physiological stress and may have bleached, AOD declined to normal background levels, or below average levels where the coral reef was severely affected. Although these covarying events may be a coincidence, the synchronous decline in AOD with the onset of coral bleaching suggests a link between coral health and atmospheric properties in the GBR.

This raises some important and concerning questions. Will the nonlinear response of DMS emissions from coral reduce their ability to cope with future temperature rises? If coral reefs significantly affect our climate, what will the consequences of ongoing coral reef degradation and coral bleaching be for local or regional climate? A decline in aerosol and LLC formation over relatively pristine coral reefs such as the GBR could occur, potentially increasing SST and establishing a positive feedback on coral stress. It is possible that we are already witnessing the early stages of this process, whereby back-to-back marine heatwaves and coral bleaching events are causing a rapid decline in coral cover in the GBR (Hughes et al., 2018).

7. Coral reef monitoring

Adaptive management of coral reefs depends on regular monitoring of coral health, cover and the impacts of environmental stressors such as coral bleaching. The ability to accurately predict the impacts of future disturbances on coral reefs is also required. Field surveys provide valuable, detailed information on the condition of coral reefs. The Australian Institute for Marine Science (AIMS) Long-Term Monitoring Program is one of the most comprehensive programs, providing more than 30 years of continuous surveys of coral reef health and community structure across 47 mid-shore and offshore reefs spanning the entire length of the GBR. This data has been used to assess the impacts of stressors such as coastal development, agricultural runoff, industrial activities such as dredging, predators and climate change. The findings have been instrumental in the development of current initiatives aimed at mitigating coral reef stressors, such as the re-zoning of the GBR Marine Park in 2004 and the Australian Government Reef Restoration and Adaptation Program. These types of programs are crucial in providing high frequency, detailed data necessary to understand the local biogeochemical processes that are driving the larger changes to community structure and climate patterns. However, field surveys are extremely cost and resource intensive (reviewed in Hedley et al., 2016) and consequently occur over relatively short time scales of days to weeks. Additionally, field surveys cannot capture processes that may be occurring down-wind of the substance's origin. This is true of field measurement of DMS/P in coral reef waters. Although these measurements provide valuable insight into the environmental factors driving variability in emission strength, the larger scale processes involved in DMS oxidation, particle formation and growth cannot be discerned from this data alone.

Remote-sensing approaches are useful in this regard, as they enable rapid, cost and time efficient analysis of a wide range of variables at large temporal and spatial scales. Several remote sensing approaches are currently used by coral reef scientists and managers to monitor environmental conditions in coral reefs. The majority of these focus on SST as this is largely considered to be the major stressor to corals and is often the dominant factor contributing to coral bleaching (Jones et al., 2002; Lesser, 2010). For example, the National Oceanic and Atmospheric Administration (NOAA) Coral Reef Watch utilises satellite-derived SST to produce several measures of coral thermal stress, including the Hotspot and degree heating week (DHW) products (Liu et al., 2006). These are based on spatially-dependent SST anomalies above the climatological summertime maximum, which when accumulated over a 12-week moving window provide a measure of the intensity and duration of coral

thermal stress. Empirical evidence has demonstrated that DHW of 8° C-weeks reliably predicts mass coral bleaching and mortality (Liu et al., 2003). This is the most widely used measure for assessing and predicting coral bleaching events (Hughes et al., 2018; Bainbridge, 2017; Berkelmans, 2009 ;Skirving et al., 2019). The NOAA Coral Reef Watch is also producing a Light Stress Damage (LSD) measure which incorporates coral light stress as a contributor to coral bleaching, based on PAR

5   anomalies (Skirving et al., 2017). This product was released in late 2012 for coral reefs in the Caribbean and has now been expanded to include the eastern Pacific as part of its seventh experimental iteration.

These products are also useful in providing insight into the coral reef sulfur cycle. Examining spatiotemporal trends in conditions that are known to enhance or suppress DMS/P biosynthesis (e.g. thermal stress), with trends in atmospheric

10 properties such as AOD, can provide insight into the role of DMS in climate over coral reefs (e.g. Jackson et al., 2018; Cropp et al., 2018). However, remote sensing approaches present their own limitations in that they do not provide the level of detail of field studies and accurate retrieval of ocean colour data in optically complex waters can be difficult, particularly in shallow coral reefs (Hedley et al., 2016). Additionally, validation of these products requires in situ observations (e.g. Bainbridge, 2017). Therefore, a multidisciplinary approach which utilises both field and remote sensing observations in conjunction with

15 earth system models, is needed to improve our understanding of the biogeochemical processes occurring in coral reefs and the ways we can effectively ensure their preservation.

8. Mitigation strategies

The predicted increase in the frequency and severity of mass coral bleaching events means that biological and/or physical interventional management strategies may be required to conserve coral reefs. In addition to promoting the propagation of

20 temperature tolerant coral species throughout coral reef ecosystems (Van Oppen et al., 2015), other strategies aimed at mitigating the warming effects of GHGs via physical means have also been proposed. Solar Radiation Management (SRM) strategies involve injecting sea-spray or sulfate particles into the atmosphere over coral reefs to increase the albedo of low-lying marine clouds (Crabbe, 2009; Irvine et al., 2017). In a modelled scenario, injecting 5 Tg SO_2 annually into the stratosphere above Caribbean coral reefs reduced SST, irradiance and sea-level rise and resulted in a substantial decline in the

25 number of mass coral bleaching events predicted to occur over the next 50 years (Zhang et al., 2017). Similarly, Kwiatkowski et al. (2015) reported that enhancing SO_2 concentrations in the tropical stratosphere reduced SST and the risk of coral bleaching over the next 30 years under an RCP4.5 scenario. Other studies have examined the effect of releasing sea-spray from ocean-based vessels to the MBL over coral reefs to brighten low-level marine clouds. Latham et al. (2013) found that an enhanced source of sea-spray aerosol over the GBR, Caribbean and French Polynesia offset the warming effects associated with a

30 doubling of atmospheric CO_2, reducing the number of coral bleaching events predicted to occur until the end of this century. An additional benefit of these SRM strategies is the potential reduction in the severity of tropical cyclones with a decline in SST (Zhang et al., 2017; Latham et al., 2012).

Another approach involves the implementation of a biodegradable calcium carbonate surface film over coral reefs. Early trials conducted as part of the Surface Films to Attenuate Light into the Great Barrier Reef project have demonstrated that the film increases light attenuation by 30% and has no adverse effects on coral physiology (Great Barrier Reef Foundation, 2018). Another initiative proposed by the Reef and Rainforest Research Centre and QLD tourism industry is investigating the

5 feasibility of pumping deep, cold water from 10 - 30 m over high economic and environmental value reefs in the northern GBR. Early pilot studies are currently being conducted to test the feasibility of the technology at Moore Reef off the coast of Cairns (Reef and Rainforest Research Centre, 2017).

Climate engineering is a realistic approach which may provide short-term protection for high-value or vulnerable coral reefs

10 from rising temperatures. However, these approaches are extremely cost and resource intensive, particularly for large coral reef systems such as the GBR and success would depend upon the willingness of governments and/or organisations to continue funding and implementing the technology. These strategies also do not address other coral reef stressors such as ocean acidification and the long-term implications are not yet completely understood (Crabbe, 2009; Irvine et al., 2017). There is enormous incentive to improve our understanding of the drivers of coral resilience, including the role of DMS/P in alleviating

15 oxidative stress and influencing the radiative balance. Recent findings demonstrate that reduced cloud cover associated with El Niño conditions is the primary driver in determining the extent and severity of coral bleaching events in the GBR (McGowan and Theobald, 2017). Further research is needed to quantify and characterise the flux of DMS from coral reefs and its influence on aerosol and cloud formation. Doing so would provide valuable insight into how to enhance the natural defences of corals and inform climate engineering proposals, which may need to be implemented as a last resort to conserve coral reefs.

20 **9. Conclusions**

There is substantial evidence that coral reefs are strong sources of dimethylated sulfur compounds. These play an important role in alleviating oxidative stress in the coral holobiont resulting from high temperatures, light levels, aerial exposure and hyposalinity. It is possible that a side-effect of this stress response provides a source of precursor compounds for the formation of secondary sulfate aerosols, with important implications for the radiative balance. There is strong seasonality in both DMS

25 emissions and aerosol loading over the 2,300 km stretch of relatively pristine coral reefs in the GBR - a relationship that is indicative of a substantial biogenic influence on AOD. Field studies have observed new particle formation events occurring over the GBR, and remote sensing analyses have demonstrated that AOD is positively correlated with conditions that have been empirically shown to enhance coral DMS emissions. It is therefore likely that pristine coral reefs such as the GBR are a source of MBA, with important implications for the radiative balance.

This biogenic aerosol source is in danger of becoming weaker with ongoing coral reef degradation. Although corals enhance DMS emissions in response to rising stress, emissions decline when coral physiological tolerance ranges are approached. The same trend has been observed for both AOD and LLC cover, which often coincide with coral bleaching events. Natural aerosols

are an important source of CCN and cloud cover is a primary determinant of the spatial extent and severity of coral bleaching. Although the response of coral DMS emissions to the changing climate is uncertain, a decline in DMS-derived particles may exacerbate warming and the degradation of coral reefs. Capturing all of the complex biogeochemical and ocean-atmosphere interactions involved in the coral reef sulfur cycle is a challenging task. A multidisciplinary approach which utilises both field and remote sensing observations, with earth system models is therefore needed to improve our understanding of the importance of DMS to coral physiology and regional climate. This will enable a better understanding of natural aerosol radiative effects and inform alternative methods of coral reef management.

Data availability

The aerosol optical depth dataset presented in this review can be obtained from NASA's OceanColor Distributed Active Archive Centre (https://oceancolor.gsfc.nasa.gov/).

Author contributions

RJ prepared the manuscript with contributions from all co-authors.

Competing interests

The authors declare that they have no conflict of interest.

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Figures
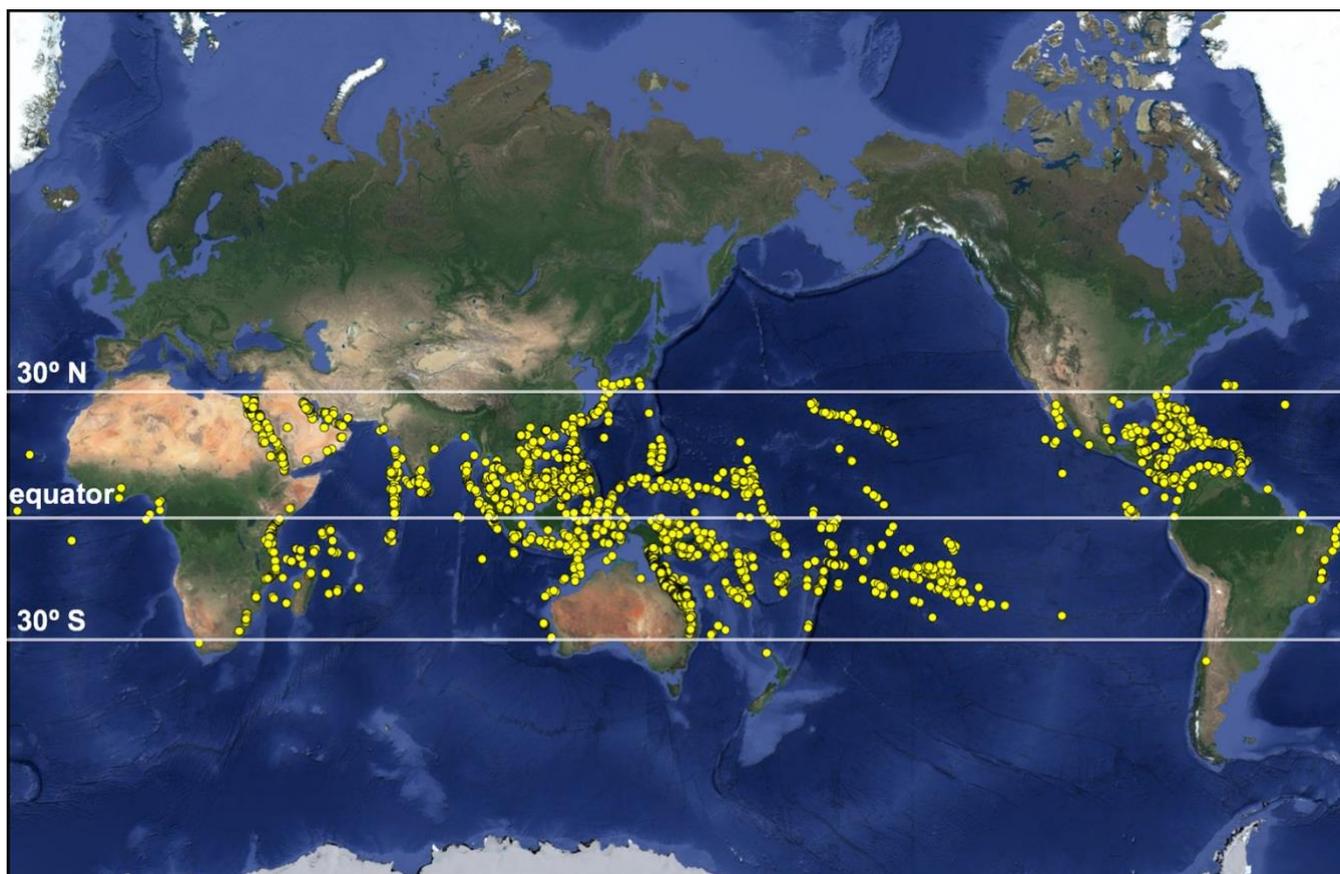
Figure 1. Global distribution of tropical coral reefs. Locations provided by ReefBase (http://www.reefbase.org).

Figure 2. Vibrant corals at Norman Reef in the northern Great Barrier Reef, Australia (R. Jackson).
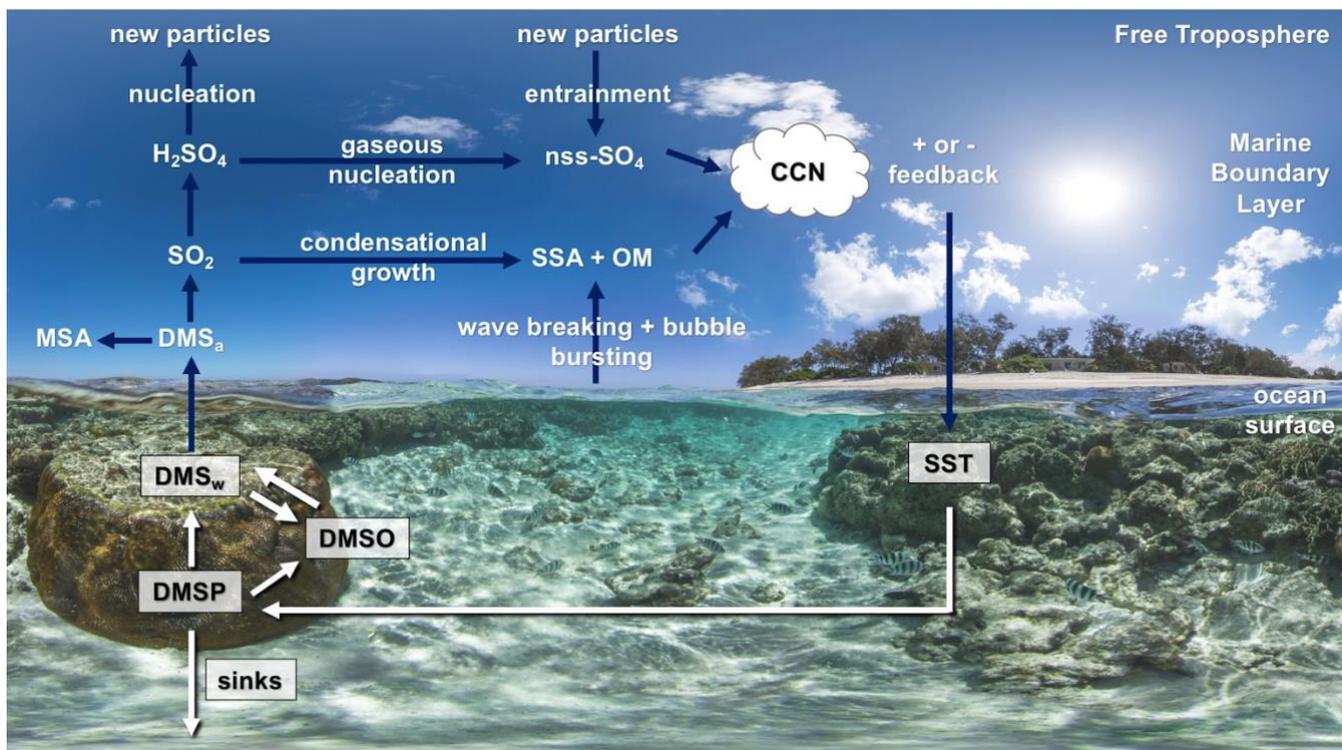
Figure 3. Simplified overview of the coral reef dimethylsulfide (DMS) - sea surface temperature (SST) feedback. Dimethylsulfoniopropionate (DMSP) is produced by the coral holobiont and may be oxidised to dimethyl sulfoxide (DMSO) or cleaved to dissolved DMS (DMS$_w$). Atmospheric DMS (DMS$_a$) is further oxidised to methanesulfonic acid (MSA) and sulfur dioxide (SO$_2$) and secondarily to sulfuric acid (H$_2$SO$_4$), which may condense onto existing particles (e.g. sea-spray aerosol (SSA) or organic matter (OM)) or nucleate to non-sea salt sulfate particles (nss-SO$_4$). These may increase the number of cloud condensation nuclei (CCN) and increase cloud albedo. Background © Underwater Earth / XL Catlin Seaview Survey / Aaron Spence. CC BY-SA 3.0.
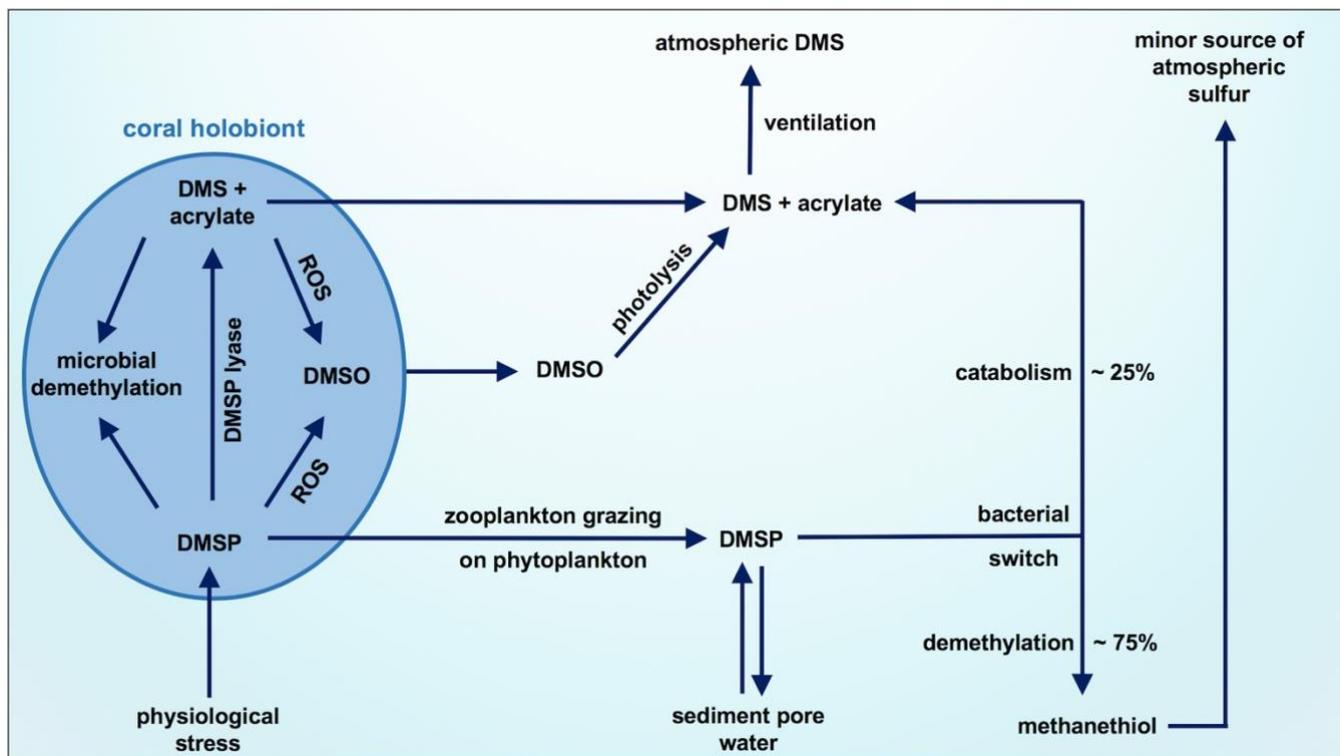
Figure 4. Basic processes involved in the cycling of dimethylated sulfur compounds involved in a coral reef.
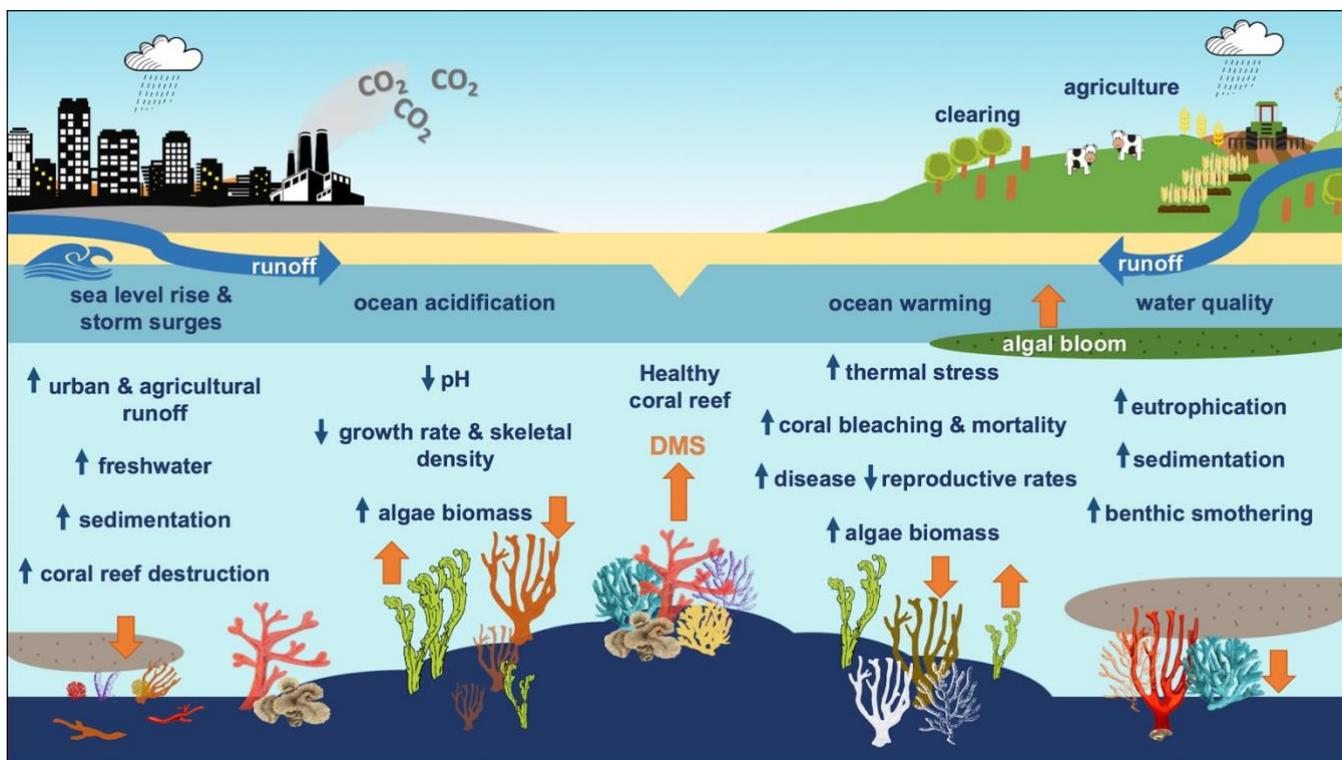
Figure 5. The impacts of climate change and land-use on coral reefs. Orange arrows reflect the predicted increase or decrease in DMS emissions from the coral holobiont and marine micro and macroalgae.
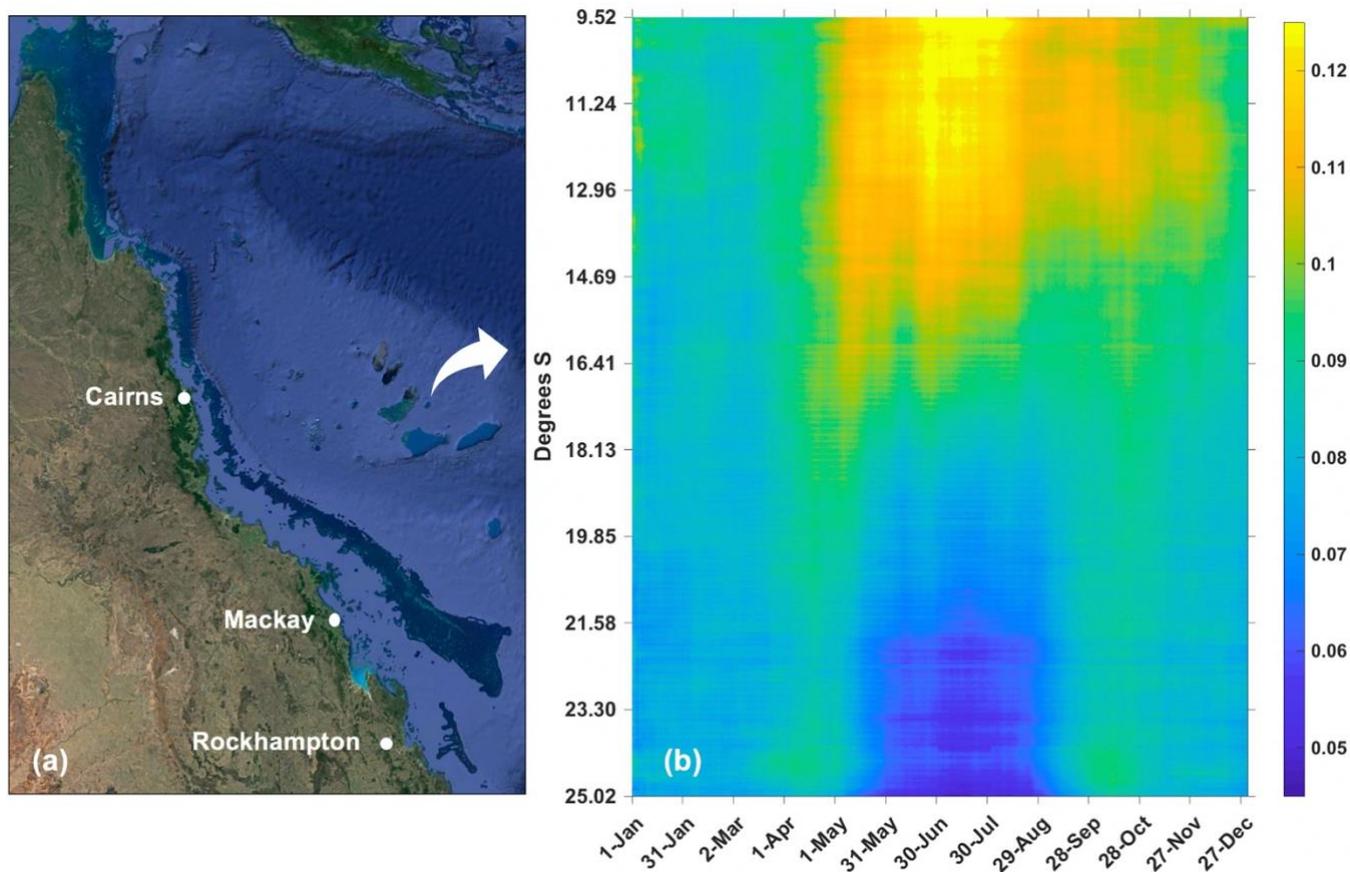
Figure 6. (a) Map of the GBR, Australia. (b) Longitude-averaged Hovmoller plot of daily mean (2001 - 2017) total AOD (869 nm) over the GBR.

Figure 7. Low-level convective clouds aligned over the Swains Reefs in the Mackay-Capricorn Management Area of the southern GBR. True colour image captured by MODIS Terra on 31st May 2018. Source: NASA Earth Observing System Data and Information System (EOSDIS).