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## Salinity from space unlocks satellite-based assessment of ocean acidification

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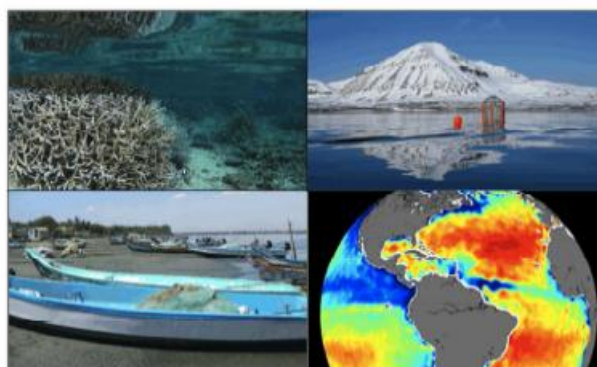
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### Abstract :

Approximately a quarter of the carbon dioxide (CO<sub>2</sub>) that we emit into the atmosphere is absorbed by the ocean. This oceanic uptake of CO<sub>2</sub> leads to a change in marine carbonate chemistry resulting in a decrease of seawater pH and carbonate ion concentration, a process commonly called 'Ocean Acidification'. Salinity data are key for assessing the marine carbonate system, and new space-based salinity measurements will enable the development of novel space-based ocean acidification assessment. Recent studies have highlighted the need to develop new in situ technology for monitoring ocean acidification, but the potential capabilities of space-based measurements remain largely untapped. Routine measurements from space can provide quasi-synoptic, reproducible data for investigating processes on global scales; they may also be the most efficient way to monitor the ocean surface. As the carbon cycle is dominantly controlled by the balance between the biological and solubility carbon pumps, innovative methods to exploit existing satellite sea surface temperature and ocean color, and new satellite sea surface salinity measurements, are needed and will enable frequent assessment of ocean acidification parameters over large spatial scales.



Abstract artwork

Note to editor (top left to bottom right): Tropical coral; Svalbard in the Barents Sea; Beach in India on the coast of the Bay of Bengal; Salinity from space (SMOS) showing the Amazon plume. All images taken by PML staff and used with permission.

## 1. Introduction

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Each year global emissions of carbon dioxide ( $\text{CO}_2$ ) into our atmosphere continue to rise. These increasing atmospheric concentrations cause a net influx of  $\text{CO}_2$  into the oceans. Of the roughly 36 billion metric tons of  $\text{CO}_2$  that is emitted into our atmosphere each year, approximately a quarter transfers into the oceans <sup>1</sup>. This  $\text{CO}_2$  addition has caused a shift in the seawater carbonate system, termed Ocean Acidification (OA), resulting in a 26% increase in acidity and a 16% decrease in carbonate ion concentration since the industrial revolution <sup>2</sup>. Recently there has been recognition that this acidification is not occurring uniformly across the global oceans, with some regions acidifying faster than others <sup>3, 4</sup>. However, the overall cause of OA remains consistent: the addition of  $\text{CO}_2$  into the oceans, and as such, it remains a global issue. Continual emissions of  $\text{CO}_2$  into the atmosphere over the next century will decrease average surface ocean pH to levels which will be deleterious to many marine ecosystems and the services they provide <sup>5</sup>.

While the seawater carbonate system is relatively complex, two parameters have been suggested as pertinent to the monitoring and assessment of OA through time and

55 space. These are pH (the measure of acidity) and calcium carbonate ( $\text{CaCO}_3$ ) mineral  
56 saturation state, with aragonite generally considered to be an important  $\text{CaCO}_3$   
57 mineral to be monitored because of its relevance to marine organisms (e.g. corals) and  
58 its relative solubility. Thermodynamically,  $\text{CaCO}_3$  is stable when the saturation state  
59 (an index of the concentrations of calcium and carbonate ions) is greater than one and  
60 becomes unstable when seawater becomes undersaturated with these ions (saturation  
61  $< 1$ ). While there is significant variability between types of organism, there is ample  
62 experimental evidence that many calcifying organisms are sensitive to OA <sup>6</sup>, and that  
63 thresholds exist below which some organisms become stressed and their well-being  
64 and existence becomes threatened <sup>7</sup>. Increasingly evidence suggests that the  
65 physiology and behaviour of calcifying and non-calcifying organisms can be impacted  
66 by increasing OA <sup>8</sup>, with cascading effects on the food chain and protein supply for  
67 humans <sup>3</sup>, and alterations to the functioning of ecosystems and feedbacks to our  
68 climate <sup>9</sup>.

69

70 In 2012 the Global Ocean Acidification Observing Network (GOA-ON, [www.goa-](http://www.goa-on.org)  
71 [on.org](http://www.goa-on.org)) was formed in an attempt to bring together expertise, datasets and resources to  
72 improve OA monitoring. At present, OA monitoring efforts are dominated by *in situ*  
73 observations from moorings, ships and associated platforms. Whilst key to any  
74 monitoring campaign, *in situ* data tend to be spatially sparse, especially in  
75 inhospitable regions, and so on their own are unlikely to provide a comprehensive,  
76 robust and cost effective solution to global OA monitoring. The need to monitor and  
77 study large areas of the Earth has driven the development of satellite-based sensors.

78

79 Increasingly, as *in situ* data accumulate, attempts are being made to use *in situ*  
80 hydrographic data <sup>10-13</sup> and/or remotely-sensed data <sup>14, 15</sup> to provide proxies and  
81 indicators for the condition of the carbonate system, enabling data gaps to be filled in  
82 both space and time. The increased availability of *in situ* data creates a substantial  
83 dataset to develop and test the capabilities of satellite-derived products, and we  
84 suggest that the recent availability of satellite-based salinity measurements provides  
85 new key insights for studying and assessing OA from space.

## 86 **2. The complexities of the carbonate system**

87

88 The oceanic carbonate system can be understood and probed through four key  
89 parameters: total alkalinity (TA), dissolved inorganic carbon (DIC), pH and fugacity  
90 of CO<sub>2</sub> ( $f_{\text{CO}_2}$ ). The latter may be replaced with the related partial pressure of CO<sub>2</sub>,  
91  $p_{\text{CO}_2}$ , from which  $f_{\text{CO}_2}$  can be calculated, and the two are often used interchangeably.  
92 In principle, knowledge of any two of these four is sufficient to solve the carbonate  
93 system equations. However, over-determination, the process of measuring at least  
94 three parameters, is advantageous.

95

96 The relationships between the different carbonate system parameters are  
97 fundamentally driven by thermodynamics, hence influenced by temperature and  
98 pressure, and knowing these is fundamental for calculating the carbonate system as a  
99 whole <sup>16</sup>. Water temperature is the major controller of the solubility of CO<sub>2</sub> <sup>17</sup>, so  
100 seasonal changes in sea temperature can, depending on the region, be significant for  
101 driving changes in  $f_{\text{CO}_2}$  (and consequently DIC and pH). Salinity affects the  
102 coefficients of the carbonate system equations. Hence to solve the equations, it is

103 necessary to estimate temperature, salinity and pressure along with carbonate  
104 parameters.

105

106 The ratio between ions (the constituents of salinity) will tend to remain constant  
107 anywhere in the global oceans, resulting in a strong relationship between TA and  
108 salinity <sup>18</sup>. Unfortunately, a universal relationship between TA and salinity does not  
109 apply in certain regions, for instance in areas influenced by freshwater outflows from  
110 rivers <sup>7</sup>, or areas where calcification and/or CaCO<sub>3</sub> dissolution occurs, such as where  
111 calcifying plankton are prevalent <sup>19</sup>. In these regions, it is therefore critical to gain  
112 additional local knowledge. For example, different rivers will have different ionic  
113 concentrations (and therefore different TA concentrations) depending on the  
114 surrounding geology and hydrology.

115

116 For DIC,  $f_{\text{CO}_2}$  (or  $p_{\text{CO}_2}$ ) and pH, the other important process is biological activity <sup>19</sup>.  
117 Removal or addition of CO<sub>2</sub> by plankton photosynthesis or respiration can be a  
118 significant component of the seasonal signal <sup>20</sup>. Biological activity, in turn, is driven  
119 by factors such as nutrient dynamics and light conditions, which again are regionally  
120 specific. Measurements of chlorophyll (a proxy for biomass) and/or oxygen  
121 concentration can be useful for interpreting the biological component of the carbon  
122 signal.

123

124 The combination of these processes means that it is extremely challenging to produce  
125 a global relationship between any component of the carbonate system and its drivers.  
126 To enable us to understand these dynamics, extrapolation from collected data points  
127 to the global ocean is needed, and along with model predictions, empirical

128 relationships and datasets are important and need to be studied and developed. OA  
 129 needs to be assessed using these relationships on a global scale, but regional  
 130 complexities, particularly where riverine and coastal processes dominate <sup>21, 22</sup>, cause  
 131 significant challenges for global empirical relationships.

132

### 133 **3. Current *in situ* approaches and challenges**

134

135 Laboratory measurements are the gold standard for assessing the carbonate system in  
 136 seawater, with accuracy far in excess of that achievable from satellites.<sup>23-25</sup> However,  
 137 research vessel time is expensive and limited in coverage, so autonomous *in situ*  
 138 instruments are also deployed, e.g. on buoys, with less accuracy <sup>26</sup>. A notable example  
 139 is the Argo network of over 3000 drifters, which measure temperature and salinity  
 140 throughout the deep global ocean. Interpolation of Argo data is much less challenging  
 141 than for most *in situ* measurements. Argo is the closest *in situ* data have come to the  
 142 global, synoptic measurements possible with satellites, but shallow or enclosed seas  
 143 are not represented (there are as yet no Argo instruments in the open Arctic Ocean).  
 144 Table 1 lists more examples. Of the four key parameters, only  $f_{\text{CO}_2}$  (or  $p_{\text{CO}_2}$ ) and pH  
 145 are routinely monitored *in situ*. As yet there are limited capabilities to measure DIC  
 146 and TA autonomously, hence these parameters must be measured either in a ship-  
 147 based laboratory or on land.

148

Dataset name and reference	Temporal period	Geographic location	Variables	No. of data points
SOCAT v2.0 <sup>27</sup>	1968-2011	Global*	$f_{\text{CO}_2}$ , SSS, SST	6,000,000+
LDEO v2012 <sup>28</sup>	1980-present	Global*	$p_{\text{CO}_2}$ , SSS, SST	6,000,000+
GLODAP <sup>29</sup>	1970-2000	Global	TA, DIC, SSS, SST, Nitrate	10,000+

CARINA AMS v1.2 <sup>30</sup>	1980-2006	Arctic	TA, DIC, SSS, SST	1500+
CARINA ATL v1.0 <sup>31</sup>		Atlantic		
CARINA SO v1.1 <sup>32</sup>		Southern Ocean		
AMT <sup>33</sup>	1995-present	Atlantic	pCO <sub>2w</sub> , SSS, SST, Chl, pH	1000+
NIVA Ferrybox <sup>34</sup>	2008-present	Arctic	pCO <sub>2w</sub> , TA, DIC, SSS, SST	1000+
OWS Mike <sup>35</sup>	1948-2009	Arctic	TA, DIC, SSS, SST, Chl	1000+
RAMA Moored buoy array <sup>36</sup>	2007-present	Bay of Bengal	SSS, SST	1000+
ARGO buoys <sup>37</sup>	2003-present	Global	SSS, SST	1,000,000+
OOI <sup>38</sup>	2014 onwards	Global (6 sites)	pCO <sub>2</sub> , SSS, SST, nitrate	New program
SOCCOM <sup>39</sup>	2014 onwards	Southern Ocean	SSS, SST, pH, nitrate	New program

149

150 Table 1. *In situ* datasets and programs that can be used for the development and  
 151 validation of OA remote sensing algorithms.

## 152 4. Potential of space based observations

153

### 154 4.1 Advantages and disadvantages

155

156 While it has proven difficult to use remote sensing to directly monitor and detect  
 157 changes in seawater pH and their impact on marine organisms<sup>22</sup>, satellites can  
 158 measure sea surface temperature and salinity (SST and SSS) and surface chlorophyll-  
 159 a, from which carbonate system parameters can be estimated using empirical  
 160 relationships derived from *in situ* data. Although surface measurements may not be  
 161 representative of important biological processes, e.g. fish or shellfish, observations at  
 162 the surface are particularly important for OA because the change in carbonate  
 163 chemistry due to atmospheric CO<sub>2</sub> occurs in the surface first. Thus satellites have  
 164 great potential as a tool for assessing changes in carbonate chemistry.

165

166 SST has been measured from space with infrared radiometry since the 1960s, but the  
167 data are only globally of sufficient quality for climate studies since 1991<sup>40</sup>. Satellite  
168 measurements of chlorophyll-*a* in the visible are more recent, starting in 1986 and  
169 delivering high quality global data since 1997<sup>41</sup>. Both measurements are made  
170 globally at high spatial and temporal resolution, but with data gaps due to effects such  
171 as cloud, which can greatly affect data availability in cloudy regions. SST is measured  
172 in the top few microns, and chlorophyll-*a* is generally measured to depths around 1-  
173 100m, depending on water clarity. Data quality can be affected by many issues, e.g.  
174 adjacent land or ice may affect both SST and chlorophyll-*a* retrievals, and suspended  
175 sediment may affect chlorophyll-*a* retrievals.

176

177 Only since 2009 has a satellite-based capability for measuring SSS existed. Increasing  
178 salinity decreases the emissivity of seawater and so changes the microwave radiation  
179 emitted at the water surface. ESA Soil Moisture and Ocean Salinity (SMOS) and  
180 NASA-CONAE Aquarius (launched in 2009 and 2011 respectively, both currently in  
181 operation), are L-band microwave sensors designed to detect variations in microwave  
182 radiation and thus estimate ocean salinity in the top centimeter. The instruments are  
183 novel and the measurement is very challenging, and research is ongoing to improve  
184 data quality<sup>42</sup>. The instruments can measure every few days at a spatial resolution of  
185 35-100km, but single measurements are very noisy, so the instantaneous swath data  
186 are generally spatially and temporally averaged over 10 days or a month, with an  
187 intended accuracy around 0.1 - 0.2 g/kg for monthly 200 km data. A particular issue  
188 close to urban areas is radio frequency interference from illegal broadcasts, which are  
189 gradually being eliminated but still result in large data gaps, particularly for SMOS.



190 The signal can be affected by nearby land or sea ice, and the sensitivity to SSS  
191 decreases for cold water, by about 50% from 20°C to 0°C<sup>43</sup>.

192

193 With these challenges, a central question is whether satellite SSS can bring new  
194 complementary information to *in situ* SSS measurements such as Argo for assessing  
195 OA. Direct comparisons<sup>44, 45</sup> indicate differences of 0.15-0.5 g/kg in a 1°x1° region  
196 over 10-30 days. The two are difficult to compare directly however, as Argo measures  
197 5m or more from the surface, so some differences are expected even in the absence of  
198 errors, especially where the water column is stratified. A better strategy might be to  
199 compare their effectiveness in estimating OA. How the uncertainties propagate  
200 through the carbonate system calculations is the subject of ongoing research.

201

202 Despite biases and uncertainties, satellite measurements of SSS in the top centimeter  
203 contain geophysical information not detected by Argo<sup>46, 47</sup>. In addition, Argo  
204 coverage can be much poorer than satellite SSS in several regions such as the major  
205 western boundary or equatorial currents and across strong oceanic fronts. The use of  
206 interpolated Argo products presents an additional source of uncertainty due to the  
207 interpolation scheme.<sup>48</sup> Satellite SSS can also resolve mesoscale spatial structures not  
208 resolved by Argo measurements<sup>49</sup>, and unlike Argo, satellites provide a synoptic  
209 ‘snapshot’ of a region at a given time.

210

211 Regular mapping of the SSS field with unprecedented temporal and spatial resolution  
212 at global scale is now possible from satellites. The impact of using satellite SSS for  
213 carbonate system algorithms can now be tested, where previously there was a reliance  
214 on climatology, *in situ* or model data. For example, this provides the means to study

215 the impact that freshwater influences (sea ice melt, riverine inputs and rain) can have  
216 on the marine carbonate system. The use of satellite SSS data will also allow  
217 evaluation of the impact on the carbonate system of the inter- and intra-annual  
218 variations in SSS.

219

220 Recent advances in radar altimetry (e.g. Cryosat-2 and Sentinel 1 satellites and  
221 sensors) are already enabling significant improvements in satellite sea-ice thickness  
222 measurements<sup>50</sup>. Thin sea ice thickness can now also be determined from SMOS,  
223 complementing altimeter estimates mostly valid for thick sea ice<sup>51</sup>. Sea ice thickness  
224 is important for OA research as it indicates whether ice is seasonal or multi-year,  
225 supporting the interpretation of carbonate parameters. Altimetry is also used to  
226 measure wind speeds and increases the coverage of scatterometer estimates in polar  
227 regions. It provides higher-resolution (along track) estimates of surface wind stress,  
228 which can potentially be used to indicate regions of upwelling. Wind-driven  
229 upwelling causes dense cooler water (with higher concentrations of CO<sub>2</sub> and thus  
230 more acidic) to be drawn up from depth to the ocean surface. This upwelling can have  
231 significant impacts on local OA and ecosystems<sup>4, 52</sup>, especially at eastern oceanic  
232 boundaries<sup>53, 54</sup>.

233

234 It is important to emphasise that the use of Earth observation data to derive carbonate  
235 parameters should not be seen as a replacement for *in situ* measurement campaigns,  
236 especially due to the current reliance on empirical and regional algorithms. Earth  
237 observation algorithms need calibration and validation with *in situ* data such as those  
238 taken by GOA-ON, and if the carbonate system response changes over time, empirical  
239 and regional algorithms tuned to previous conditions may become less reliable.

240

241 **4.2 Algorithms for estimating carbonate parameters**

242

243 The four key OA parameters (pCO<sub>2</sub>, DIC, TA, pH) are largely driven by temperature,  
 244 salinity and biological activity, allowing empirical relationships to be developed using  
 245 *in situ* measurements of OA parameters. Table 2 shows a range of published  
 246 algorithms based on such relationships, while Figure 1 shows their geographical  
 247 coverage. Both illustrate that most of the literature has focused on the northern basins  
 248 of the Pacific and Atlantic and the Arctic, especially the Barents Sea, with all other  
 249 regions only attracting algorithms for a single parameter or none at all.<sup>55</sup>

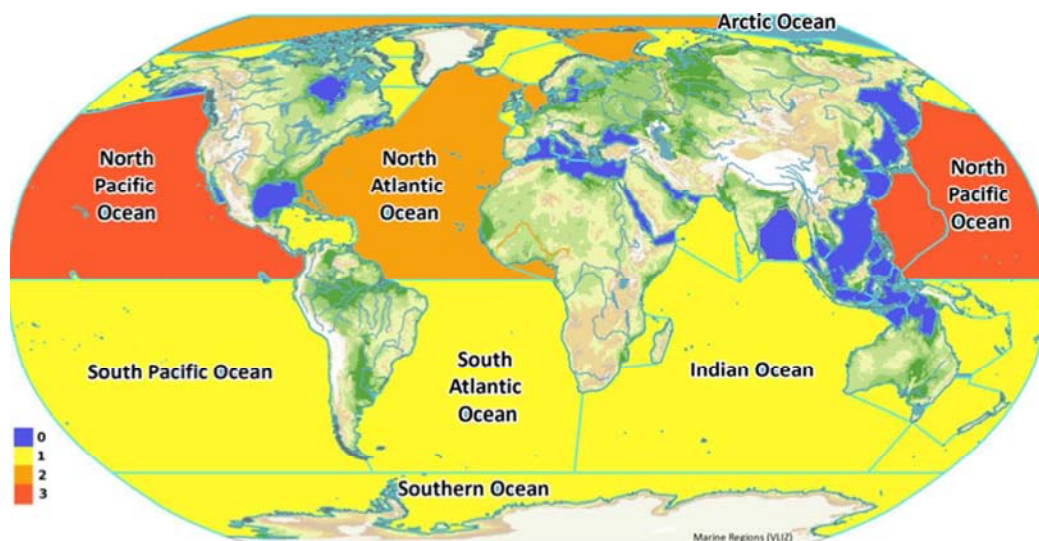
250

Parameter	Dependencies	Region and references
pCO <sub>2</sub>	SST	Global <sup>56</sup> , Barents Sea <sup>57</sup>
	SST, SSS	Barents Sea <sup>58</sup> , Caribbean <sup>14</sup>
	SST, Chl	N Pacific <sup>59</sup>
	SSS, Chl	North Sea <sup>60</sup>
	SST, SSS, Chl	N Pacific <sup>61</sup>
	SST, Chl, MLD	Barents Sea <sup>62</sup>
TA	SSS	Barents Sea <sup>57</sup>
	SST, SSS	Global <sup>18, 63</sup> , Arctic <sup>15</sup>
	SSS, nitrate	Global <sup>55</sup>
DIC	SST, SSS	Equatorial pacific <sup>64</sup>
	SST, SSS, Chl	Arctic <sup>15</sup>
pH	SST, Chl	N Pacific <sup>10</sup>

251

252 Table 2. Example regional algorithms for each carbonate parameter illustrating the  
 253 variable dependencies. Chl is chlorophyll-*a* and MLD is mixed layer depth.

254



**Figure 1.** The number of key carbonate parameters ( $f_{\text{CO}_2}$  or  $p_{\text{CO}_2}$ , TA, DIC, pH) for which regional algorithms exist in the literature that can be implemented using just satellite Earth observation data. Regions are indicative of open ocean areas, as implementation of algorithms in coastal areas may be problematic.

255

256 NOAA's experimental Ocean Acidification Product Suite (OAPS) is a regional  
257 example of using empirical algorithms with a combination of climatological SSS and  
258 satellite SST to provide synoptic estimates of sea surface carbonate chemistry in the  
259 Greater Caribbean Region<sup>14</sup>.  $p_{\text{CO}_2}$  and TA were derived from climatological SSS and  
260 satellite SST, then used to calculate monthly estimates of the remaining carbonate  
261 parameters, including aragonite saturation state and carbonate ion concentration. In  
262 general the derived data were in good agreement with *in situ* measured data (e.g.  
263 mean derived TA =  $2375 \pm 36 \mu\text{mol kg}^{-1}$  compared to a mean ship-measured TA =  
264  $2366 \pm 77 \mu\text{mol kg}^{-1}$ ). OAPS works well in areas where chlorophyll-*a* is low,  
265 however in regions of high chlorophyll-*a*, where net productivity is likely to perturb

266 the carbonate system, and in areas where there are river inputs, the approach tends to  
267 underestimate aragonite saturation state, for example <sup>21</sup>.

268

269 A quite different approach is the assimilation of satellite data into ocean circulation  
270 models <sup>65</sup>. The model output carbonate parameters can then be used directly. This  
271 allows satellite-observed effects to be extended below the water surface, albeit with  
272 the uncertainties inherent in model data. Here we seek to assess the direct use of  
273 satellite data through empirical algorithms to improve OA estimates.

274

### 275 **4.3 Regions of interest for Earth observation**

276

#### 277 **Arctic Seas**

278 It is increasingly recognised that the Polar Oceans (Arctic and Antarctic) are  
279 particularly sensitive to OA <sup>66</sup>. Lower alkalinity (and thus buffer capacity), enhanced  
280 warming, reduced sea-ice cover resulting in changes in the freshwater budget <sup>67</sup>, and  
281 nutrient limitation make it more vulnerable to future OA <sup>68</sup>. Retreating ice also  
282 provides increased open water for air-sea gas exchange and primary production <sup>69</sup>.

283

284 The remote nature of the Arctic Ocean provides difficulties for collecting *in situ*  
285 datasets, with limited ship, autonomous vehicle and buoy access, and *in situ* data  
286 collection during winter months is often impossible. Therefore the use of remote  
287 sensing techniques is very attractive, if sufficient *in situ* data can be found to calibrate  
288 satellite algorithms, and if the challenges of Arctic remote sensing can be overcome.  
289 These waters are very challenging regions for satellite remote sensing. For instance,  
290 low water temperatures reduce the sensitivity range of SSS sensors <sup>43</sup>, and sea ice can

291 complicate retrievals of SSS and chlorophyll-*a* <sup>70, 71</sup>. Improvement in the accuracy of  
292 high latitude satellite SSS is expected soon by combining observations from SMOS,  
293 Aquarius and the upcoming SMAP sensor, all polar-orbiting L-band radiometers.

294

### 295 **The Bay of Bengal**

296 This region is clearly a focus of current OA research with unique characteristics due  
297 to the large freshwater influence. The flow of fresh water from the Ganges Delta into  
298 Bay of Bengal (42,000 m<sup>3</sup>/sec) represents the second greatest discharge source in the  
299 world. Additionally, rainfall along with freshwater inputs exceeds evaporation,  
300 resulting in net water gain annually in the Bay of Bengal. Collectively these provide  
301 an annual positive water balance that reduces surface salinity by 3-7 g/kg compared to  
302 the adjacent Arabian Sea <sup>72, 73</sup>, resulting in distinctly different biogeochemical regimes  
303 <sup>74</sup>. Biogeochemically, the Indian Ocean is one of the least studied and most poorly  
304 understood ocean basins in the world <sup>74</sup>. This is particularly true for the Bay of Bengal  
305 where a relatively small number of hydrographic sections and underway surface  
306 observations have been undertaken, despite the notable influence of freshwater on  
307 particle dynamics, air-sea carbon flux and surface carbonate chemistry <sup>75-79</sup>. North of  
308 15° S, TA increases relative to salinity <sup>80</sup>, indicating the presence of an important land  
309 source that can broadly affect acidification dynamics.

310

311 To date there is little work on acidification dynamics and air sea exchange of CO<sub>2</sub> in  
312 the Bay of Bengal <sup>81-83</sup>. In 2013, the Bay of Bengal Ocean Acidification (BOBOA)  
313 Mooring was deployed for the first time in Bay of Bengal (15°N, 90°E) by PMEL  
314 (NOAA) and the Bay of Bengal Large Marine Ecosystem Program (BOBLME). Data

315 from the buoy will improve our understanding of biogeochemical variations in the  
316 open ocean environment of the Bay of Bengal.

317

318 It is an open question whether SSS can be used to estimate TA in the Bay of Bengal.  
319 An important step towards answering this question would be to investigate the spatial  
320 variability of the TA to salinity relationship in the region. Use of satellite SSS in the  
321 region is also challenged by heavy radio frequency interference.

322

### 323 **The Greater Caribbean and the Amazon plume**

324 The reefs in the Greater Caribbean Region are economically important to the US and  
325 Caribbean nations with an estimated annual net value of US\$3.1-4.6 billion in 2000 <sup>84</sup>.

326 At least two thirds of these reefs are threatened from human impacts including OA.

327 The skeleton of a coral is made of aragonite and the growth of their skeletons is  
328 reduced by OA <sup>6</sup>, and numerous studies have shown a net decline in coral  
329 calcification (growth) rates in accordance with declining CaCO<sub>3</sub> saturation state <sup>85</sup>.

330 The waters of the Greater Caribbean region are predominantly oligotrophic and  
331 similar to the subtropical gyre from which it receives most of its water <sup>14</sup>. Whilst the

332 often shallow water environments of coral reefs and the plethora of small islands can

333 make it challenging for Earth observation instruments to collect reliable data, the

334 oligotrophic nature and the similarities in water type across the whole region make it

335 ideal for the development of novel products. This region therefore provides an ideal

336 case study to develop and evaluate algorithms representative of a shallow,

337 oligotrophic environment.

338

339 The Amazon plume, south of the Greater Caribbean, is the largest freshwater  
340 discharge source in the world (209,000 m<sup>3</sup>/sec). It can cause SSS decreases of several  
341 units many hundreds of kilometers from land, and has an area that seasonally can  
342 reach 10<sup>6</sup> km<sup>2</sup>. These characteristics make it an ideal case study for testing and  
343 evaluating remote sensing algorithms, particularly to study the space-time resolution  
344 tradeoffs using SSS sensors.

## 345 **5. Future opportunities and focus**

346

347 The Copernicus program is a European flagship initiative, worth more than €7 billion,  
348 which aims to provide an operational satellite monitoring capability and related  
349 services for the environment and security<sup>86</sup>. The launch of the Sentinel-1A satellite in  
350 2014 signaled its start. Of the five Sentinel satellite types, Sentinels 2 and 3 are most  
351 appropriate for assessment of the marine carbonate system<sup>87-89</sup>. These satellites will  
352 provide chlorophyll-*a* and SST with unprecedented spatial and temporal coverage.  
353 The development of higher spatial resolution geostationary sensors that continually  
354 monitor chlorophyll-*a* and SST over the same area of the Earth also holds much  
355 potential for the future of OA assessment and research<sup>90</sup>. These satellites and sensors  
356 are able to provide 10 or more observations per day, allowing the study of the effect  
357 of tidal and diurnal cycles on OA. The societal importance of measuring and  
358 observing the global carbon cycle was further highlighted with the launch of the  
359 NASA Orbiting Carbon Observatory (OCO-2) in 2014. This satellite and its sensors  
360 are designed to observe atmospheric CO<sub>2</sub> concentrations, but its potential for marine  
361 carbon cycle and OA is likely to be a focus of future research.

362



363 SMOS and Aquarius have recently passed their nominal lifetimes, with SMOS now  
364 extended until 2017. Based on the lifetimes of previous satellite Earth observation  
365 sensors, they may well operate until the early 2020s. NASA's SMAP satellite, to be  
366 launched in January 2015, should provide short-term continuity. The development of  
367 the technology and the clear importance of monitoring ocean salinity are likely to  
368 support the development of future satellite sensors. Also, historical time series data  
369 from alternative microwave sensors hold the potential for a 10+ year time series of  
370 satellite based SSS observations <sup>91</sup>, and this sort of measurement record is likely to  
371 extend into the future as it forms the basis of a global SSS monitoring effort.

372

373 In summary, satellite products developed up to now in the OA context have been  
374 regional, empirical or derived with a limited variety of satellite datasets, rendering an  
375 effort to systematically exploit remote sensing assets (capitalizing on the recent  
376 advent of satellite salinity measurements) absolutely timely. To-date there is only  
377 regional application of satellite SST to address the issue of assessing OA <sup>62</sup>, along  
378 with two non-peer-reviewed attempts to calculate carbonate system products using  
379 satellite SSS data <sup>92,93</sup>. Supported by good *in situ* measurement campaigns, especially  
380 in places with currently poor *in situ* coverage such as the Arctic, satellite  
381 measurements are likely to become a key element in understanding and assessing OA.

382

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386 **Author Contributions**

387 The manuscript was written through contributions of all authors. All authors have  
388 given approval to the final version of the manuscript.

389

### 390 **Funding Sources**

391 This work was funded by the European Space Agency Support to Science Element  
392 Pathfinders Ocean Acidification project (contract No. 4000110778/14/I-BG).

393

### 394 **ACKNOWLEDGMENT**

395 This work was enabled by European Space Agency (ESA) Support to Science  
396 Element (STSE) Pathfinders Ocean Acidification project (contract No.  
397 4000110778/14/I-BG). The authors gratefully acknowledge the assistance of Diego  
398 Fernandez (STSE programme manager).

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