

Observation and data processing needs to fully utilise Earth Observation for monitoring carbonate chemistry in the Arctic Ocean

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Abstract

Areas of the Arctic Ocean are acidifying three to four times faster than other ocean basins. Our understanding of this changing carbonate chemistry is fragmented due to lack of data on both a temporal and spatial scale. Here we highlight the potential of satellite Earth Observation as a tool to monitor surface carbonate chemistry in the Arctic Ocean. We highlight two main research priorities to improve this capability: 1) coordinated *in situ* data collection of total alkalinity and dissolved inorganic carbon with satellite observed salinity, temperature, and chlorophyll a; and 2) continued development and expansion of databases of satellite and *in situ* observations that are well matched in time and space.

Introduction

Carbon dioxide (CO₂) has been increasing in the atmosphere since the industrial Revolution. The ocean is a natural CO₂ sink and absorbs approximately 26% of all anthropogenic carbon dioxide emissions (Friedlingstein et al., 2022). The long-term absorption by the oceans of CO₂ is leading to the slow decline of ocean pH, a process termed ocean acidification (Caldeira and Wickett, 2003). The Arctic Ocean is particularly susceptible to ocean acidification as CO₂ is more readily absorbed as surface waters cool and the Arctic Ocean has a lower buffering capacity compared to other ocean basins (Fabry et al., 2009) because the Arctic Ocean has lower carbonate ion concentration due to river run off and ice melt (Jones et al., 2021). Marine life can be impacted by ocean acidification (OA) in multiple ways, including shifts in acid-base balance, with resulting impacts on physiology, and the associated lowering of carbonate ion concentration can affect how calcifying organisms build and maintain their shells and skeletons (Feely et al., 2008). Short and OA-sensitive food webs (steps between different trophic levels) in Arctic waters means that small impacts towards the bottom of the food web, like plankton or shellfish, can have significant and catastrophic impacts on larger animals at the top like seals or whales. The Arctic Ocean is already experiencing low saturation levels of aragonite, a crucial calcium carbonate mineral for some shell building organisms (Niemi et al., 2021). This is not only important for calcifying organisms, but lower carbonate ion concentration results in a lower buffering capacity, and consequently means the pH can reduce faster, in response to CO₂ uptake. For example, in the Western Arctic Ocean there has been an observed decrease in pH three to four times faster than other ocean basins (Qi et al., 2022). However, pH and other carbonate chemistry data is spatially and temporally sparse in the Arctic, and seasonally biased towards summer data collection. Hence our knowledge on how Arctic waters, and the species and ecosystems within it, are responding more widely to ocean acidification is incomplete. Not only is it important to understand the carbonate chemistry in the Arctic in order to monitor for change, but there is also a need to map the present carbonate system habitat-space in relation to what is being experienced by Arctic Ocean organisms, such as fish populations (Green et al., 2021) on which we rely for food. This is needed to ensure that future projections of ecosystem response to climate change also include appropriate changes in carbonate chemistry.

The development of surface carbonate chemistry observation in the Arctic Ocean on greater spatial and temporal scale.

The ability to use alternative data sources to fill data gaps for the carbonate chemistry was first identified in the North Atlantic, where algorithms were generated to calculate total alkalinity and dissolved inorganic carbon (the whole carbonate system can be calculated from two carbonate variables) from other oceanographic variables collected *in situ*, such as salinity, temperature, silicate, nitrate, oxygen, and phosphate (Brewer et al., 1995). Algorithms were then further developed for global ocean basins and Arctic specific locations in following years through collating large *in situ* datasets, e.g. (Millero et al., 1998; Lee et al., 2000; Bellerby et al., 2005; Kaitin and Anderson, 2005; Arrigo et al., 2010). Nonetheless, the use of Earth Observation data as an input data source was not demonstrated until later after Land et al., (2015) and Salisbury et al., (2015) identified the possibility of using satellite salinity and temperature as inputs to exploit the *in situ* relationships to calculate spatially resolved and large scale dissolved inorganic carbon and total alkalinity. The use of satellite data as input methods is highly beneficial because salinity, temperature, and chlorophyll-a observations are available from satellites on much greater temporal and spatial scales than that possible from *in situ* data and data are collected throughout all seasons. For example, Land et al., (2019) demonstrated that satellite salinity and temperature could be used to estimate dissolved inorganic carbon and total alkalinity on a global scale with a root mean squared difference, RMSD of $17 \mu\text{mol kg}^{-1}$ and bias of $< 5 \mu\text{mol kg}^{-1}$ for total alkalinity, and RMSD of $30 \mu\text{mol kg}^{-1}$ and bias $< 10 \mu\text{mol kg}^{-1}$ for dissolved inorganic carbon. Green et al., (2023) applied these approaches to the Arctic scale using regionally specific data, and analysed published algorithms to demonstrate that spatially resolved total alkalinity and dissolved inorganic carbon can also be mapped for Arctic surface waters with well understood uncertainties. Satellite products showed potential however, there was a smaller number of corresponding data points between the satellites and *in situ* total alkalinity or dissolved inorganic carbon compared to other re-analysis products which currently limits their full exploitation.

Coordinated measurement effort between *in situ* and satellite community needed.

The small number of match-up points available between *in situ* data and satellites in the Arctic region, as demonstrated by Green et al. (2023), affects the ability to robustly analyse the performance of the satellite datasets. Moreover, any improvement in reducing uncertainties of algorithms will not be possible without more *in situ* data collection of total alkalinity and dissolved inorganic carbon as algorithm training is limited by the *in situ* data availability. The large seasonality in the Arctic Ocean plays an important role in driving the carbonate system dynamics, and hence a proxy for seasonality is important for future algorithm development to reduce uncertainties. However, in several areas it was not possible to include seasonal relationships because more *in situ* total alkalinity and dissolved inorganic carbon measurements are needed in winter. We recommend a pan-Arctic coordinated observation programme to provide a means of verifying and fully exploiting satellite data (e.g. salinity observations collected during times of satellite overpasses and observations). These will provide data for testing and conducting uncertainty analysis of algorithms that derive the carbonate system from satellite observations. This requires elevated communication and coordination between Earth Observation and *in situ* observation scientists and funders.

Continued development of match-up database between *in situ* and satellite datasets

In conjunction with targeted *in situ* data collection, the community also will need to use these data to continue the development and expansion of match-up databases which co-locate *in situ* and satellite in a consistent manner, such as OceanSODA match-up database (Land et al., 2023). There are presently few resources where *in situ*, satellite, re-analysis products and models are brought together in a consistent space and time representation so they can be effectively used for algorithm generation, testing and ongoing evaluation. We recommend that the observation community works towards a

unified database that allows coherent and spatially and temporally matched data to be collected and collated between these different data sources.

Conclusion

Satellite derived carbonate chemistry offers an untapped potential to fill the ability and identified need for synoptic and routine study of the surface carbonate chemistry data in the Arctic Ocean. Coordinating *in situ* measurement collection with satellite pass overtimes to improve available data for future algorithm development and continued development of matchup databases is needed to fully exploit these Earth Observation capabilities. The current families of salinity, temperature and chlorophyll-a observing satellites are enabled through long-term investments by international governments and agencies, and most of these observing frameworks have been making observations since the 1990s. Therefore fully exploiting them offers a long-term solution to year-round study and monitoring of the carbonate system in Arctic waters.

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