Pacific Ocean Acidification Working Group – 2014/2015 Report

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PACIFIC OCEAN ACIDIFICATION WORKING GROUP – 2014/2015 REPORT

by

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ABSTRACT

Hunter, K.L., Ross, A.R.S., Ianson, D., Miller, L.A., Pearce, C.M, Christian, J.R., and Pena, M.A. 2015. Pacific Ocean Acidification Working Group – 2014/2015 Report. Can. Manuscr. Rep. Fish. Aquat. Sci. 3070: iv + 23p.

Approximately one quarter of anthropogenic carbon dioxide (CO_2) released into the atmosphere is absorbed by the oceans, causing rapid and persistent changes in ocean chemistry, including a 30% increase in acidity during the last century. These changes are likely to have negative impacts on marine ecosystems and organisms that contribute significantly to the economy and ecology of the Pacific Region, particularly those living in nearshore environments where ocean acidification and its biological effects remain largely unmonitored and unstudied (Haigh et al. 2015). The Pacific Ocean Acidification Working Group (POAWG) was formed in 2014 to identify and suggest practical ways of addressing gaps in monitoring and research with regard to ocean acidification in Pacific Region. This POAWG report identifies those gaps and provides recommendations as to the minimum requirements for DFO Science Branch to maintain and support appropriate expansion of ocean acidification monitoring and research in Pacific Region.

RESUME

Hunter, K.L., Ross, A.R.S., Ianson, D., Miller, L.A., Pearce, C.M, Christian, J.R., and Pena, M.A. 2015. Pacific Ocean Acidification Working Group – 2014/2015 Report. Can. Manuscr. Rep. Fish. Aquat. Sci. 3070: iv + 23p.

Environ le quart du dioxyde de carbone anthropique (CO_2) relâché dans l'atmosphère est absorbé par les océans, menant à des changements rapides et persistants de la chimie de la mer, y compris une augmentation de 30 % de l'acidité au cours du dernier siècle. Ces changements auront probablement des incidences négatives sur les écosystèmes marins et les organismes qui contribuent de façon importante à l'économie et à l'écologie de la Région du Pacifique, particulièrement pour ceux qui habitent les environnements côtiers où l'acidification des océans et ses effets biologiques sont très peu surveillés et étudiés. Afin de combler les lacunes en matière de surveillance et de recherche de façon aussi pratique que possible, le groupe de travail sur l'acidification de l'océan Pacifique a été mis sur pied en 2014. Le groupe de travail sur l'acidification de l'océan Pacifique a travaillé à l'élaboration du présent rapport, ainsi qu'à la formulation de recommandations justifiant les « besoins minimaux » de la Direction des sciences du MPO en vue d'appuyer la recherche et la surveillance de l'acidification de l'océan dans la Région du Pacifique.

1.0 INTRODUCTION

Changes in the ocean carbonate system caused by increased absorption of atmospheric carbon dioxide (CO_2) pose a significant threat to marine ecosystems and resource use (Riebesell et al. 2010; Denman et al. 2011; Mathis et al. 2014; Waldbusser et al. 2014; Ekstrom et al. 2015). The ocean's absorption of anthropogenic CO_2 influences its buffering capacity and has led to increasing levels of acidity throughout the world's oceans, with a 30% change occurring over the last century (Solomon et al. 2007). Additional, non-CO_2 sources of acidification are numerous but not well quantified, and are mentioned only briefly in this report.

Carbon occurs naturally and in abundance in seawater in the form of dissolved inorganic carbon (DIC), which is the total of aqueous CO_2, carbonic acid (H_2CO_3), bicarbonate (HCO_3^-) and carbonate (CO_3^{2-}) ions (Eq. 1). The saturation state of several important carbonate minerals (e.g. aragonite and calcite) and the pH of seawater are determined by the relative proportions of these ions, which are controlled by abiotic and biologically-mediated reactions (Feely et al. 2012; Waldbusser and Salisbury 2014).

$$CO_2(aq) + H_2O \leftrightarrow H_2CO_3 \leftrightarrow HCO_3^- + H^+ \leftrightarrow CO_3^{2-} + 2H^+$$

Addition of CO_2 to seawater reduces the ratio of carbonate to bicarbonate ions and is associated with a decline in pH, increase in pCO_2 (partial pressure of carbon dioxide), and decline in saturation state. At lower pH, carbonate ions combine with hydrogen ions to form more bicarbonate, resulting in a lower saturation state of carbonate minerals. Solid calcium carbonate structures of marine animals (e.g. shells, skeletons, exoskeletons) dissolve when ambient conditions are undersaturated.

1.1 Ocean acidification in Canada's Pacific Region

Changes in the carbon chemistry of oceanic and coastal waters are being observed in the North East Pacific, including Canada's Pacific waters and adjacent jurisdictions (Takahashi et al. 2006; Wong et al. 2010). In the open waters of the North Pacific, CO_2 concentration at depth is naturally high because of global ocean circulation, i.e., this water is very old and so has accumulated remineralization products over a long period (Feely et al. 2004). West Coast Vancouver Island, as well as more southerly zones of the California Current, has been identified as an area of growing concern because annual coastal upwelling brings deep cold waters that are naturally acidic to the surface and over continental shelf waters (Feely et al. 2008). This upwelled water is rich in naturally-produced CO_2, but also carries an ever-growing load of human-generated CO_2. Exposure of the continental shelf to this water is variable because the uptake of CO_2 by phytoplankton and outgassing of CO_2 to the atmosphere removes some of the excess dissolved inorganic carbon (Ianson and Allen 2002). In contrast, when organic matter produced in surface waters sinks, its remineralization reduces the pH as well as the oxygen concentration of bottom waters on the shelf (Bianucci et al. 2011). The volume of shelf water containing this CO_2 signal associated with remineralization is small in relation to the very large volumes of deep, high-CO_2 waters offshore, but because the water column is shallow there is a resulting concentrating effect (Ianson et al. 2003), which enhances vulnerability to acidification. Thus, shelf marine ecosystems are particularly vulnerable to ocean acidification impacts for two reasons: (1) upwelling waters have relatively low pH, and (2) organic matter produced by upwelling remineralizes to further lower pH of shelf waters (Feely et al. 2008).

Decreases in pH correspond to decreases in calcium carbonate saturation level. The most significant impacts of declining pH on carbonate saturation state occur below the surface waters. In the northeast Pacific Ocean the aragonite saturation horizon is naturally shallow, as little as 100 m below the surface (Feely et al. 2004), and can be as little as 30-40 m below the surface in the coastal upwelling zone of the northern California Current (Feely et al. 2012). As global atmospheric CO_2 concentrations increase over the coming century, the saturation depth is likely to become even shallower, putting aragonite-dependent organisms close to the sea surface at risk (Orr et al. 2005; Feely et al. 2012). The aragonite saturation horizon in the Northeast Pacific is projected to continue rising (Christian and Riche 2013).

Although there are few data to support trend analysis at this time, open ocean observations of the decline in ocean pH in the Canadian Northeast Pacific are consistent with the global trend (Tanhua et al. 2015). In contrast, the carbon system in nearshore waters remains mostly unmonitored and unstudied. Existing investigations show high variability of the CO_2 system, but little is known about the overall oceanographic context or how land-based inputs (e.g., eutrophication, freshwater discharge) contribute to conditions in the nearshore marine environment.

1.2 POAWG mandate

Research is underway in various government and university research laboratories across Canada to model, measure and understand the extent and impact of acidification in Canadian oceans. Considerable multi-jurisdictional strategic planning and monitoring efforts are being made elsewhere (e.g., Washington State Blue Ribbon Panel 2012; National Science and Technology Council 2014; State of Maine 2014). Efforts in the USA now operate within a legal framework to manage ocean acidification. The Pacific Ocean Acidification Working Group (POAWG; a small group of DFO and university scientists) was formed in 2014 with the relatively modest ambition of initiating collaborative discussions regarding the minimum requirements needed to support and maintain ocean acidification monitoring and research in Canada's Pacific Region. This report provides the information and justification used to generate POAWG's recommendations to Science managers at Fisheries and Oceans Canada. The briefing note presented in the Appendix was the main communications document culminating from two meetings of POAWG members (biologists and oceanographers meeting separately) and a half-day workshop involving POAWG biologists and oceanographers on January 8th, 2015.

2.0 MONITORING OCEAN ACIDIFICATION IN PACIFIC REGION

2.1 Monitoring locations

2.1.1 Open ocean

Sampling for dissolved inorganic carbon has occurred as a regular part of Line P surveys (three trips/year) since 1986, and alkalinity since 1992, but the quality of the alkalinity data is low prior to 2000. Similarly, four shelf locations are sampled on LaPerouse Bank (two trips/year; Fig. 1). Trends in offshore waters are difficult to evaluate given the large spatial and temporal data gaps, and funding for the collection of these data has generally been fragmented and non-secure, although the Line-P program continues to provide a sustained platform for OA monitoring (Fig. 1). In June 2007, the US NSF and NOAA collaborated with DFO to deploy a surface mooring at Station P to monitor ocean-atmosphere interactions, carbon uptake, and ocean acidification. The mooring is serviced each spring during one of 3 annual cruises to Station P by the CCGS John P. Tully.

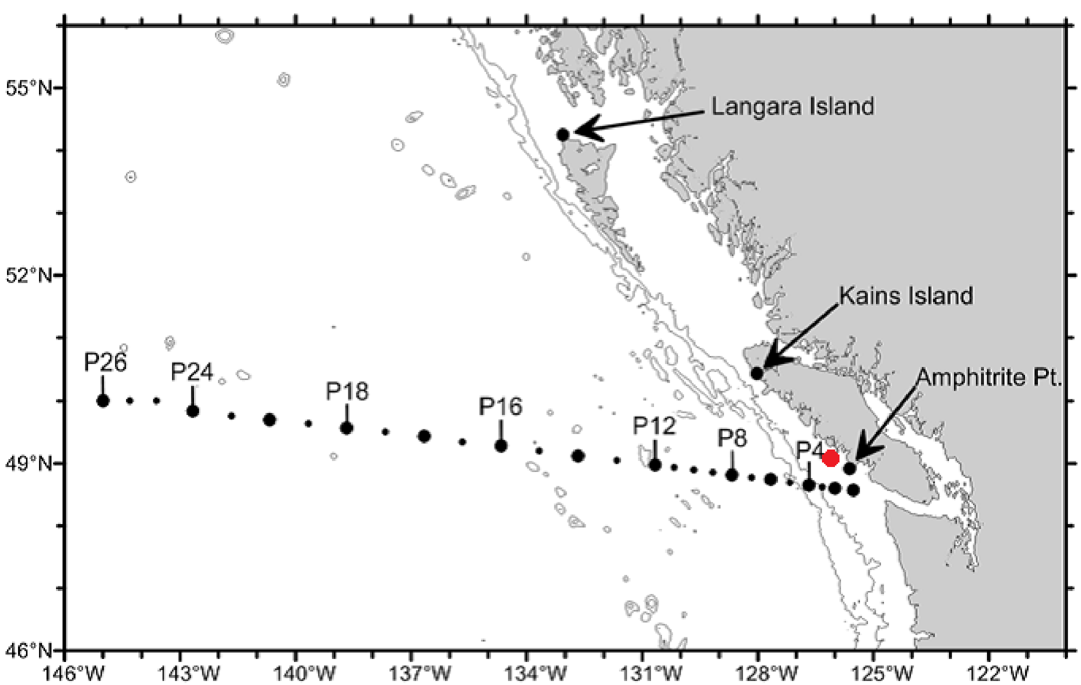

Figure 1. Location of Line P (stations P4-P26 shown) and LaPerouse Bank (approximate location indicated by red dot).

Global ocean time series were recently summarized by Tanhua et al. (2015) and downward trends in pH were identified for areas with sufficient data (Fig. 2). POAWG members Christian, Johannessen, and Miller reviewed the available data from the Pacific Region open-ocean time series. These show increasing acidification in the surface waters at open ocean sites. Variance in Line P observations is relatively high (Fig. 2) and could be result of frequency of collections, spatial/temporal variations in range of conditions within region, or underlying dynamic processes. These time series demonstrate the lack of global monitoring as well as the limitations of data collected along Line P, where low temporal resolution adds to the difficulties in trend detection (Wong et al. 2010).

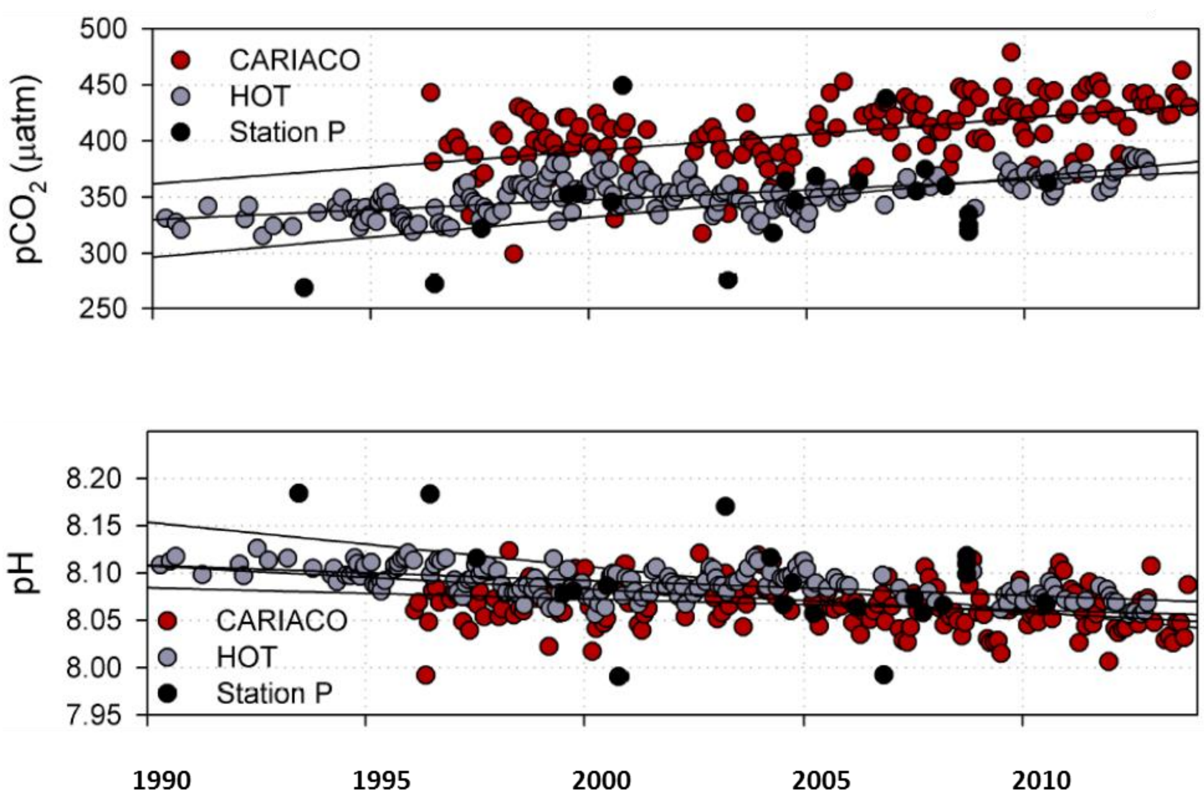

Figure 2. Station P and other oceanic time series (HOT and CARIACO) observations of pCO2 and pH from 1990-2015.

2.1.2 Nearshore waters

Since 2003, carbonate system samples have been collected and measured between 2-4 times per year at 4 stations as part of the Strait of Georgia monitoring program (Fig. 3). There are currently no estimated trends in OA for Pacific coastal waters because the data are too limited for trend analysis.

A recent review of BC coastal OA measurements highlighted the difficulties in monitoring OA in dynamic/semi-enclosed nearshore waters (Ianson 2013). The variable nature of nearshore waters, including fluctuations in fresh-water and organic matter (e.g., algal blooms, detritus, riverine organic input) inputs, needs to be considered when measuring carbonate parameters. In general, closing the carbonate system is simpler in open ocean seawater with its relatively uniform chemical composition, and care is required when adapting the methodologies developed for open-ocean conditions for measurements in nearshore waters. Present efforts to obtain discrete pCO_2 and calcium ion measurements should increase confidence in determining saturation states from dissolved inorganic carbon (DIC) and total alkalinity (TA) measurements for specific locations in nearshore waters.

Readers should refer to Ianson (2013) for more detailed information on Pacific Region nearshore OA observations and monitoring.

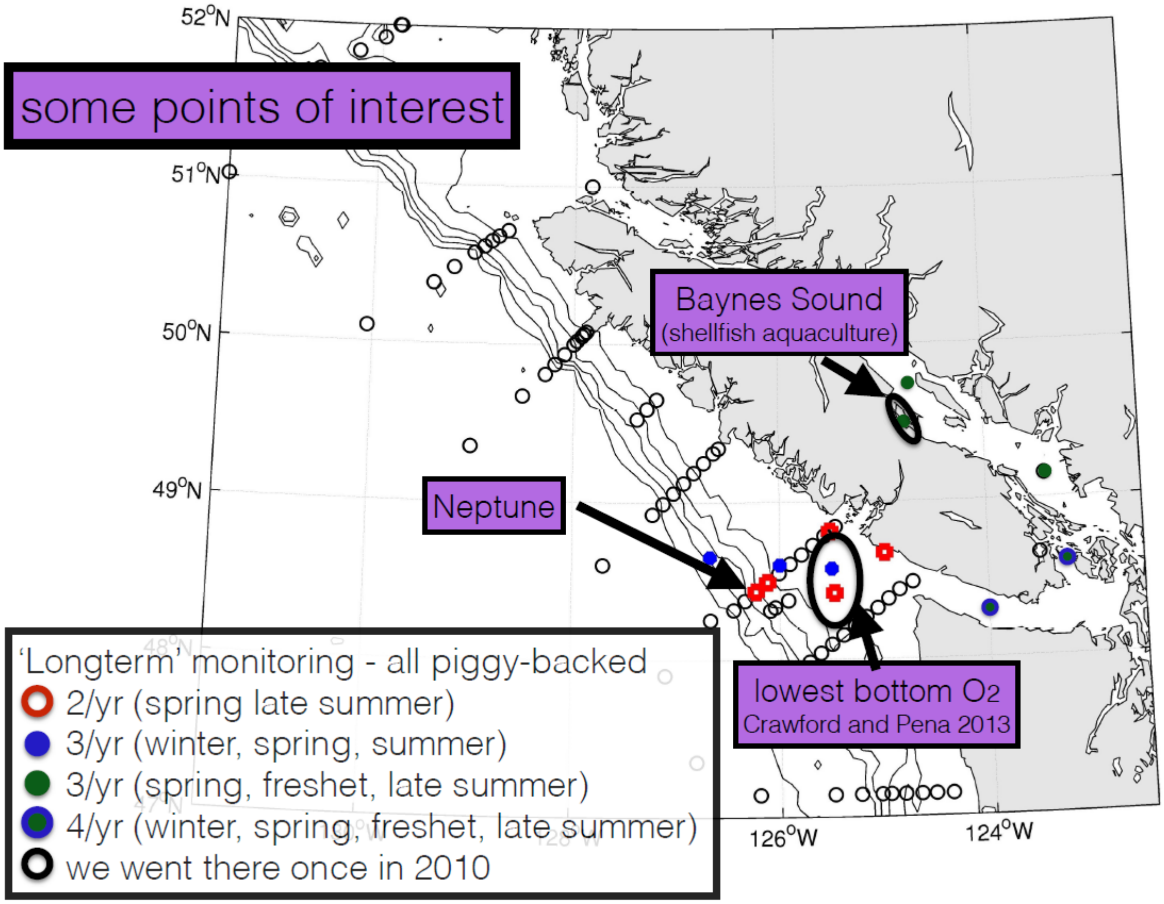

Figure 3. Baseline observations of carbon system parameters in coastal/nearshore waters in Pacific Region.

Because of the limited sampling and measurement of ocean acidification parameters in Pacific Region, our knowledge is incomplete and most of what we know about OA is restricted to the offshore area. This limits our understanding of the ocean carbonate system in Canadian waters and the interpretation of biological studies that monitor health, abundance, and diversity of Pacific Region resources.

2.2 Modeling changes in ocean chemistry

A biogeochemical model that includes the nitrogen, carbon and oxygen cycle has been developed for the British Columbia (BC) Shelf by Angelica Peña (DFO Pacific). The model was recently coupled to the ROMS (Regional Ocean Modeling System) ocean circulation model developed by Masson and Fine (2012) that covers the entire BC Coast, as part of the ACCASP project "Understanding the impact of climate change and variability on the plankton ecosystem and biogeochemistry of the BC coast". The model grid has a horizontal resolution of 3 km and 42 non-uniform vertical levels, with clustering near the surface. The model is constrained by tides, winds, atmospheric forcing, and fresh water discharge from rivers. The model has been successfully run for a decade and was validated by comparison with satellite and field observations. Model results are being analyzed to gain a better understanding of the interactions between circulation and local biogeochemical processes that lead to the development of coastal hypoxia and ocean acidification. The physical model has also been used to downscale future projections (climate change scenarios) (Foreman et al., 2014) and the biogeochemical model will be used to simulate the response of the BC shelf ecosystem to projected future climate, including dissolved oxygen concentration, pH, and aragonite and calcium carbonate saturation state.

The simple Ianson and Allen 2002 west coast model is also being used with stochastic forcing to predict extremes in pH (and O2) and determine how they are related to physical forcing and biogeochemical cycles (Ianson and Monahan in progress). In addition a surface (40m) model in the SoG predicts the timing of onset of surface saturation (with respect to aragonite) or the end of winter saturation in the southern SoG (Moore-Maley et al. submitted JGR) and carbonate modelling will be included in the full 3D SoG (MEOPAR) model.

2.3 Improvements for monitoring ocean acidification

Science-based decisions regarding the potential impacts of OA on marine resources in Pacific Region cannot be reliably achieved without long-term monitoring elements in place. Monitoring for OA needs to support oceanographic trend analysis (both nearshore and offshore) and track real-time changes in nearshore areas that overlap with important resources and aquaculture activities. Two methods of monitoring are required to establish trends in OA measurements and understand biological impacts in dynamic nearshore environments: 1) bottle samples collected at discrete locations away from and on shore and measured in the laboratory (as used historically by DFO to monitor ocean chemistry); and 2) new continuous field-based sensors with the capacity to measure carbonate parameters *in situ* and monitor biologically-significant OA changes in key nearshore areas.

It is essential that we gain an understanding of what drives pH in nearshore and coastal environments, including biological influences and feedbacks (e.g. ecosystem structure changes). In order to do this, the frequency of discrete measurements at La Perouse Bank and Strait of Georgia needs to be increased. Further work is also needed to establish what and where to monitor over the long term. In particular, priorities need to be established regarding the location of biological monitoring sites, which should ideally form part of a larger coast-wide monitoring network. Important shellfish growing sites (Baynes Sound/Quadra Island, Seal Island) have been suggested as candidate sites for continuous measurement system by POAWG.

Biologists and aquaculture industry leaders need reliable estimates of changes in ocean pH in the areas of most importance to them, including nearshore waters and inlets. Presently, long-term collections of biological information exist with no paired physical data relating to OA. Continuous recording/real-time data is the preferred protocol to understand larger variation and trends in the nearshore, complemented by more accurate but spatially and temporally limited data captured by discrete water samples.

There is a need to inform and engage the aquaculture industry with regard to the potential for collaboration, including the establishment of on-farm monitoring activities at key locations and best practices for sample collection and preservation.

2.3.1 Regional example of real-time pCO_2 measurement of nearshore seawater

Partnerships among west-coast shellfish farmers and scientists are operating several highly-accurate, continuous pCO_2 sensor systems (a.k.a. 'Burkalators') designed and built by Burke Hales (Oregon State University) as part of a coast-wide sensor array in US Pacific waters. Helen Gurney-Smith (Vancouver Island University) has partnered with Oregon State University and the Tula Foundation to run shellfish experiments at the closest location to Vancouver Island, using a continuous/real-time sensor recently installed at Quadra Island.

Such devices cost approximately US$55K to build and are not, as yet, commercially available. Although POAWG has established communication with the engineers of the US Pacific array it was made clear that a commitment from DFO to maintaining the array in Canadian waters would be needed before the present monitoring network could be expanded in that direction. Nevertheless, POAWG members saw this as a great opportunity to become part of, and contribute to, a coast-wide OA monitoring initiative while taking advantage of the recent technical advancements made by US colleagues.

This type of continuous monitoring system requires a highly-trained technician to oversee operation, maintenance, and data quality, although calibration issues are relatively minor for such systems. Investigation into other OA monitoring systems coming online could be advantageous.

2.4 OA monitoring gaps

Coarser-scale sampling at the present frequency does not allow for an accurate assessment of OA trends nor the resolution of issues surrounding short-term variability (e.g., seasonality, tidal influence). Knowledge of short-term variability is necessary to understand biological responses and oceanographic trends, especially in dynamic coastal environments. Higher-resolution data will also help to establish specific monitoring needs, including sampling locations and temporal resolution, in nearshore and coastal waters. Further work is also needed to determine differences between trends in pH at the surface and at depth.

There is a need to establish priorities for selecting monitoring sites and parameters that will enhance general biological understanding and address industry needs. The lack of information regarding land-based sources of OA amplification (e.g. eutrophication, fresh water input) and of a coordinated effort should be addressed when prioritizing monitoring locations. Further discussion of surface and/or depth measurements is also needed.

WHAT IS NEEDED TO IMPROVE OA MONITORING IN PACIFIC REGION?

- Include carbonate system parameters as DFO core measurements in Pacific coastal waters, at the ocean surface and at depth.
- Collaborate with real-time Pacific OA monitoring array by installing OA sensors at vulnerable locations (e.g. Baynes Sound, other important shellfish areas).
- Monitor OA at sites that capture range of variability to develop the coastal oceanographic context and understanding of biological responses to 'extremes'.
- Continue to monitor and work to understand extreme pH/pCO_2 variability in the SOG.
- Secure funding to support and improve existing discrete and continuous field-based OA monitoring. Secure funding to support nearshore research and monitoring, linked to laboratory experiments (Pearce, Harley laboratories).
- Sound monitoring of marine carbonate chemistry will contribute to further model development and refinement.

2.5 Considerations for measuring ocean acidification

Carbon data for Pacific region is currently generated by collecting water samples in the field and completing chemical analysis in the laboratory. Total alkalinity ($HCO_3^- + CO_3^{2-}$), pH, DIC and pCO_2 define the carbonate system in sea water. A critical step in validating OA methods and data is establishing that results for different carbonate parameters in a particular sample are consistent with each other. In any case, at least two of these parameters need to be measured in each water sample. Confidence in the measurement of individual parameters is also important because some biological effects may be specifically related to pH rather than, for example, alkalinity. Temperature and salinity determine the relationships among the different species and must be measured simultaneously and to a high precision and accuracy.

It is essential that carbonate system measurements are made using standardized analysis and quality control methods so that results are comparable and trends can be clearly established. Standard Operating Procedures for determining carbon parameters in sea water have been established (Dickson et al. 2007). Best practices for OA research and data reporting for field and laboratory applications have also been developed (Riebesell et al. 2010), including Certified Reference Materials made available by A. Dickson at Scripps Institution of Oceanography.

It is important to establish the requirements, in terms of precision and resolution, for proposed monitoring in coastal waters before deciding what is practical and feasible with the present methodology. The frequency and precision of OA measurements have been considered by the Global Ocean Acidification Observation Network (http://www.pmel.noaa.gov/co2/GOA-ON/),.

WHAT IS NEEDED TO IMPROVE OA MEASUREMENTS IN PACIFIC REGION?

- Researchers and industry must apply the correct, established protocols for sample calibration and use standardized field methods.
- Measurements must include a minimum of 2 of the 4 carbonate system parameters, as well as simultaneous measurements of temperature and salinity.

3.0 BIOLOGICAL IMPACTS

Calcification (the biotic precipitation of calcium carbonate-based minerals) is required for the formation of anatomical structures, including shells, in many marine organisms including oysters, clams, sea urchins, shallow water corals, deep sea corals, and calcareous plankton. This process becomes increasingly difficult as pH and calcium carbonate saturation state decrease. The two most important calcifying minerals in marine organisms are aragonite and calcite. Aragonite is more susceptible to increased acidity than calcite (Mucci 1983). Many organisms that are ecologically and economically relevant in the Pacific Region, or are staple food sources for culturally and economically important species (e.g. pteropods) use aragonite in their shells and structures (Boldt and Haldorson 2003; Armstrong et al. 2005).

Significant knowledge gaps exist concerning biological impacts of OA on marine ecosystems. Critical effects rooted in food web changes will be highly complex and difficult to predict even with extensive study (Haigh et al. 2015). Concurrent increases in water temperature and decreases in dissolved oxygen and are likely to produce synergistic effects.

According to Haigh et al. (2015) the most relevant risks posed by ocean acidification to Pacific Canadian fisheries and marine ecosystems are as follows:

- Shellfish aquaculture is highly susceptible to OA due to the direct impact of OA on shell formation and the dependence of the industry on hatchery production. These impacts are already experienced in BC (and WA). Wild shellfish experience similar difficulties but have the opportunity to adapt (*e.g.* Parker et al. 2013) and so will likely not be affected as rapidly and severely.
- The commercial BC fishery is dominated monetarily by salmon aquaculture. While uncertainty remains low, it is anticipated that the fish-killing alga *Heterosigma akashiwo* will gain a competitive advantage under OA, making blooms more frequent. Such blooms are already a significant issue for this industry in BC.

- Neurotoxins produced by other harmful algae are expected to become more potent under OA. Such blooms already cause shellfish closures in BC. If this increase in toxicity occurs, the shellfish industry will be affected. In addition, these toxins may cause decreased reproductive success, and even mass mortality, at higher trophic levels including fish, seabirds and marine mammals.
- Finfish are likely to experience OA impacts through foodweb changes. In BC examples include: the decline of pteropods, that are directly preyed upon by some fish (particularly Pink Salmon), and the anticipated decline of some echinoderms, that are eaten by various species of rockfish and flatfish.
- Habitat changes may also have a critical negative impact, in particular for juvenile fish. While these impacts remain highly uncertain, there may be a shift from upright macroalgae to algal turf. Also, local coral species (in BC primarily octocorals) that provide vertical structure may decline. Direct impacts of OA on finfish may also occur, but only at relatively high levels of CO_2.
- Behavioural changes at various trophic levels have been observed (*e.g.* increased downward swimming in phytoflagellates, decreased detection and avoidance of predators in larval fish) and postulated (*e.g.* increased movement to OA refugia such as eelgrass meadows). Such behavioural changes might alter the structure of marine communities in BC, and present another knowledge gap.
- Crabs may experience negative impacts under OA while other crustaceans significant to the harvest fishery in BC, like prawns, have not been well studied but appear to be more strongly sensitive to temperature than OA. In general, the juvenile stages of crustaceans are most vulnerable to OA, growing more slowly because they need to expend more energy under OA.

Regarding the potential impacts of OA on shellfish aquaculture, in a recent study Waldbusser et al. (2014) successfully decoupled pH, $p\mathrm{CO}_2$, and aragonite saturation state effects and found saturation state was the primary variable affecting early larval shell development and growth in two bivalve species. Because organisms will likely not experience low saturation states without concurrent low pH, the conclusions from this study do not contradict the importance of pH on marine bivalve larvae, but rather highlight the overwhelming significance of saturation state of bivalve shell development and growth.

3.1 Key knowledge gaps

There remain significant knowledge gaps with respect to the biological impacts of OA on marine ecosystems both globally and locally. The most critical of these impacts will likely be indirect as a result of food web changes, and so are complex and difficult to predict even with extensive study. Furthermore, OA-related changes will occur in concert with other climate-change impacts that may be even more severe. In particular, increasing temperature and decreasing oxygen levels are likely to produce synergistic effects.

Some key knowledge gaps, as summarized by Haigh et al. (2015) are as follows:

- There are no studies on Geoduck Clams, which form the basis of a lucrative fishery and a growing aquaculture industry in BC (although the latter is still in its infancy).
- Food web changes due to OA (*e.g.* in BC changes in the species composition of phytoplankton and decline of pteropods) are anticipated but remain unknown, as are the impacts of these lower level changes on higher trophic levels.
- There are few direct OA studies on local finfish species and none on Pacific Halibut and salmon, which drive the sport fishing industry. Similarly there are no studies on the adaptation of these local species to OA and multiple stressors, like temperature and O_2, that will be changing at the same time. Because sport fishing dominates fishery related income in BC, this knowledge gap is significant.
- Behavioural changes at various trophic levels have been observed (*e.g.* increased downward swimming in phytoflagellates, decreased detection and avoidance of predators in larval fish) and postulated (*e.g.* increased movement to OA refugia such as eelgrass meadows). Such behavioural changes might alter the structure of marine communities in BC, and present another knowledge gap.

WHAT IS NEEDED TO IMPROVE UNDERSTANDING OF BIOLOGICAL IMPACTS IN PACIFIC REGION?

- Conduct research and monitoring at vulnerable locations (e.g. Baynes Sound, other shellfish aquaculture sites) and at sites that capture the natural range of pCO_2 variability in order to understand the coastal oceanographic context and biological responses to 'extremes'.
- Conduct research during seasons with overlapping detrimental impacts for organisms of concern (such as harmful algal blooms) and at times that capture system variability and organism life cycle of interest.
- Laboratory research is essential for experimental study of biological effects.
- Ensure future funding for research on biological impacts.
- Develop biological OA research priorities (POAWG biologists).

4.0 HUMAN RESOURCES – BUILDING OA CAPACITY AND COLLABORATION

A number of human resource issues related to capacity and collaboration were identified during POAWG's discussions.

1) POAWG members expressed concerns regarding the Department's capacity to coordinate research and monitoring in a meaningful way given the lack of an OA program or directed OA funding within DFO.
    - Collaboration between DFO and stakeholders could support a wider sampling program. Local colleagues at several academic institutions are already working and collaborating to support coast-wide monitoring and research efforts (e.g. Gurney-Smith/Evans sensor).
    - To begin to address the needs raised by POAWG, it was highly recommended that a full-time position be created or allocated to (i) maintain coordination of regional activities related to OA research, and (ii) manage new OA monitoring infrastructure that may result from future OA funding and program initiatives.

2) Timely laboratory analysis of water samples is also a concern given the limited capacity (though high level of expertise) that currently exists within DFO.
    - Field crews may be able to collect additional water samples for OA analysis on existing surveys, but would require specialized equipment and training to do this correctly. Similar considerations would apply where industry partners are collecting and measuring samples to determine pH or other parameters.
    - There may be great potential for involvement of DFO Aquaculture staff in this regard.

5.0 POSSIBLE OA STRATEGIES AND ACTIONS IN PACIFIC REGION

The states of Washington and Maine have recently released reports on their approaches to managing the risks of OA (Washington State, 2012; State of Maine 2014). Not unlike BC, these states have strong seafood sectors that are reliant on shellfish species for a large proportion of their profits (Casey et al. 2008; Radtke 2011; DFO 2015). Strategy and action plans involving various levels of government support monitoring of and research into OA and its impacts on local ecosystems and species. These documents include strategies to improve the larger issue of anthropogenic carbon dioxide emissions and land-based sources/amplifiers of acidification. Key priorities stated in these documents include:

1. Understand the present landscape of OA monitoring and status in coastal waters.
2. Identify factors that contribute to ocean acidification and estimate the relative contribution of each.
3. Identify and investigate technical impediments to monitoring trends in biologically significant areas (coastal, nearshore).

4. Develop a collaborative approach to monitor status and trends of OA in marine waters.
5. Characterize biological responses of local species to OA and associated stressors.
6. Build capabilities for short-term forecasts and long-term projections of OA (and biological response).

These priorities were used as a starting point for POAWG discussions during a half-day workshop held in Nanaimo, BC on January 8th, 2015. During this workshop POAWG members generated a list of proposed strategies and actions intended to address the minimum requirements for effective OA monitoring and research in Pacific Region (Table 1). These recommendations are a first effort to align oceanographic sampling with biological research needs and to address the data gaps and quality issues identified in current sampling programs and surveys, with some additional suggestions on how to improve baseline and long term OA observations.

5.1 Risks of inaction

Lack of action on OA will limit DFO's ability to address Management and Science priorities including sustainable aquaculture and fisheries management, protection of fish habitat and species at risk, and potential solutions for mitigating threats. Lack of an effective monitoring and research program will limit options for adaptation by DFO and industry, since the data required to understand and predict the timing and location of impacts will be unavailable. Inaction on the part of DFO may also lead to negative responses from industry, First Nations, and the public. Considerable expertise already exists, and is being further developed in the Pacific Region; however, as stated in the original memo for the Pacific Science Executive Committee regarding the creation of the POAWG (April 2, 2014), lack of coordination may lead to inefficiencies and dysfunctional prioritization.

5.2 Future role of POAWG

As discussed during the workshop on January 8th, 2015 POAWG members are willing and able to continue working together on monitoring OA, sharing data and resources, conducting OA-impact research, and building research capacity in the Pacific Region, although the group will need some internal resources to continue working effectively with academic, industry, and other partners (e.g., MEOPAR, Ocean Networks Canada), including a dedicated co-ordinator position (see Table 1).

5.3 Next Steps

1) Continue building the business case for monitoring and researching OA in Canada, with the Pacific Region as our primary focus.
2) Potentially engage in an informal discussion on OA with industry to establish dialogue on industry concerns, expectations and needs to manage risks posed by OA.

3) Communicate the requirement for dedicated human resources to continue coordination activities related to OA monitoring and research in Pacific region.

Table 1. Summary of strategies and potential actions linked to minimum requirements for OA monitoring and research in Pacific region.

	Strategy	Action
WHERE	**AT** existing study and survey locations. **AT** surface and at depth. **AT** economically vulnerable locations (e.g. particularly Baynes Sound, other shellfish growing areas). **AT** sites that capture range of pCO_2 variability to develop the coastal oceanographic context and understanding of biological responses to 'extremes'. **IN LABORATORY** for experimental study of biological effects.	Include carbonate system parameters as DFO core measurements in Pacific coastal waters; POAWG members to connect with existing survey managers; Provide sampling training and equipment (2 additional surveys per year until coverage is complete). Secure funding for staff and training to operate a continuous pCO_2 monitoring system with bottle sample processing capacity. Work with VIU/Gurney-Smith and Evans for development of network of ocean monitoring nodes in BC. Secure funding to support nearshore research and monitoring, link to laboratory experiments (Pearce, Harley laboratories).
WHEN	**DURING** existing surveys and cruises. **DURING** seasons with overlapping detrimental impacts for organisms of concern (such as harmful algal blooms). **DURING** times that capture system variability and organism life cycle of interest.	Link to WHERE. POAWG to work with additional DFO staff, aquaculture industry representatives, and academia to determine collaborations. Propose a joint industry-POAWG meeting in 2015.
HOW	**BY** using existing knowledge of sample calibration and standardized field methods. **BY** developing a pCO_2 monitoring system at fixed location. **BY** increasing human resources capacity. **BY** supporting collaborations of POAWG/DFO and industry.	POAWG familiar with most recent methodologies. ½ FTE OA technician + ½ FTE POAWG Coordinator. Work with non-DFO colleagues to support coast-wide efforts (e.g. Gurney-Smith/Evans sensor); Potential for greater involvement of DFO Aquaculture staff.
WHAT	**CONTINUE** research on extremes in SOG. **CONTINUE** measuring a minimum of 2/4 carbonate system parameters and temperature and salinity simultaneously. **INITIATE** determinations of potential biological impacts of ocean acidification in BC on commercially important fisheries and aquaculture species.	Secure funding to support and improve existing discrete and continuous field-based OA monitoring. Working with POAWG coordinator, biological experts to develop and propose a collaborative work plan. Ensure future funding to allow experiments on biological impacts.

6.0 CONCLUSION

To address these knowledge gaps in as practical a manner as possible, the POAWG is recommending a 'minimum needs' research and monitoring agenda (Strategy, Action Plan, and Budget) for consideration, endorsement, and funding by the Science Executive Committee in 2015. There are likely to be significant consequences if no consistently-funded monitoring occurs or if DFO does not engage fully in other coast-wide monitoring discussions and developing programs.

7.0 ACKNOWLEDGEMENTS

POAWG Coordinators, Karen Hunter and Andrew Ross, are indebted to all POAWG members and advisors for their participation in discussions and a workshop and their review of this document and briefing materials prepared between May, 2014 to January, 2015. Robin Brown and the Pacific Science Executive Committee supported the formation of this working group. Burke Hales provided additional helpful information regarding the 'Burkalator' system. DFO's Aquatic Climate Change and Adaptation Services Program funded the POAWG workshop held in Nanaimo in January 2015.

7.1 2014-2015 POAWG Members

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9.0 APPENDIX

<u>MEMORANDUM FOR PACIFIC SCIENCE EXECUTIVE COMMITTEE</u>

<u>Recommendations for Research and Monitoring of Ocean Acidification in Pacific Region</u>

SUMMARY

Approximately one quarter of anthropogenic carbon dioxide (CO_2) released into the atmosphere is absorbed by the oceans, causing rapid and persistent changes in ocean chemistry, including a 30% increase in acidity during the last century. [1]

These changes are likely to have negative impacts on marine ecosystems and organisms that contribute significantly to the economy and ecology of the Pacific Region[2], particularly those living in nearshore environments where ocean acidification and its biological effects remain largely unmonitored and unstudied.

To address these knowledge gaps in as practical a manner as possible, the Pacific Ocean Acidification Working Group is recommending a 'minimum needs' research and monitoring agenda (Strategy, Action Plan, and Budget) for consideration, endorsement, and funding by the Science Executive Committee.

<u>BACKGROUND</u>

In 2014, DFO Science initiated the Pacific Ocean Acidification Working Group (POAWG) to establish minimum requirements for monitoring and studying changes in the ocean carbon(ate) system that affect fisheries (commercial, recreational, aboriginal) and the aquaculture industry in Pacific Region.

POAWG members are involved in limited OA monitoring and research activities regionally. For example, Ianson conducts research on ocean carbon state at limited sites off shore and nearshore. Gurney-Smith and Evans operate a new pCO_2 sensor with water piped continuously from nearshore waters to be linked into a wider nearshore OA monitoring network on the Pacific coast from Oregon to Alaska. Pearce is establishing a state-of-the-art experimental pCO_2 system at the Pacific Biological Station.

Two methods of monitoring are required to establish trends in OA measurements and understand biological impacts in dynamic nearshore environments: 1) bottle samples are limited to discrete locations away from shore and must be measured in the laboratory, and have traditionally been used at DFO to monitor ocean chemistry; and 2) new continuous field-based sensors with the capacity to measure carbonate parameters *in situ* can monitor for biologically-significant OA change in key nearshore areas. Science-based conclusions on the impacts of OA on Pacific Region resources cannot be reliably achieved without these long-term monitoring elements in place.

<u>RECOMMENDATION</u>

Relating directly to the *2016 Science Initiative*, POAWG recommends the following Strategy, Action Plan and, Budget for endorsement by the Science Executive Committee. These represent the minimum requirements for collaborative research and monitoring of ocean acidification in Pacific Region needed to address the priorities identified by POAWG during two meetings held in 2014 and a Workshop in 2015 as to where, when, and how monitoring and research should be carried out, and what parameters must be measured (Table 1). An accompanying budget is found in Table 2.

Table 1. Strategy/Action Plan

	Strategy	Action
WHERE	**AT** existing study and survey locations. **AT** surface and at depth. **AT** economically vulnerable locations (e.g. particularly Baynes Sound, other shellfish growing areas). **AT** sites that capture range of pCO_2 variability to develop the coastal oceanographic context and understanding of biological responses to 'extremes'. **IN LABORATORY** for experimental study of biological effects.	Include carbonate system parameters as DFO core measurements in Pacific coastal waters; POAWG members to connect with existing survey managers; Provide sampling training and equipment (2 additional surveys per year until coverage is complete). Secure funding for staff and training to operate a continuous pCO_2 monitoring system with bottle sample processing capacity. Work with VIU/Gurney-Smith and Evans for development of network of ocean monitoring nodes in BC. Secure funding to support nearshore research and monitoring, link to laboratory experiments (Pearce, Harley laboratories).
WHEN	**DURING** existing surveys and cruises. **DURING** seasons with overlapping detrimental impacts for organisms of concern (such as harmful algal blooms). **DURING** times that capture system variability and organism life cycle of interest.	Link to WHERE. POAWG to work with additional DFO staff, aquaculture industry representatives, and academia to determine collaborations. Propose a joint industry-POAWG meeting in 2015.
HOW	**BY** using existing knowledge of sample calibration and standardized field methods. **BY** developing a pCO_2 monitoring system at fixed location. **BY** increasing human resources capacity. **BY** supporting collaborations of POAWG/DFO and industry.	POAWG familiar with most recent methodologies. ½ FTE OA technician + ½ FTE POAWG Coordinator. Work with non-DFO colleagues to support coast-wide efforts (e.g. Gurney-Smith/Evans sensor); Potential for greater involvement of DFO Aquaculture staff.
WHAT	**CONTINUE** research on extremes in SOG. **CONTINUE** measuring a minimum of 2/4 carbonate system parameters and temperature and salinity simultaneously. **INITIATE** determinations of potential biological impacts of ocean acidification in BC on commercially important fisheries and aquaculture species.	Secure funding to support and improve existing discrete and continuous field-based OA monitoring. Working with POAWG coordinator, biological experts to develop and propose a collaborative work plan. Ensure future funding to allow experiments on biological impacts.

Table 2. Budget (Annual)

	Salary	**O&M**	**Tota l**
Continuous pCO_2 monitoring sensor with bottle sample processing capacity		100K (one time purchase) + 6K annual maintenance	106K
Training and technical support for *in situ* sensor maintenance, sample processing, QC/QA, data management (1/2 FTE; PC1 or equivalent; or combine with coordinator for 1 FTE)	60K +20% benefits =72K	30K (initial training)	102K
POAWG Coordinator (1/2 FTE; BI-02/3 or equivalent)	40K +20% benefits = 48K		48K
Nearshore and offshore cruise water sample collection and analysis (1200 samples/yr @$50/sample).		60K *ACCASP renewal to fund?	60K
TOTAL 2015-16	120K	196K	316K
TOTAL 2016-17 onwards	120K	66K	186K

STRATEGIC CONSIDERATIONS

RISKS OF INACTION – Lack of action on OA will limit DFO's ability to address Management and Science priorities including sustainable aquaculture and fisheries management, the protection of fish habitat and species at risk, and potential solutions for mitigating threats. Lack of an effective monitoring and research program will limit options for adaptation by DFO and industry, since the data required to understand and predict the timing and location of impacts will be unavailable. Inaction on the part of DFO may also lead to negative responses from industry, First Nations, and the public, with the possibility of litigation. Considerable expertise already exists, and is being further developed, in the Pacific Region but lack of coordination may lead to inefficiencies and dysfunctional prioritization.

ROLE OF POAWG – This group is willing and able to continue working together on monitoring OA, sharing data and resources, and building research capacity in the Pacific Region, but will need some internal resources to continue working effectively with academic, industry, and other partners (e.g. MEOPAR, Ocean Networks Canada).

POAWG MEMBERSHIP

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Jim Christian – DFO Science, OSD (Advisor role)
Lyanne Curtis – DFO Science, MEAD
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