Note: This is a draft of a whitepaper that will be used to inform our presentation on ocean acidification in the Gulf of Maine at the GOM2050 conference. It does not yet contain figures or contributions and edits from some team members.

Title: Draft Whitepaper report on Ocean Acidification for the Gulf of Maine 2050 conference

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Background

Ocean acidification (OA) in the Gulf of Maine and elsewhere is increasing predictably as rising levels of atmospheric CO_2 lead to higher oceanic carbon concentrations as carbon dioxide is increasingly absorbed by the ocean across the air-sea interface. The term "carbonate system" refers to a combination of chemical species produced by the equilibria,

$$CO_2 \leftrightarrow H_2CO_3^- \leftrightarrow HCO^- \leftrightarrow CO_3^{2-}$$

Over time, ocean uptake of CO_2 perturbs the carbonate system, with a concomitant reduction in surface pH. Since the beginning of the 19th century, the world's surface ocean has decreased by 0.1 pH units (Orr et al,2005; Calderia and Wickett, 2003) and further reductions on the order of 0.2-0.3 pH units are expected by 2100 (Feely et al. 2009) predictable from the increase in atmospheric carbon dioxide. These changes in ocean carbonate chemistry are not restricted to increased acidity; additionally, OA causes reductions in carbonate ion (CO_3^{2-}) concentration and in the saturation states of calcium carbonate minerals (Ω) (Bates et al. 2014). While there is some debate on the role that CO_3^{2-} availability and its proxy Ω play in shell development (Bach 2015, Jokiel et al. 2015, Bednaršek et al. 2015), it is presently thought that reductions in CO_3^{2-} and Ω represent a stressor to a variety of shelled marine invertebrates (e.g., Waldbusser et al. 2015). How OA affects marine ecosystems over time is a subject of growing concern (Intergovernmental Panel on Climate Change (IPCC), Fifth assessment).

The carbonate system in coastal waters is not only impacted by changes in atmospheric CO_2 concentrations, but also by varying fluxes of dissolved inorganic carbon, total alkalinity, and nutrients derived from local or remote sources. These processes are collectively known as *coastal acidification* which includes acidic river discharge (Salisbury et al. 2008), atmospheric deposition of acidic and alkaline compounds (Doney et al. 2007), and coastal eutrophication. The latter is stimulated by land- and atmospherically-derived nutrient fluxes that promote intense autotrophic production in the surface with subsequent CO_2 production and pH reductions via heterotrophic respiration at depth (e.g. Cai et al. 2012). Further, the local carbonate system can be profoundly affected by mixing of water masses of unique chemical composition.

The Gulf of Maine (GOM) is a region of confluence for many processes that affect the carbonate system. For example, five large rivers discharge into the GOM, it is downwind of many of the coal fired power plants that produce acidic and alkaline compounds, and there is a south the north gradient in population density and eutrophication. Additionally, regional mixing of fresher and more saline waters near the coast from large tides, and the variability of large scale circulation patterns delivering water from warmer, saltier water masses from the South or cooler fresher waters of the North, contribute to temporal and spatial variability in carbonate chemistry. While studies over the last decade, including the 2015 Maine OA Study Commission, have identified these drivers of acidification in the Gulf of Maine (Salisbury et al. 2008; Wang et al, 2013; Strong et al. 2014; Gledhill et al. 2015; Maine OA Commission 2015; Salisbury et al, 2018), the relative contributions of each, and in particular the mixing of water masses, are not well understood.

The GOM is a productive temperate continental shelf sea bounded by Cape Cod to the south and Nova Scotia to the northeast. It is well known for its large semidiurnal tides and their resulting impact on mixing, and also for the high commercial value of its fish and shellfish landings. It is separated from the open northwest Atlantic by both Georges and Brown's Banks. Considerable control on seasonal to interannual circulation patterns is exerted via shelf-sea exchange through the narrow Northeast Channel (NEC) which separates Georges and Browns Banks and also from the fresher coastal source waters from along the Scotian Shelf (Geyer et al, 2006; Hetland and Signell, 2006; Townsend, 1991; Pringle, 2006; Feng et al, 2017). The GOM has an average tidal range > 3.0 m, and experiences large seasonal amplitudes in surface salinity (Geyer et al., 2004), net primary productivity (O'Reilly et al., 1987), sea surface temperature (SST) and pCO_2 (Vandemark et al, 2011). The key circulation feature impinging on the region is the Maine Coastal Current (MCC), which flows counterclockwise and delivers freshwater and constituents from the northeast into our region (Pettigrew et al., 2005).

Physical processes that deliver and mix the nutrient pools supporting the GOM ecosystem (e.g., strong tides, wind-driven mixing, large annual ranges in temperature and salinity) also generate thermodynamic variability in carbonate system parameters at diurnal and annual scales. Further, such processes contribute to an intense annual cycle of CO_2, whereby disequilibrium with the atmosphere is partially balanced by an air sea flux of CO_2 (Shadwick et al, 2012; Vandemark et al, 2012; Wang et al, 2017). The degree to which physical variability can modify OA in the Gulf of Maine is substantial (Salisbury and Jonsson, 2018). In a climatological study using data from 1950-2013, the GOM records an intra-annual SST range of 15.5°C y^{-1} and salinity range of 2.2 (Richaud et al. 2016). The annual temperature range alone elicits a significant change in the carbonate system. For example, assuming the approximate mean GOM salinity (32.2), mean TA (2184 umol kg^{-1}) and an atmospherically equilibrated seawater surface of pCO_2 (400uatm), temperature variability causes an annual change of 0.013 in pH_{TOT} (pH, total scale) and 1.06 in the saturation state of the shell forming mineral aragonite (Ω_{AR}).

Within the GOM, the period spanning 2003-present (the period for which moored data exist [NERACOOS]) has been characterized by temporally coherent oceanographic phases that last on the order of one to three years. These phases result from periods of primarily warm slope water intrusions into the GOM's deeper layers, bringing warm, salty and high nutrient waters, which generally alternate with episodes of increased shelf water fluxes from the Nova Scotian Shelf that bring colder and fresher, low nutrient waters to the GOM (e.g., Townsend et al., 2014; 2015). Beginning about 2008 the GOM entered an extended warm and salty phase that persisted until just recently, and which was an important contributor to the anomalously warm surface waters reported by Pershing et al. (2015). However, the last seven years, since 2013, has witnessed greater short-term variability, with some of the coldest (and freshest) and warmest (and saltiest) episodes in the 15+ year record. The timing of these water mass fluxes and associated surface temperature changes supported by atmospheric heat flux (Chen et al, 2014; 2018) have combined to produce short-term, rapid warming of surface waters in the Gulf (on the order of 0.15°C^{-y}) as reported by Pershing et al. (2015). Such water mass fluctuations may be related to changes in the Labrador Current (Mountain, 2012; Townsend et al., 2010; 2015; Claret et al, 2018) and a northerly shift of the Gulf Stream as described in Saba et al. 2015 (also see Grodsky et al. 2017).

Under the IPCC "business-as-usual" CO_2 emission scenarios for 2100 used to drive global coarse resolution models, OA is projected to cause global annual economic losses in the $100s billions, representing decreased shellfish production and the loss of functional and economic value of coral reefs (Narita et al. 2012). Oceanographic, social, and economic variability all dictate that the impacts of OA will not be uniform. Recent large-scale and regional studies show that the combination of global and local drivers of acidification in the Northeast United States region make New England's shellfisheries – including both its wild harvest fisheries and aquaculture production, and the communities that rely on them – potentially among the most vulnerable to OA in the United States (Ekstrom et al. 2015, Gledhill et al. 2015). Regional economic analyses, focused on the scallop industry and scallop landings in Massachusetts, found that OA in the region is projected to threaten tens of thousands of jobs and cause hundreds of millions of dollars of losses during the 21st century (Rhueban et al, 2018, Cooley and Doney 2009, Ekstrom et al. 2015, Cooley et al. 2015).

Acidification In the Gulf of Maine

Over longer (centennial) time-scales ocean acidification in the Gulf of Maine plays out in similar fashion to the global ocean whereby it has experienced considerable declines in pH and carbonate ion availability since the pre-industrial period due to rising atmospheric CO_2 concentration. The seasonal variability of the carbonate system of the water column in the GOM is mostly affected by and largely synchronized with the seasonal progression of stratification-overturn, primary production, respiration-remineralization and water mixing, where different processes may alternate to exert the main control on the variability at certain times of the year (Wang et al., 2017). Surface production can be tightly coupled with remineralization in the lower water column, especially during high production seasons that can result in occasional aragonite undersaturation. From spring to summer, carbonate chemistry in the surface shows a progression from a production-respiration balanced system to a net autotrophic system. Overall, photosynthesis-respiration is the main driver controlling the seasonal variability of Ω_{AR} (Wang et al, 2017). However, as with other coastal systems, other short-term and decadal modulations of the carbonate system can maintain a state, such that there is a dis-equilibrium of ocean CO_2 with respect to the atmosphere. Interannual variability of the system is governed by the magnitude of ocean productivity (which can significantly raise or lower ocean CO_2) and by the relative supply of differing water sources. Waters sourced from the Labrador Current and Gulf of St. Lawrence tend to have lower carbonate ion concentrations (and thus lower Ω) versus those supplied by the higher salinity Gulf Stream. Within the Gulf, these waters are subsequently modified by remineralization/respiration processes as well as from riverine inputs (Wanninkhof et al., 2015; Wang et al., 2017). Sutton et al., (2016) performed an analysis of several buoyed assets in the region and, adopting assumptions about past atmospheric CO_2 values, concluded that Ω_{ar} never dropped below 1.6 througout the preindustrial period. However, the threshold of Ώ=1.6 is currently exceeded in the surface waters of the Gulf 11-31% of the time from late winter to spring with peak exposure to low Ω_{ar} in February and March.

Another important consideration, however, is that the direct observations on which these findings were based are likely biased provided the relative short history of direct high-quality carbonate chemistry observations in the GOM. In fact, the direct observational record does not reliably extend back beyond the turn of the millennium. Perhaps the earliest recorded regular observations in the carbonate system in the GOM started with the NOAA AOML underway pCO2 program which provided for repeated runs that transected through the GOM aboard the Skogafoss starting in late 2003 (ref). This was followed three years later by the deployment of the Coastal Western Gulf of Maine Mooring (43.023,-70.542). Each of these provide for limited spatial and only surface coverage and it wasn't until 2007 that regular dedicated research cruises began conducting near-synoptic inorganic carbon cruises of the full water column along select transects. Since then, these surveys have been repeating roughly every 3 - 4 years and are supplemented by seasonal surveys each year performed as part of the NOAA NMFS ECOMON surveys and individual studies (e.g., Wang et al., 2017). Such direct observations have described a system exhibiting the least buffered waters of the northeastern U.S. shelves which may make them exceptionally susceptible to acidification (Wang et al., 2013). Indeed, if the GOM generally tracked the pace of ocean acidification in open ocean, a large part of the region might experience persistent subsurface aragonite undersaturation in 30-40 years.

In an effort to extend the observational record back several decades, Salisbury and Jönsson (2018) adopted the use of a General Circulation Model (GCM) applied to empirical algorithms trained from the Surface Ocean $CO_{2(aq)}$ Atlas (Bakker et al. 2016) and informed by satellite chlorophyll to derive estimates of past OA conditions in the GOM. The analysis of a 34-year reconstructed record (1981-2014) revealed instances of 5-10 year anomalies where the carbonate system is perturbed to an extent greater than expected solely from atmospheric uptake of CO_2. In fact, thermodynamic forcing resulting from recent temperature and salinity changes in the Gulf of Maine (between 2005-2014) appears to have partially compensated the effects of ocean acidification over the past decade by causing an actual increase in Ω_{ar} of 0.4. The analysis also revealed markedly different behavior between pH and Ω_{ar} whereby pH declines at a rate of 0.018 decade,$^{-}$ primarily driven by OA; but the OA effect on Ω_{ar} is partially obscured by increased temperature and buffering by higher salinity waters entering the Gulf of Maine. Using these data, a "time of emergence" estimate that describes the time it takes for the atmospheric CO_2 signal to emerge from background natural variability, found that it may require 30 years of sustained measurements to observe a discernible OA signal in pH and up to a century to observe the OA signal in Ω_{ar} (Salisbury and Jönsson et al., 2018).

Emerging Aquaculture in the Gulf of Maine

Expansion of sustainable aquaculture, including shellfish production, is seen as a critical solution to meeting global demand for protein (FAO 2016). Traditional agricultural resources are challenged by environmental changes and overuse, and wild harvest fisheries are stressed to the point of collapse. As the global population is projected to reach 10 billion by 2050 (UN 2015), meeting the world's nutritional demand will become increasingly difficult. Aquaculture has the potential to help increase the food supply. As of 2014, aquaculture provides half of the fish consumed by humans (FAO 2016). Additionally, a recent analysis suggests that the current total landings of all wild-caught fisheries could be produced through aquaculture using less than 0.015% of the total world ocean area (Gentry et al. 2017). Further, as wild harvest of geographically traditional species declines, transition to aquaculture can help maintain working waterfronts vital to rural coastal economies (Love 2016), including many communities surrounding the Gulf of Maine. While the US lags behind other countries, particularly Asian countries, in aquaculture production (FAO 2016), aquaculture is growing in the Gulf of Maine (Gulf of Maine Council 2010), with substantial potential for additional growth (Hale Group, 2016).

Aquaculture in the Gulf of Maine currently includes Atlantic salmon, the eastern oyster, blue mussels, quahogs, and sugar kelp, with technology being developed for raising sea scallops, soft-shell clams, sea lettuce, American eel, and Atlantic halibut. The Maine Department of Marine Resources does not report farm gate values for salmon, but based on total aquaculture harvest values, the salmon farm gate value was roughly $60.5 M in 2018 (Maine DMR, 2019). For all of Atlantic Canada for the period between 2011 and 2015, the annual average salmon farm gate value was just under $300M (Fisheries and Oceans, Canada, 2019). In Massachusetts, there has been a 526% increase in aquaculture growth from 2005 to 2014, resulting in a harvest of $23 million dollars (primarily oysters) by 2016 (Coastal Enterprise, Inc., 2018). Adding to this, the landed value of oysters in Maine was $8 M in 2018, up roughly 945% from $848,000 in 2005 (Maine DMR, 2019). The GOM provides ideal conditions to grow blue mussels, which perhaps represent the greatest source of affordable farm raised protein from the sea, but with only a 4% increase since 2008 (Hale Group, 2016). Pilot studies in the GOM have found favorable conditions for aquaculture production in the open ocean (Mizuta et al. 2019, Mizuta et al. 2019). Tlusty et al. (2017) found that in the GOM aquaculture could increase by 15.2% without affecting other marine uses.

There are currently five commercial shellfish hatcheries in Maine and Massachusetts and two-three research hatcheries. Hatcheries provide the means to: control growing conditions for the most vulnerable early life stages of marine species; use selective breeding to produce genotypes that are better able to endure changing environmental conditions; increase production of shellfish that are currently underrepresented in landings, which will improve the resiliency of the working waterfront as ocean acidification and warming make the Gulf of Maine less hospitable for traditional wild harvest species. This is critical because the Gulf of Maine wild harvest is dominated by two species: lobsters and sea scallops. In 2017, these two species represented 73.4% of total commercial fishing landings values in Maine, New Hampshire, and Massachusetts (NOAA Fisheries 2019). The dependence on these two species has grown substantially since the 1950s due to declines in landings of other species (Gledhill et al. 2015). Unfortunately, both species are vulnerable to ocean climate change, increasing the socio-economic vulnerability of the Gulf of Maine to OA and warming (Ekstrom et al. 2015).

Species sensitivity to Ocean Acidification in the Gulf of Maine

Many marine species are likely to be affected by projected scenarios in ocean and coastal acidification (OCA) by 2050 in the Gulf of Maine. Supporting evidence is striking for calcifying organisms (Gazeau et al. 2013; Waldbusser et al. 2014), and data continuously become available for other groups such as fish (e.g. Dixson et al. 2010; Rodriguez-Dominguez et al, 2018). The physiological effects of OCA on life stages and populations of particular species, including different and sometimes unknown mechanisms, are better understood than the consequences at ecological and ecosystem levels. Also, the short-term effects on marine organisms of changes in ocean chemistry such as decreasing Ω, pH and buffer capacity have been better characterized than long-term effects. Thus, a unified understanding of long-term combined effects of OCA with accompanying changes in circulation patterns, freshwater inputs and productivity, among other factors that are also projected to change in the region is still lacking.

In the Gulf of Maine, some progress has been made in understanding the effects of carbonate chemistry in key fisheries, such as lobsters, oysters and scallops (Gledhill et al 2015; Rheuban et al, 2018). A summary of the studies made on seven commercially important species of the New England/Nova Scotia region are shown in Table 1 of Gledhill et al 2015, including the American lobster, four species of bivalves, the summer flounder and the Atlantic longfin squid. Studies on more than 140 additional species living in, or related to species living in the region are also available in the online Supplemental Table S1 of Gledhill et al. 2015. Since that publication, more than 50 additional studies have been performed, some of which are highlighted below.

Fisheries landings in the Gulf of Maine (GOM) comprised over $1.2 billion in 2017, out of which bivalves and crustaceans, two groups identified as highly susceptible to ocean acidification and temperature increases, accounted for 74% of the total landings. In this region, bivalves supplied 36% of the total landings revenues in 2017, with the Atlantic sea scallop yielding $341 million dollars (28%) followed by the eastern oyster yielding $35 million (3%). The Atlantic Sea Scallop is also susceptible to increasing CO_2 (White et al, 2013) and recent integrated assessment models suggest that under different CO2 emission scenarios, and different impact and management conditions, sea scallop biomass could be reduced between 13% and 50% by the end of the century (Cooley et al. 2015, Rheuban et al. 2018). There is an obvious and urgent need to conduct research on how sea scallops respond to OCA and increased water temperature, so that the industry and managers can respond accordingly to maintain sea scallop stocks. Similarly, the Atlantic surf clam, another commercially prized species, distributed from Canada's Gulf of St. Lawrence to the state of North Carolina in the USA, has already experienced a northward shift in its geographic distribution of its populations (Timbs et al. 2019). Responses of bivalve species to OA depend on the life stage at the moment of exposure, with early life stages typically being more susceptible than juveniles and adults. The eggs, larvae, and juvenile bivalves tend to have reduced growth rates, biomass, and survival for most studied species (Richard 2015; Richards, 2017; Young and Gobler, 2018, Ventura et al. 2106, Gledhill et al. 2015). Although there are more studies with larvae, a few studies have focused on short term effects of OCA on adults and have found minimal change in length or in gaping behavior of the eastern oyster *Crassostrea virginica* (Clements et al. 2017, Clements et al. 2018). Also, most bivalve studies have been performed in the laboratory, but there have been a few studies in the field showing reduced settlement rates when low pH conditions prevail in sediments (Green et al. 2009; Clements and Hunt, 2018; Meseck et al. 2018). Research on other adult bivalves such as blue mussels, bay scallops, hard clams have shown reduced growth rates and tissue weights when exposed to OA (Griffith and Gobler, 2017; Ramesh et al. 2017; Young and Gobler 2018). Griffith and Gobler (2017) exposed adults of hard clams *Mercenaria mercenaria* and of bay scallops *Argopecten irradians* to increased pCO2 conditions (lower omega) to evaluate the response of their offspring to OCA conditions. Contrary to expectations, the offspring of elevated pCO2-treatment adults were significantly more vulnerable to acidification as well as additional stressors (ie thermal stress, food-limitation, and exposure to a harmful alga). Further research on the effects of OCA on bivalves in the GOM should continue targeting entire life cycles where feasible, multigenerational effects, regional populations, and combined effects of OCA with changes in other physical parameters (i.e, salinity, temperature) that are also changing in the GOM.

For bivalve species of the region, negative responses have been commonly obtained at aragonite saturation states lower than 2 (Table 1 of Gledhill et al 2015). Across species and life stages, many studies support a biological capacity to cope with changes in carbonate chemistry but this capacity is largely dependent on factors such as time of exposure, field versus experimental approaches, and methods for estimating aragonite saturation state (eg from seawater pH versus sediment pH), among others. For example, larvae of the soft-shell clam *Mya arenaria* reared for various hours at different omega levels, were unable to accrete new shells at Ω1.6 or lower (Salisbury et al. 2008), while a field study showed reduced larval recruitment at a much lower omega value during 18 to 35 days of observations (Green et al. 2009, 2013). Despite such differences, a critical threshold estimated from studies with as many species as available within a functional group (such as benthic bivalves), appears to be a useful criterion used to predict changes and set management actions.

American lobster is the top landing product in weight and revenue in the region, with $551 million harvested from the US GOM in 2017 alone (NOAA Fisheries 2019). Studies on the effects of OCA on different life cycle stages in lobster have produced conflicting results. Larval studies including up to stage IV of development found that warming had greater adverse effect than increased pCO_2, with a significant interaction between temperature and pCO_2 that resulted in changes in dry mass, carapace length, swimming speed and feeding rates (Waller et al. 2017). On the other hand, experiments with stage V to juveniles found increases in mortality, slower development, and increases in aerobic capacity under increased pCO_2 conditions (Menu-Courey et al. 2019). Similarly, McLean et al. (2018) found that increasing pCO2 resulted in decreases in length and biomass, longer intermoling periods, and more susceptibility to shell disease in juvenile lobsters. Juvenile lobsters also showed various detrimental physiological responses when exposed to increased pCO_2 and acute thermal stress for 60 days, including immunosuppression and reduced cardiac performance under increased OA and temperature (Harrington and Hamlin 2019). In summary, depending on the life stage, the American lobster may respond differently to OCA and they may be more susceptible to warming temperatures in acidified conditions (eg Rheuban et al 2018) than to OA alone (eg Ries et al. 2009).

Several studies on recreational and commercial fisheries from the region have also highlighted the complex response of finfish to OA. Atlantic sea herring (*Clupea harengus*) is an important commercial and keystone species at the base of the food web for forage fish in marine ecosystem in the region. Studies have looked at the effects of ocean acidification on swimming behavior, energetic costs, and survivorship with contrasting results. Leo et al. (2018) found significant differences in survival with increased OA and temperature conditions that resulted in higher metabolic rates. However, similar experiments found that increases in OA resulted in minimal changes in survival (Sswat et al. 2018), or that swimming behavior was unaffected (Maneja et al. 2018). The variability in results between experiments may be due to different populations, suggesting that population responses to OA should be further explored (Leo et al. 2018). Studies on the forage fish Atlantic silverside *(Menidia menidia*) and inland silverside *(M. beryllina)* highlighted differences between results from experiments where OCA is a unique factor and those from experiments including other stressors (i.e., temperature) in addition to OCA (Baumann, 2019; Gobler et al. 2018).

Additional laboratory and field studies have been undertaken with individuals from native populations living primarily in the Gulf and Shelf waters, or with larvae reared from local brood populations (e.g. Waller et al 2017, Zakroff et al. 2019). Cumulative progress made with multi-factorial experiments has highlighted interactions among environmental factors and the complexity of responses elicited among different life cycle stages of the same species. For example, restricted food availability seems to typically emphasize negative responses to increase pCO2 levels (or lower aragonite saturation estate) in various species of sea scallop (Sanders et al, 2013; Ramajo et al, 2016) and in the blue mussel (Thomsen et al, 2013).

Experimental studies have also illustrated the variability among different physiological parameters within the same life cycle stage for a single species. For example, Stiasny et al (2018) observed that cod larvae were larger under energy limitation in the elevated CO_2 treatment compared to the ambient CO_2 treatment but larvae under elevated CO_2 had developmental impairments in critical organs, such as the liver. From all these studies it is clear that our capacity to replicate environmental and biological complexity in experimental studies is limited, but more sophisticated and longer term studies are foundational to enable further understanding of physiological mechanisms, energetic balances in organisms, and population dynamic consequences of OCA in marine species. A handful of other studies, including responses through trophic webs (e.g. Jin et al. 2015) and other ecological interactions (eg

Schulz et al. 2017) have suggested potentially larger but varied ecological and ecosystem consequences of OA in GOM. Thus, a better integration of our current knowledge, regional capacity, predictive capability and collaboration potential will be key in addressing management and societal changes that ameliorate OA consequences in the region and preserve the sustainability of marine resources and the services they provide to the GOM.

Ocean Acidification Projections for the Gulf of Maine for 2050

Earth system models (ESMs) are the main tool for evaluating future climate conditions and currently, many are run simulating past and future climate conditions. Modeling identifies causes of historical changes, projects future conditions, and - when forced with global emissions scenarios - represents the consequences of the choice we face as a society. Many national and international agencies run such simulations. The results of these efforts are coordinated globally by the IPCC and referred to as the Coupled Model Intercomparison Project (CMIP). CMIP considers various representative concentration pathways (RCP) that are primarily based on human consumption of fossil fuels. Four pathways have been, namely RCP2.6, RCP4.5, RCP6, and RCP8.5, are identified according to a possible range of radiative forcing values in the year 2100 (2.6, 4.5, 6.0, and 8.5 W/m2, respectively). CMIP6, the latest round of projections, was just released in September of 2019. Global simulations project surface open ocean pH values to decrease by 0.3 pH units by 2081-2100 relative to conditions in 2006-2015 under RCP8.5 (IPCC, 2019). For RCP2.6, these conditions will very likely be avoided this century (IPCC, 2019).

The models used for CMIP6 coarsely resolve the ocean (~1 degree) and consequently neglect important coastal processes that can modify global rates of acidification locally in regions like the Gulf of Maine. Global models can be used to drive regional higher resolution models designed to resolve coastal processes important for constraining regional rates of acidification. The results of some of these regional projections are discussed below.

Dynamically downscaled biogeochemical projections

Lambert et al. (2019) projected ocean conditions using a coupled physical-biogeochemical regional climate model developed for the GSL and the Scotian shelf (Lavoie et al. 2019a) driven by three global projections from CMIP5 for the RCP 8.5 scenario. The three ensemble members include CanESM2, MPI-ESM-LR, and HadGEM2-ES, and the simulations are run for the 1970 to 2100 period. Future boundary conditions were built by adding the simulated trends from the ESMs to the observed climatology for the physical variables (see Z. X. Long et al. (2016) for temperature and salinity), as well as for nitrate, dissolved inorganic carbon (DIC) and dissolved oxygen. The trends from the ESMs that were used to build future boundary conditions for the regional model are generally consistent (Lavoie et al, 2019b). The regional model includes the Gulf of Maine but the results for that region were not analyzed until now.

The pH continues to decline in the future under the RCP8.5 scenario, with an average simulated decline of about 0.1 pH unit between 1991-2010 and 2041-2060 with the regional model (Fig. ?), which is consistent with the direction but not the magnitude of the global projections for the region. This decline is driven in the regional model mainly by the increase in DIC in the region, which occurs at all depths and in all three simulations (Fig. ?). We note that increasing

DIC is mainly attributable to increasing atmospheric CO2, but may also be exported into the region, or result via increasing rates of respiration. The DIC increase is greatest at depth. Alkalinity generally decreases at the surface and increases in all the regional simulations at depth (150-300m), the surface trend cannot be agreed upon by the three ensemble members in magnitude and thus is highly uncertain. These changes in alkalinity primarily correspond to the changes in salinity in the region with fresher surface waters and saltier deep waters.

The decrease in pH is greater in the GOM than in the Scotian Shelf or GSL (Lambert et al. 2019) because the DIC increase is greater in that area. The model suggests that this is caused by an increase in primary production, mainly by diatoms, and a greater mesozooplankton mortality in summer resulting from the higher water temperature, that both lead to an increase of local respiration of organic matter at depth in the region. Stratification is also stronger in the future which reduces the ventilation of subsurface waters.

Because the results were simulated continuously between 1970 and 2100, the simulations project the timing when key thresholds are exceeded in the region. Like pH, saturation state (Ω) continues to decline under RCP8.5. For key thresholds like the Ω aragonite and calcite, the thermodynamic threshold of 1 (annual mean) is reached in the benthic environment in all three ensemble members by 2060 in the southern GOM for aragonite, but is not exceeded by 2081 for calcite anywhere in the water column. For a Ω_{ar} state of 1.5, suggested to be energetically relevant to juvenile oysters, the threshold is surpassed surface by 2040-2060 with some uncertainty between the simulations, and is already surpassed in the benthic environment by 2020 for aragonite and by 2060 for calcite in the southern portion of the GOM.

Dynamically downscaled physical projections with empirical biogeochemistry

Dynamically downscaled projections exist for the GOM as described in the temperature white paper, but most neglect to include biogeochemistry. One approach to include biogeochemical fields in the projected conditions is to apply an empirical model for the carbonate system to the future conditions and uniformly add carbon dioxide to the DIC pool using the RCP scenario's atmospheric concentration in 2050 assuming the anthropogenic signal is well mixed throughout the domain. An empirical model for each carbonate system parameter was developed using a least-squares multiple linear regression

(MLR) of the carbonate system parameter on hydrographic variables from a series of cruises along the east coast of the US spanning 2007 to 2018 following the methods of Juranek et al. (2009), Alin et al. (2012) developed for sub-regions of the California Current System (McGarry et al. *in prep*). Anthropogenic carbon dioxide concentrations were added to the DIC computed from the MLR by first assuming the atmospheric concentration in 2050 from RCP 4.5 (475 ppm) and RCP 8.5 (550ppm) were equilibrated with the ocean using the solubility equations from Weiss et al (1974) for the projected temperature and salinity. The additional CO2 contributes to the DIC predicted from the MLR and was then computed using CO2sys (Lewis and Wallace, 1998) by inputting the pCO2 and TA computed using the MLR for the projected conditions in the future. The same method was done for the modern and the difference was added to the projected DIC from the MLR. This method will only be representative of the conditions experienced by the training data for the MLR. Because the dynamics of oxygen and carbon are linked, the inclusion of oxygen in the MLR improves the representation of the carbonate system.

However, the regional models used here did not have those variables available, so the MLR was made with temperature and salinity only. The results of these efforts are reported below from two different suites of dynamically downscaled regional climate projections.

DFO projections

The BNAM future climate simulation forcings are derived as anomalies from an ensemble of six IPCC coupled atmosphere-ocean future climate runs, for 2 future periods (2055 (2046-2065) and 2075 (2066-2085)), and 2 RCPs: 8.5 & 4.5. The results for 2050 predict lower TA in the region in general for both RCP scenarios, but with slightly higher TA at the surface for RCP8.5. In both cases, the TA anomaly is higher in the late fall/early winter (December-January) in the future scenarios. Under RCP8.5, this positive anomaly extends into the early fall as well (September -October) indicating increased TA during that period in the future.

In terms of DIC, projected conditions for 2050 are very different for RCP8.5 & RCP4.5. RCP8.5 conditions produce higher DIC concentrations across the year with nearly 80 umol/kg greater conditions than RCP4.5 – especially in offshore waters in the fall months. In both cases, the empirical model alone, without the adjustment for the higher atmospheric carbon dioxide concentrations, DIC concentrations are *less* than modern conditions suggesting the physical changes to the GoME along with biological feedbacks are acting to mollify the increases from the atmospheric change. The atmospheric contribution is nearly equivalent to this offset in RCP4.5 but far exceed the RCP8.5 atmospheric concentration in 2050.

ESRL results

The delta method was applied to the fields from three different global climate models (GFDL, IPSL and HadGEM) to drive the boundary conditions for a regional ocean model (ROMS) in the Northwest Atlantic, including the Gulf of Maine using RCP8.5 (Alexander et al. *in press*). All three ROMS simulations experienced lower TA at the surface, consistent with the projected salinity and dynamically downscaled biogeochemical projections described above. Seasonally, the late fall conditions (October – December) experienced the greatest magnitude of change – although the three simulations vary widely in the magnitude of the changes overall.

Projected conditions for 2050 are very different from modern for RCP8.5 in terms of DIC for all three ensemble members. However in all cases, DIC anomalies are highest offshore and lowest near the coast. While the magnitude varies across ensemble members, the fall produces the sharpest gradients in the anomaly between the coast and offshore and experiences the most variability between ensemble members. In all three ensemble members using the empirical model alone, without the adjustment for the higher atmospheric carbon dioxide concentrations, DIC concentrations are *less* than modern conditions suggesting the physical changes to the GoME along with biological feedbacks are acting to mollify the increases from the atmospheric change.

Comparison with observed historical trends

Uncertainty discussion

Gulf stream position

Internal vs external scenario driven...

Adaptive Measures

While elimination of fossil fuel emissions is the most credible solution for OA, several states have taken local actions to reduce local stressors and impediments to adaptation while technology is developed to transition to a fossil fuel free economy (e.g. Kelly et al. 2013). Local rates of acidification can be exasperated by coastal processes like nutrient runoff, land use change, and local emissions (Gobler et al 2014?; Kelly et al. 2013). Reduction of nutrient loading to coastal embayments and estuaries through the improvement of wastewater treatment plants and reduction of fertilizers will improve water quality measures including variables relevant to ocean acidification (Gobler et al 2014; Kelly et al. 2013). In addition, local emissions have been found to be important to OA signals in Monterey Bay (Chavez et al. year?). While this has yet to be shown for the Gulf of Maine, research can be done to determine the relative importance of these local stressors, but relieving them will not add to the problem. They are considered "no regret" actions for the region to take to adapt and mitigate to ocean acidification. Some regional actions can also be undertaken to promote improved water quality that are pro-active rather than regulatory (Maine OA Commission Report). Restoration of seagrass beds and support for the local production of kelp beds can consume DIC and raise pH, while recycling of shell material can act as a sediment buffer.

Regional models exist for the Gulf of Maine (See section above) and can be used as virtual laboratories to investigate these important choices prior to implementing these decisions. These models can also be modified and adapted to forecast ocean conditions relevant to coastal communities. One such forecast system for the region on the timescales of weather is in development with ocean acidification relevant variables included – the Northeast Coastal Ocean Forecast System (NECOFS). These tools can be used in combination with real time monitoring activities to keep coastal communities aware and ahead of the changing ocean conditions.

Local policies can limit adaptation options for the marine resource industry. These policies can be made more adaptive to allow for adaptation in the fishing communities in response to projected changes. Diversification of the working waterfront would allow access to emerging species and increase aquaculture. Commercial-scale hatchery technology research needs to be prioritized for species currently not produced in hatcheries (blue mussels, sea scallops) but will likely need to be in the future. Broodstock management programs for aquaculture species can help create disease resistant offspring, or offspring that are resistant to environmental changes such as OA. These actions look to the future and ensure its sustainability.

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