Communicating Ocean Acidification; Problems, Solutions, and Shellfish

Mentors: Heather Kerkering, Dr. Francisco Chavez

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ABSTRACT

The West Coast Shellfish industry is seeing negative changes in shellfish farming productivity, and ocean acidification is suspected to be the culprit. Scientists are seeking to understand both natural ecosystem variability and the impacts of anthropogenic changes on the acidity of the ocean. The Central and Northern California Ocean Observing System (CeNCOOS) is working to bridge the communication gap between research and the application of marine science. By bringing both scientists and stakeholders into a network, a better and more applicable understanding of changing oceanic conditions can be gained.

Shellfish recruitment and growth are very susceptible to acidic waters (low pH). Low pH periods of several days are a naturally occurring process on the West Coast associated with upwelling season, but anthropogenic inputs of CO_2 has exacerbated the natural affect on the aquaculture industry. Anthropogenic inputs to this system have decreased ocean pH by 0.1 over the last decade, and coincidently the aquaculture industry has suffered a decrease in shellfish larvae recruitment in recent years, costing hundreds of thousands of dollars to small coastal farmers (Feely et al, 2008, NOAA Ocean Acidification Steering Committee, 2010).

Better communication between stakeholders and scientists, and increased spatial and temporal data collection are called for by the NOAA Ocean Acidification Steering Committee (2010). Through MBARI I accessed data from two Ocean Acidification monitoring buoys located in the Northern Monterey Bay, and analyzed local interactions between pH and temperature parameters over a 2 months period. This temporal data was supplemented with data from a 2007 research cruise that spanned from Canada to Mexico. From these temporal and spatial data sets I was able to develop an algorithm to predict potential sea surface pH from satellite observed sea surface temperature was developed to aid shellfish farmers.

INTRODUCTION

As science has progressed so has the need to communicate cutting edge research to stakeholders and the public. Increases in CO_2 in the atmosphere have been mitigated by natural oceanic uptake of Carbon Dioxide, but this global favor has come at a cost. Ocean pH had been decreasing, and the West Coast of the United States is one of the first places to see negative biological and economic effects of ocean acidification. Ocean Acidification (OA) is the combination of natural, anthropogenic and climate factors. In the last decade low oceanic pH levels have gone from being a theoretical problem in the realm of chemical oceanography to one of economic and social parameters. On the West Coast of the United States in the last decade, the shellfish industry has seen noticeable decreases in production, leading to financial losses. Family aquaculture businesses add to the culture and heritage of coastal California, Oregon and Washington, and will be lost without these industries.

The ocean acts as giant buffer, absorbing approximately 30% of atmospheric CO_2 (NOAA Ocean Acidification Steering Committee, 2010). This oceanic favor comes at a cost, decreasing ocean pH by 0.1 in the last decade (Feely et al, 2008). The affects of decreased pH have been seen on many different levels, of which aquaculture is just one of many. Coral bleaching is one of the most personable and dramatic affects, endangering tropical ecosystem health, and the livelihood of small coral islands through sea level rise and loss of habitats. Shellfish farming has seen a decrease in larvae setting (NOAA Ocean Acidification Steering Committee, 2010). In the Central California region the affects of decreased pH are exacerbated by upwelling conditions, which are projected to increase in the next decades as inland global temperatures increase (Feely et al, 2008).

In 2009 the Federal Ocean Acidification Research and Management (FOARAM) act made it necessary by an act of congress to consolidate OA research under one director that funds and advises data collection, fisheries managers, sensor development, and fisheries scientists. The NOAA OA office is charged with implementing a research plan by 2017, which includes inland lakes, open ocean, coastal ocean, estuaries and inlets, and coral reefs. The federal government is particularly interested in resources and economic benefit, but the OA plan is from an academic point of view. The growers and industry make OA issues real to the government, and for this reason the California Current Acidification Network (C-CAN) brought together multiple agencies in July of 2010 and 2011 to collaborate on a West Coast shellfish industry and scientific contribution to NOAA's OA plan. In addition to these workshops, two more workshops will be held in the future; an OA data management workshop, and an international observing network workshop.

West Coast shellfish aquaculture accounts for over 3000 jobs and brings in over $117 million in revenue to mostly small coastal communities (C-CAN 2010 meeting). Since 2005, aquaculturists have observed significant reduction in shellfish larvae production and recruitment. From these large financial losses rises the need for a monitoring and communication network between scientists and industry stakeholders. In 2008 and 2009 Taylor Shellfish Company (Dabob Bay, WA) observed a loss of 80% in their hatchery production. Likewise in 2008, Whiskey Creek Shellfish Company (Netarts Bay, OR) produced only 25% of their normal crop. Both businesses suspected low pH events to be the culprit, and contacted local scientists for more information, spurring an academic and industry collaboration studying the effect of low coastal pH events on shellfish aquaculture.

PROJECT GOALS:

Through this summer internship with the Monterey Bay Aquarium Research Institute (MBARI) and the Central California Ocean Observing System (CeNCOOS) I have combined the information collected by cutting edge scientific research at MBARI into a format that could be used by a modern communication platform such as CeNCOOS.

- **Communication:**

1. Understand and effectively communicate ocean acidification science to growers through CeNCOOS.
2. Learn what methods are best for communicating science to shellfish growers

- **Science:**

3. Find an easily measured indicator of pH. Sea surface temperature is a common physical characteristic that is collected in many locations along California's coastline. This variable can be used to develop an algorithm to calculate potential pH.

MATERIALS AND METHODS

COMMUNICATION:

The Central California Ocean Observing System (CeNCOOS) uses a modern interactive webpage to communicate ocean issues and observing systems to the public, educators, managers and stakeholders. As a network platform, CeNCOOS has already directly assisted aquaculture in the Monterey region by providing relevant real time and near real time data during a Harmful Algal Bloom event (HAB) in 2007. Through real-time satellite and mooring wind and temperature data the Monterey Abalone Company was able to mitigate their crop losses due to this uncommonly strong HAB event.

On July 6th and 7th I attended the C-CAN workshop in Costa Mesa to discuss the affect of Ocean Acidification on shellfish farmers. Scientists, managers, and shellfish industry representatives were brought together to discuss the need and plan for an ocean acidification monitoring network. Approximately 20 organizations collaborated on the ongoing design of an ocean acidification network. By attending this workshop I was able to communicate with many different stakeholders and ask a series of questions. As a CeNCOOS intern I was introduced to the Pacific Coast Shellfish Growers Association, and provided the opportunity to distribute a survey amongst West Coast shellfish farmers to better understand their operations, needs and concerns, and offered a communication link between shellfish growers and the services CeNCOOS is able to provide. The survey and a compilation of the survey results are attached as appendix 1, and have provided valuable insight, and are included throughout the text as anecdotal evidence. The results of the C-CAN meeting are discussed in Case Study 1.

Oyster farms are the poster child of OA, and near the end of my internship I toured an oyster farm to observe and better understand the needs of an oyster business. The Hog Island Oyster Company is part owned by Terry Sawyer, and is one of the larger oyster farms in the CeNCOOS region. Located in Tomales Bay, the Hog Island Oyster Farm buys oyster seed from the Pacific Northwest and has felt the negative effects of ocean acidification on their seed supply. The details of my tour of the Hog Island Oyster Company are discussed in Case Study 2.

SCIENCE:

The Monterey Bay Aquarium Research Institute (MBARI) is one of many oceanographic research institutes studying ocean dynamics and observing OA. In May two moorings were deployed in the Northern Monterey Bay by Dr. Francisco Chavez to collect ocean acidification data. The ability to accurately collect accurate pH data is still in its infancy, and these two moorings (OA1 andOA2) are a rare resource for the Monterey Bay. The first Ocean Acidification Mooring (OA1) is located at Sand Hill Bluff, and the second (OA2) at Terrace Point (Figure 1). Both sites are PISCO long term ecological research sites, and as such are well situated for a long term study.

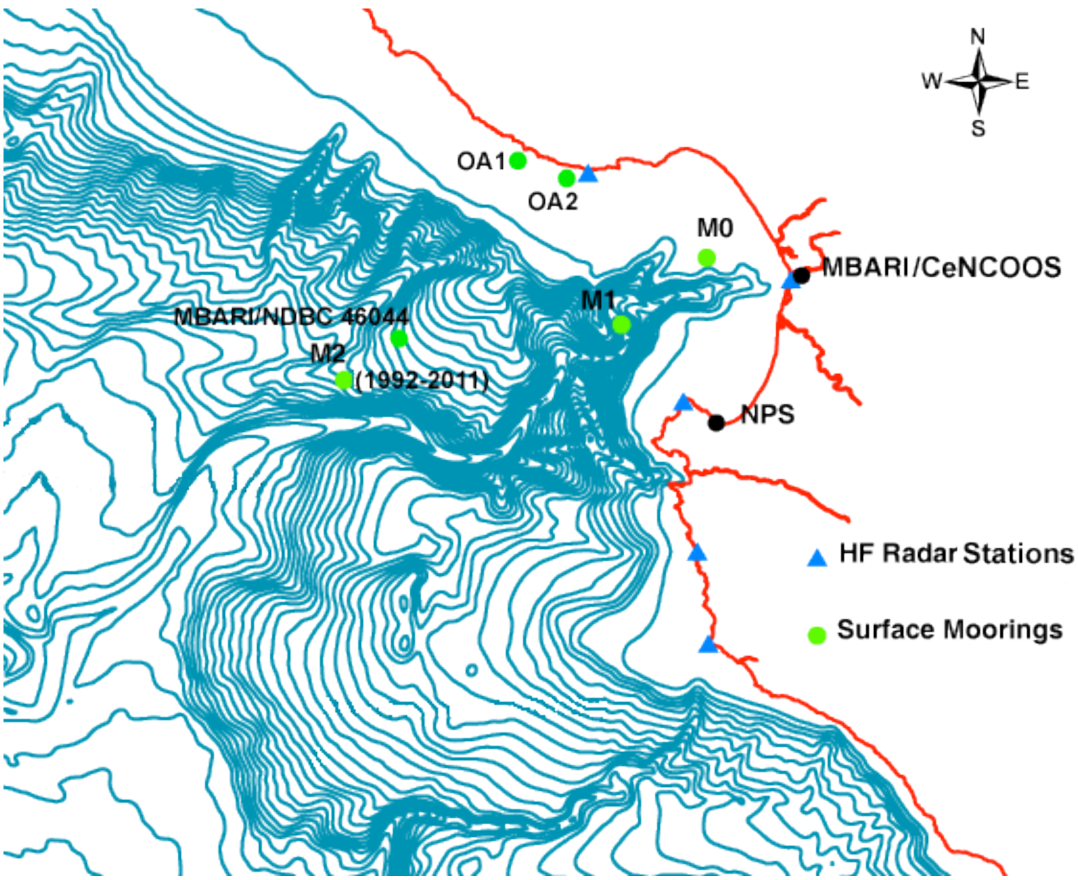


Figure 1: Map of Monterey Bay with surface monitoring stations and High Frequency Radar Stations. The MBARI OA moorings are located in the Northern part of Monterey Bay, and are labeled A1 and OA2.

Large scale spatial (California Coastal) carbonate chemistry data were collected on a 2007 North American Carbon Program (NACP) research cruise, and used in conjunction with current (2011) satellite sea surface temperature data. In the late Spring of 2007 Dr. Richard Feely PMEL group conducted a West Coast Cruise (Feely et al, 2008). The cruise sampled along 13 cross-shelf transects from Queen Charlotte Sound, Canada, to Baja California Sur, Mexico. Full carbonate chemistry along with physical oceanographic data were collected. Sea surface satellite data are communicated through the CeNCOOS website and are publicly available. I compiled the temperature and pH data and analyzed the spatial relationship of pH and temperature along this cruise track. The results of these moorings and spatial data are discussed in Case Study 3.

RESULTS:

CASE STUDY 1: California Current Acidification Network (C-CAN)

At the C-CAN workshop scientists, managers, and shellfish industry stakeholders collaborated to design an ocean acidification observing network. The data needs of both the industry and science groups were stated (Table 1) and each speaker made the point that the practical application of science to industry is necessary for the growth of both fields. The different needs of scientists and industry are some of the problems that were addressed in the workshop.

Science:	**Industry:**
High accuracy (0.001 pH)	Some accuracy (0.1 pH)
Low cost	Low cost
Low maintenance	Some maintenance OK
Long processing time acceptable (years)	Fast processing time necessary (days)
Information communicated after publication of results	Information communicated quickly

Table 1: The needs of scientists and the shellfish industry differ in 5 notable aspects.

The California Current system intensifies the affect of anthropogenic CO_2 on pH because it is both a sensitive and a dynamic environment. There is a high spatial difference in wind stress along the west coast, and thus pH is a spatially dependant variable, changing depending on upwelling strength. We have 10 years of High Frequency Radar (HFR) data and mooring measurements of currents and physical oceanography. By adding p CO_2 and O_2 we will have a valuable data set with ability to forecast and hind cast low pH events. p CO_2 is increasing at station ALOHA off the coast of Hawaii, and it is increasing at a faster and far more variable rate off the US West Coast, due to increases in upwelling. In 2009 the FORAM Act was passed by congress, recognizing the need to research and understand the affects of Ocean Acidification

Alan Barker, of the Pacific Coast Shellfish Growers Association (PCSGA) discussed the problems affecting shellfish growers. The PCSGA is trying to keep growers afloat. Shellfish growing is a multi-million dollar industry, and a way of life for entire families, and coastal communities. Growers need water quality data in real time/near future, and modeling on the 5-10 year range. Growers have been experiencing poor recruitment, especially those near upwelling centers. One way to adapt to this is to spawn the shellfish during light wind periods, before upwelling occurs. Spawning is best at high pH, high O_2 conditions, which generally occur in the late afternoon. Thus, understanding daily patterns is important to growers. They need to know when to spawn, when to pump water, and when to replace tank water; this often translates simply into a number on the wall every morning. Scientists need to figure out how upwelled deep water flows into estuaries and bays, and be able to communicate this to the growers. Finding a low cost and reliable method to measure acidity is necessary.

Burke Hales, from the Oregon State University Oceanography department told the story of Whiskey Creek shellfish hatchery. Whiskey Creek sees high fluctuations of pH on a daily basis, and since 1999 have had high larvae losses, costing hundreds of thousands of dollars. Burke Hales presented data that showed that second generation larvae production at 150µm are dependent on pH and temperature at spawning. There is a high variability in both pH and temperature during upwelling periods. He is still looking for a cheap and accurate proxy for acidification as pH sensors need frequent calibrating with in-situ measurements. Proxies developed in one place are not applicable to another place, and measuring pCO_2 and TCO_2 are expensive.

Tessa Hill of the Oregon State Biological Ocean Acidification Research group, discussed the need for moorings, and coast wide transects. She presented results from her own research that included the Van Damme upwelling center, the Bodega head upwelling (less strong), and Tomales Bay (no upwelling). Her moorings are sampling temperature, salinity, fluorescence, oxygen, pH, and pCO_2. Mussels are hung off the moorings, providing a biological parameter to the study. Discrete bottle samples are taken weekly of oxygen, temperature and salinity. At upwelling centers there are daily pH variations of 0.1, and changes in pH between relaxation and upwelling are up to 0.3.

NETWORK IMPLEMENTATION:

Scientists asked for better technology to accurately sample carbonate chemistry. The cost and difficulty of measuring carbonate chemistry include:

1. Overall uncertainty required
2. Cost
1. Equipment, maintenance
2. Cost of training
3. Analysis
3. Convenience of measurement
4. Availability
5. Sample size
6. Time until results are available
4. Cost of making a wrong measurement

To accurately and efficiently implement an ocean acidification network we must first:

1. Articulate measurement quality
    a. Map pH ‘hotspots’
    b. Resolve differences in data accuracy needs
    c. Relate chemistry, physical oceanography and biology

These parameters need to be studied:

- Carbonate Chemistry; pCO2, pH, alkalinity, DIC., oxygen, Aragonite saturation depth
- Physical; temperature, salinity, wind stress, atmospheric pressure, currents
- Biological; Nutrients, larvae, Chlorophyll, Backscatter.

The C-CAN group agreed that the most valid ocean acidification parameter is aragonite saturation. Essentially any proxy for aragonite saturation would be accepted into the network (Group 1, below), but ideally verified Carbonate chemistry parameters would be sampled in as many locations as possible (Group 2).

Group 1: Temperature, Salinity, Oxygen.

Group 2: Carbonate Chemistry; pCO2, DIS, pH, alkalinity.

Group 1 data are already being collected over large temporal and spatial scales, and can be used as proxies for OA with accurate and congruent collection of Group 2 data.

Problems to be addressed;

1. Bio-fouling,
2. pH and pCO_2 sensor need to be re-calibrated manually every month.
3. Time and equipment and money are needed to test discrete calibration samples. Confidence in data is needed for modeling; the higher the confidence the farther into the future you can predict. Low data quality is ok for very short term predictions.
4. Data quality/quantity.

Ocean acidification observation platforms:

1. Moorings
2. Intake sensors
3. Cruise data
4. Gliders
5. AUVs
6. ROVs

What makes a successful network?

As discussed by Jan Newton, NANOOS

1. Data management and communication
2. Communication amongst networks
3. Understand current financial situation
4. Understand needs
5. Be flexible
6. Do no harm
7. Vision
8. Leverage
9. Exploit capabilities
10. Sustain strong communication
11. Translate between data providers and data consumers
12. Assure that credit is maintained

The IOOS network already exists, is practiced at seeking out data sources, and has the ability to flag bad or poor quality data, and transmit in near-real time. By providing data quickly industry will be able to make informed decisions based on real time and near real time data. Industry naturally finds this an attractive addition to an ocean observing communication platform, but scientists raised concerns over the ability to flag data or filter data, and the ability to keep important data private while papers are written.

Ocean Acidification observation network plan, as discussed by C-CAN.

Monitoring problems and needs were discussed at the meeting:

1. pH sensors aren't accurate enough for long term monitoring, and require frequent calibration.
2. Understanding of low pH 'hotspots' is not comprehensive.
3. Need to better understand cost vs. effectiveness of a monitoring system.

4. Need to create a map of coastal and marine spatial planning that includes bio/geo/chemical information.
5. Stakeholders would like an alert system to warn of low O2 and pH events. This alert could trigger a response, such as industry sponsored small boat sampling to assist scientists' understanding of the event dynamics.

The next steps:

1. Prioritize
2. 'Best practices' guidelines
3. Define parameters
4. Develop open access to real time data and data exchange
5. Link regions to national and international observing systems
6. Monitoring in hotspots and areas of interest (such as Marine Protected Area) with the end result of creating a map of aragonite saturation chemistry.

CASE STUDY 2: Hog Island Oyster Company.

Shellfish farmers have been seeing a decrease in seed survival, larvae recruitment, and growth rates over the last 5 years. These losses in production have ranged from seed hatcheries in the Pacific Northwest to Oyster growers in Central California. Loss of production translates to job losses in coastal communities, decrease in income potential, and limited supply to the shellfish industry. Oysters are always more in demand than supply can provide.

Terry Sawyer learned aquaculture husbandry at the Monterey Bay Aquarium before joining the Hog Island Oyster Company in 1983, in Tomales Bay. He grows 5 species of oysters in addition to mussels and clams. The extra small commercially sold oyster is credited with beginning at the Hog Island Oyster Co. In addition to reviving a small historical village by refitting an 1880 stage town post office into the main building housing his business, Hog Island Oyster Co. employees 83 people in the small coastal community. An outdoor retail booth, picnic tables, barbecues and an oyster bar are nestled between the shoreline and the old Post office building. Over 3000 oysters are sold from the site alone, not to mention bread, beer, wine and barbeques and shucking tools. On any given day hundreds of people journey out to the peninsula to picnic and eat oysters in the open air.

Each step of the oyster growth process is documented and recorded. Oyster seeds are bought from a seed hatchery, where their health is determined before entering the Hog Island Oyster Company tanks. Oyster seeds are placed in large ‘upwelling’ tanks where water is pumped upwards through a seed and sand mixture until seeds have hatched to larvae. The larvae are placed in a ‘down-weller’ tank where water is pumped downwards, pushing the larvae against a screen to encourage them to set separately (oysters like to clump together, making them hard to sell individually). Once individual baby oysters have begun to grow they are placed in net bags to protect them from predators such as bat rays, and anchored into seafloor lease areas in the bay. It takes between 18 months and 3 years for most commercially raised oyster species to become large enough to sell commercially.

Once oysters are harvested they are sorted into size categories, and separated either into market mesh bags, or returned to the Bay to grow into larger oysters. The largest commercial oyster is the barbeque oyster, and it takes 3 years to reach a large enough size to place on a barbeque, and until recently was the most popular oyster. Hog Island began selling the extra small oyster, and people have found them to be tastier. A commercially valuable oyster comes in several sizes, ranging from extra small to extra large. At each stage a desirable oyster is an individual animal with a hard enough shell that is able to clamp tightly to avoid water loss and will not be easily crushed during transport (i.e. death). Oyster meat resists toxins the cooler it is, so Oysters spend at least 24 hours 'chilling' in 45°F salt water tanks, where the meet is chilled and all bay sand, grit and toxins are flushed out.

Oyster farming in Tomales bay is affected by a range of factors originating in seasonal wind patterns to California gold rush mining practices. Oysters are susceptible to water borne toxins and low pH. In general warmer water contains more toxins, and colder water has a lower pH. In Tomales Bay summertime is doubly harmful to juvenile oysters. Because of a low mixing of ocean water with the estuary and low input of fresh water during the summer, Tomales bay has a summer residence time of up to 75 days (Smith et al, 1987). Change in land use practices after gold rush changed sedimentation patterns in the bay. Native oysters with genetic tolerance for Tomales Bay conditions are no longer available, and are very delicate for commercial use, and take a long time to grow. Adaptation of new oyster species such as upwelling resistant species from other eastern boundary areas is needed.

Seeds sold from Northern California and the Pacific North West are becoming weaker, are less successful setting, and are more susceptible to stress. These factors require businesses to change their business model; more money is lost to seed buying. Planning is based on hatcheries being able to supply seeds, and an oyster farm business plan is disrupted by seed losses on the hatchery end of the supply track.

Recommendations from Hog Island Oyster Co.

1. Grow pH resistant oyster crops, or interbreed these with fast growing crops.

2. Currently reactive to problems; need to be proactive to decrease the cost to the industry. Better planning is needed, and communication of ideas would be helpful.

3. Industry could communicate the variables they collect to scientists to use. (T, Salinity, pH, O_2)

4. Does not need daily 'event' monitoring, but does need seasonal predictions, such as rainfall.

5. More study on the residence time and circulation of Tomales Bay dynamics.

CASE STUDY 3: Ocean Acidification Science.

MBARI MOORING Data.

Variability in spatial and temporal conditions can be monitored by moorings, satellites, and research cruises. Terrestrial and oceanic carbon dioxide from both OA moorings was plotted on the same scale to show a comparison in the daily variation during upwelling season. Although data was continuously collected from the beginning of April, only data from April 15th to May 30th was analyzed, due to possible instrument fouling or malfunction. Cruise CTD temperature and pH data were collected along the continental shelf from Canada to Mexico. Satellite sea surface data were collected from the CeNCOOS website.

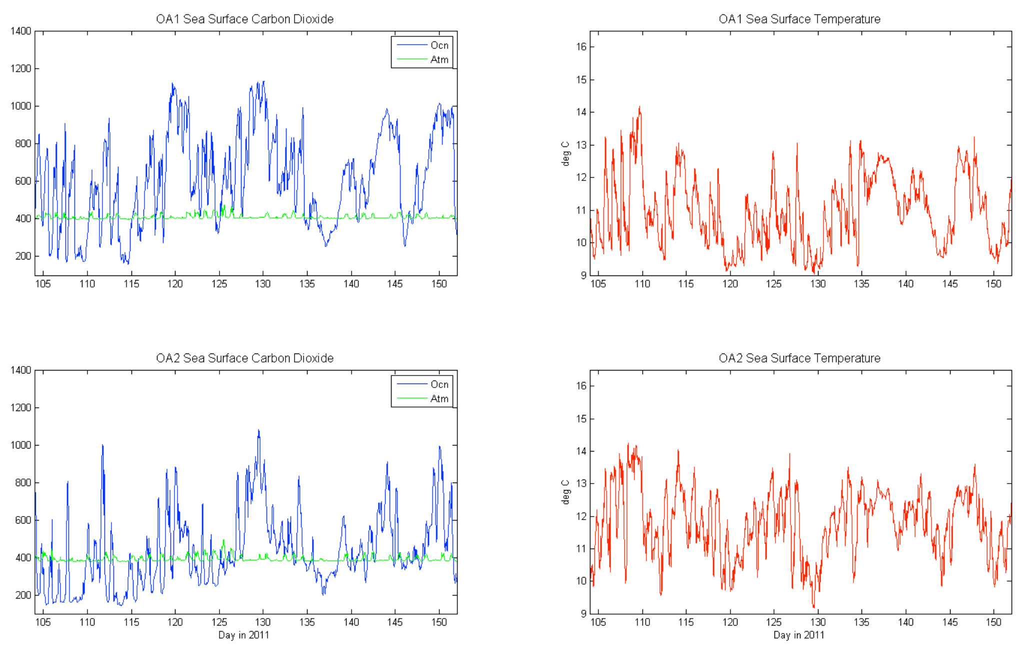


Figure 2: Oceanic (blue line) and atmospheric (green line) carbon dioxide at moorings OA1 and OA2 off Sand hill Bluff and Terrace point from year day 104 to 150 (April 15th to May 30th). Sea surface temperature at moorings OA1 and OA2 off Sand hill Bluff and Terrace point from year day 104 to 150 (April 15th to May 30th).

Sea surface measurements of Carbon Dioxide from both OA1 and OA2 showed daily variability in both atmosphere and ocean. Over a 46 day period in April and May (Year-day 104 to 150), oceanic carbon dioxide varied from 200 µmol/L to 1150 µmol/L, sometimes changing from one extreme to another in a 2 day period. (Figure 1) During the same period, terrestrial carbon dioxide varied from approximately 400 µmol/L to 420 µmol/L on a diurnal time scale. (Figure 2) Oceanic CO_2 was higher than terrestrial CO_2 for the majority of the 46 day period. Sea surface Temperature varied at moorings OA 1 and OA 2 from a minimum of 9 ºC to a maximum of 14 ºC on a daily time scale. (Figure 2)

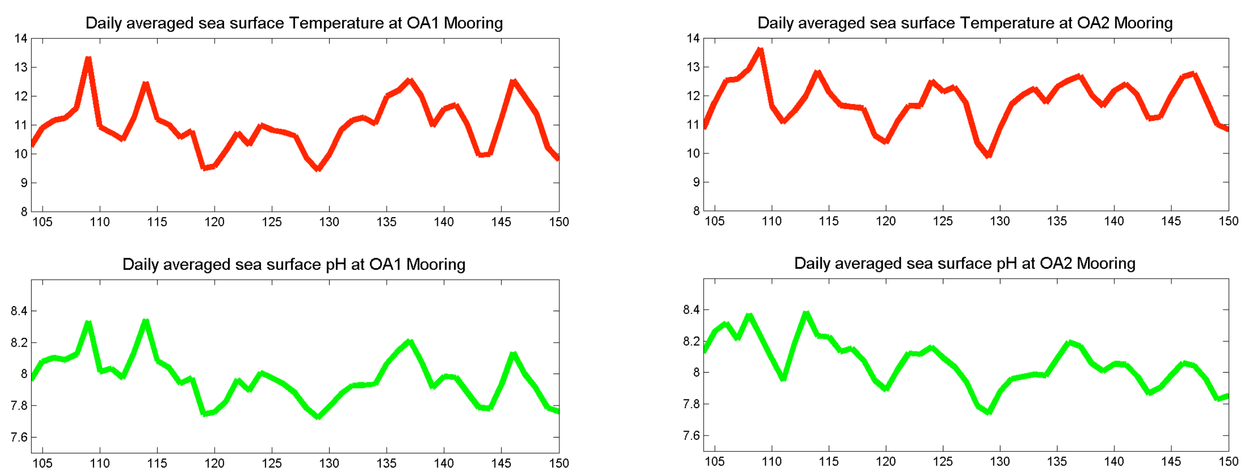


Figure 3: Daily averaged Sea surface temperature (red) and pH (green) at moorings OA 1 (left) and OA2 (right).

Sea surface temperature and pH were averaged over a 24 hour period to remove diurnal variation. At OA1, both pH and temperature had distinctive low fluctuations on year days 112, 119, 129 and 144 when pH dropped below 8.0 and temperature dropped below 11 ºC. (Figure 3) Sea surface temperature reached a maximum of 13.5 ºC and a minimum of 9.5ºC. pH reached a maximum of 8.4, and a minimum of 7.8. (Figure 3) At OA2, both pH and temperature had distinctive low fluctuations on year days 111, 120, and 129 when pH dropped below 8.0 and temperature dropped below 11 ºC. (Figure 3) Sea surface temperature reached a maximum of 14 ºC and a minimum of 10 ºC. pH reached a maximum of 8.4, and a minimum of 7.8. (Figure 3) Mooring OA1 has slightly lower sea surface temperature and pH than OA2.

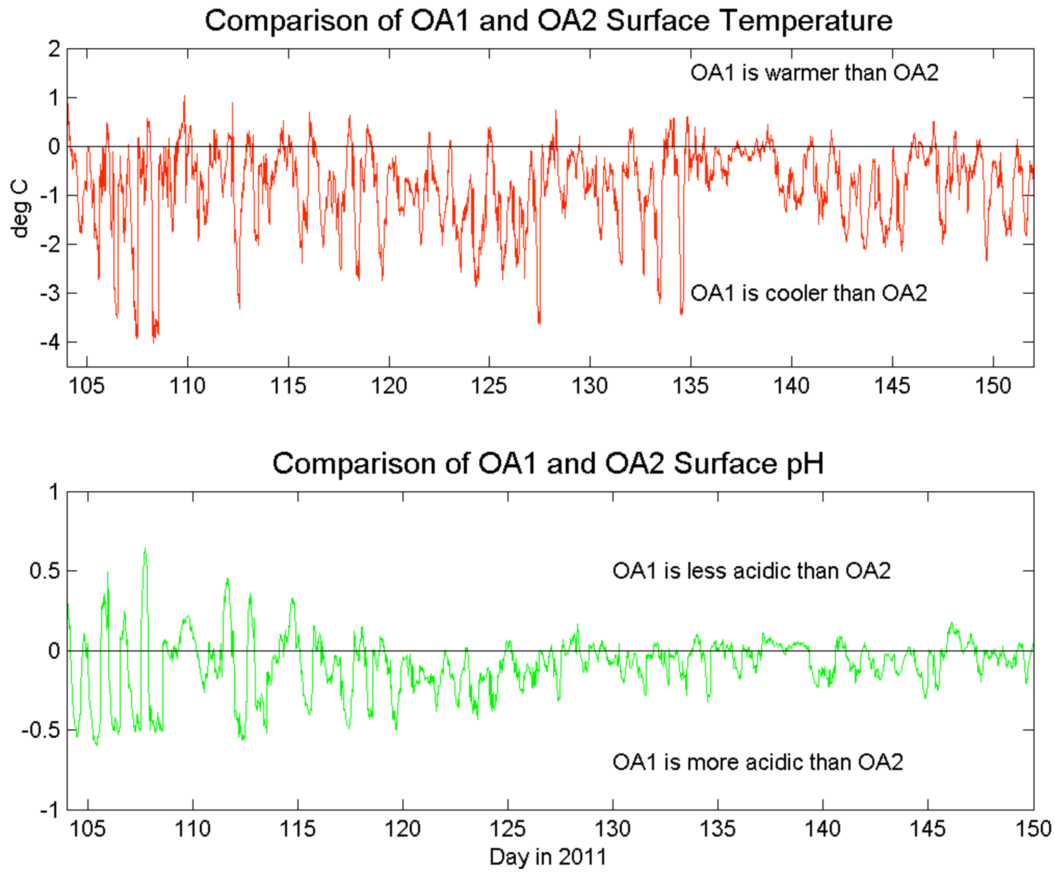


Figure 4: Comparison of OA1 and OA2 sea surface temperature and pH. The black line in both figures is zero difference between moorings. A positive value means OA 1 is warmer or less acidic; a negative value means that OA 2 is warmer or less acidic.

The difference in sea surface temperature and pH values between the two moorings was found by subtracting OA2 from OA1. On average OA 1 is 0.82 ºC than OA2. (Figure 4) pH at OA1 is an average of 0.08 more acidic (lower) than at OA2. Sea surface temperature at OA1 can be up to 4 ºC cooler than OA2 . (Figure 4) Between OA 1 and OA2 pH can vary up to 1 over a 24 hour period. Both OA 1 and OA2 have a strong diurnal signal; OA 2 is more acidic and cooler than OA 1 approximately once per day.

PARAMETER CORRELATION:

Correlation between chemical and biological parameters is an effective way to describe a predictive relationship. Temperature is an easily and frequently measured physical parameter, and by comparing temperature data with pH, I was able to better understand the relationship between the two parameters. The Ocean Acidification moorings in Northern Monterey Bay, the relationship between temperature and pH was linear.

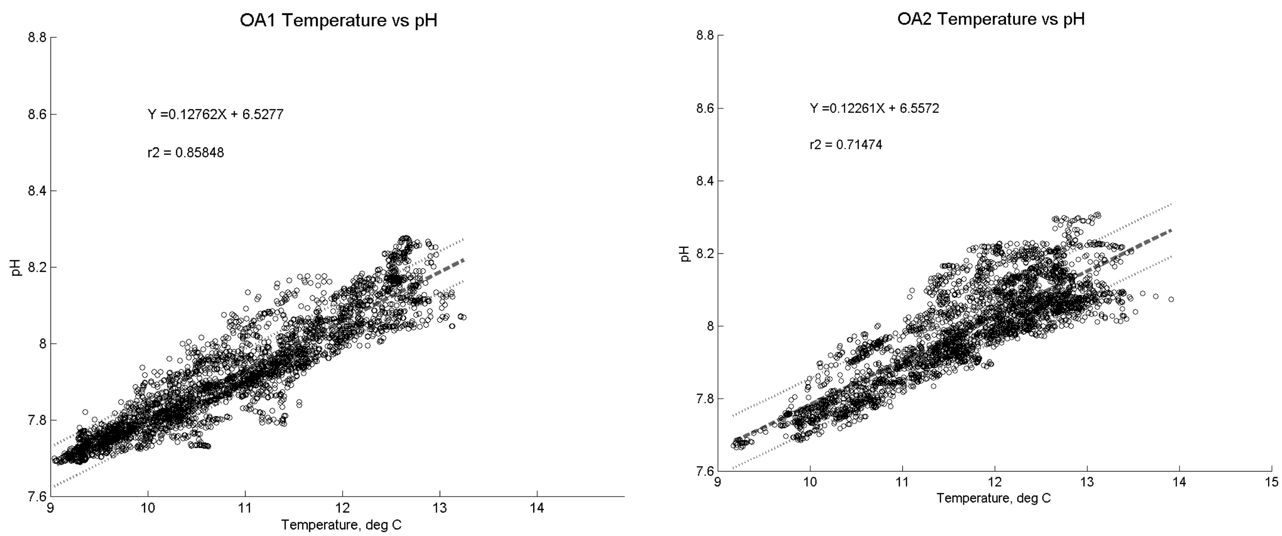


Figure 5: Correlation of 45 days of sea surface temperature and pH data at OA1 and OA2 moorings. Linear equation and r2 value are on the figure. Y is pH, and X is temperature.

Sea surface temperature and pH were compared at each mooring respectively over the 45 day period of analysis. At OA1 the linear equation was:

$$pH = 0.128 * Temperature + 6.53 \qquad \textbf{EQN. 1}$$

At OA2 the linear equation was

$$pH = 0.123 * Temperature + 6.56 \qquad \textbf{EQN. 2}$$

OA1 and 2 had r2 values of 0.86 and 0.72, respectively. OA1 had a steeper slope, and a lower intercept, and a higher correlation. (Figure 5)

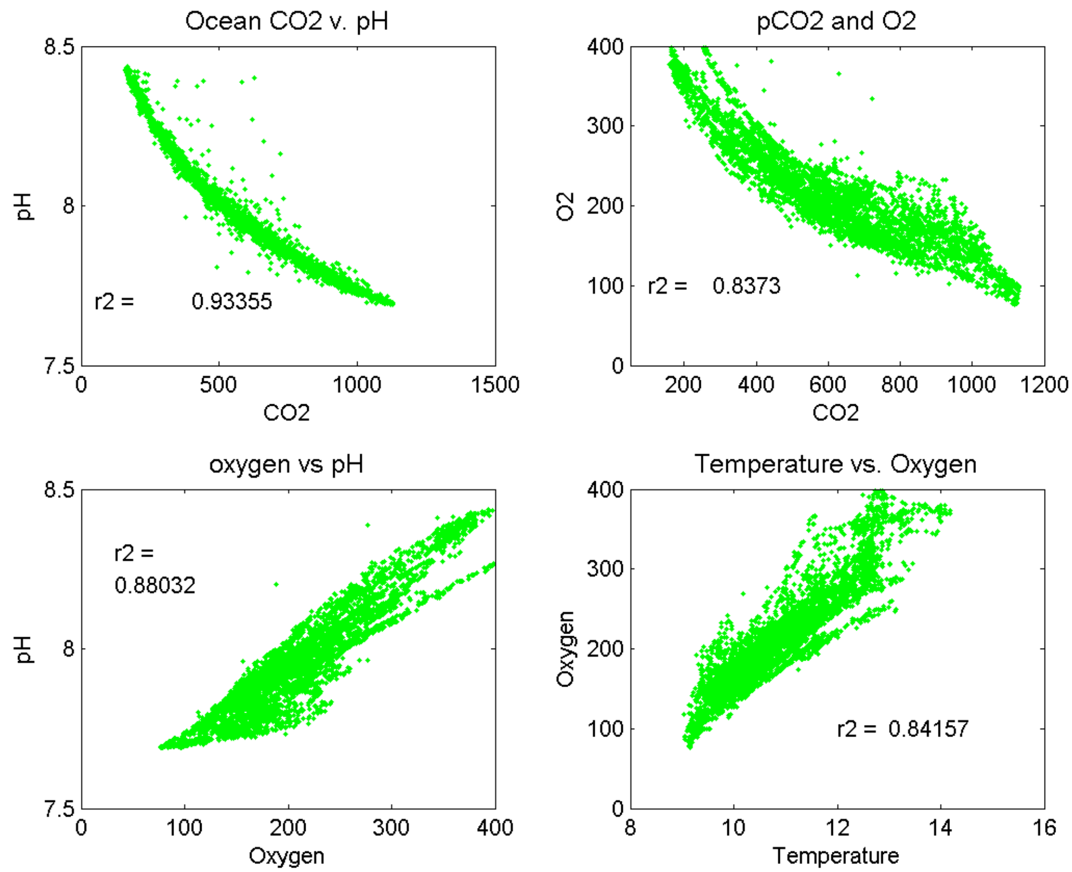


Figure 6: Correlation of (from top right to bottom left), CO2 vs pH, CO2 vs O2, oxygen vs. pH, Temperature vs. oxygen.

In addition to temperature and pH, several other variables measured by OA1 and 2 were compared. Sea surface CO_2 and pH were found to have the highest correlation (r2 = 0.93), followed by oxygen and pH (r2 = 0.88), temperature and oxygen (r2 = 0.84), and closely followed by pCO_2 and oxygen (r2 = 0.84). (Figure 6) Other values were compared but are not shown in a figure.

CRUISE DATA AND MAPS:

The PMEL cruise sampled carbonate chemistry and physical characteristics from British Columbia, Canada to Baja, Mexico. Along the PMEL cruise line 13 cross shelf transects were taken. The three nearest to shore stations of each transect were analyzed from a depth range of 50 m to 250 m. (Figure 7)

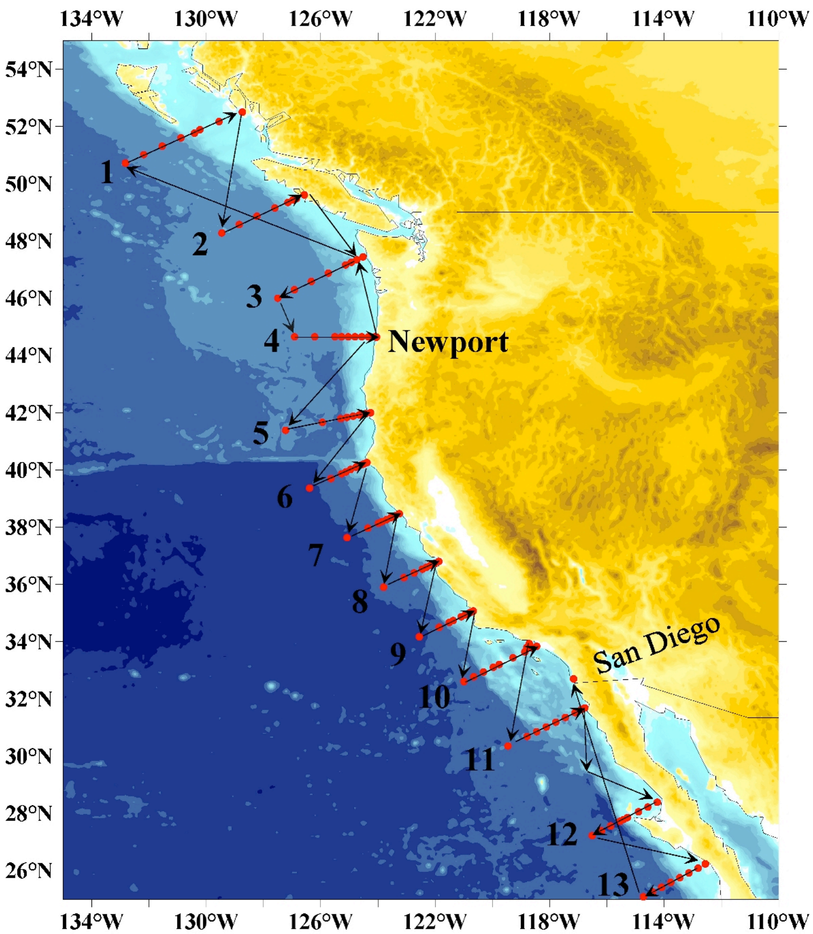


Figure 7: Map of PMEL cruise from British Columbia, Canada to Baja, Mexico. Correlation of temperature and pH at the 3 most onshore stations at the most northerly transect in the PMEL cruise.

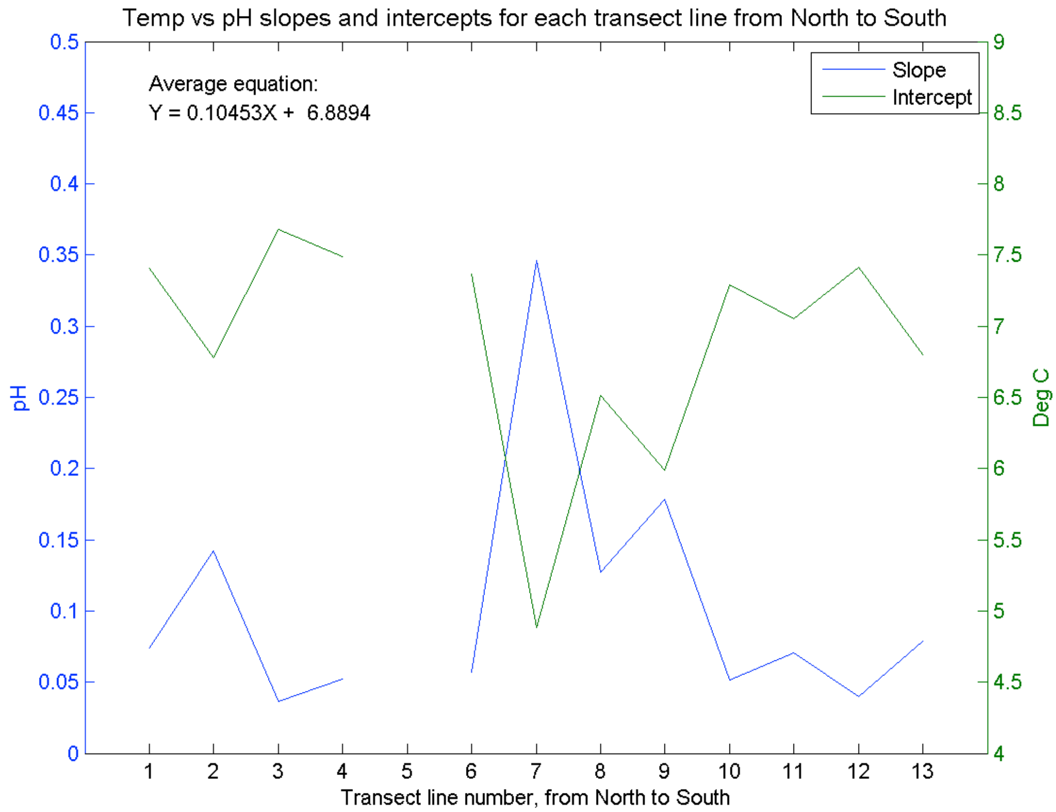


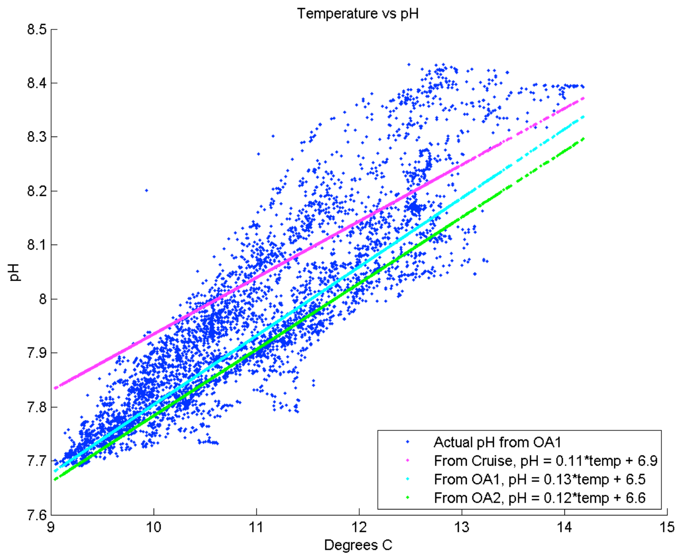
Figure 8: Average slope and intercept of temperature versus pH at each transect, from North to South along the PMEL cruise. Slope is the blue line, and Intercept is the green line. The average equation (Y = slope * X +intercept) is at the top left of the figure.

Temperature and pH data from the PMEL cruise were compared. Data were analyzed from between 250 m and 50 m deep at each of the three nearest to shore stations along each of the 13 transects. A linear relationship between temperature and pH was found for each of the 13 locations. The slope did not change more than 0.1 (pH) from North to south and the intercept did not change more than 1ºC, with the exception of location 7, of the coast of San Francisco, where the slope because very high, and the intercept very small. (Figure 8) Including this point, the average equation for converting temperature to pH along the PMEL cruise track is:

$$pH = 0.105 * Temperature + 6.89 \qquad \textbf{EQN. 3}$$

Equation #	*Method:*	*Slope:*	*Intercept:*
1	**PMEL**	0.105	6.89
2	**OA1**	0.128	6.53
3	**OA2**	0.123	6.68

Table 2: Slope and intercept of predictive relationships.



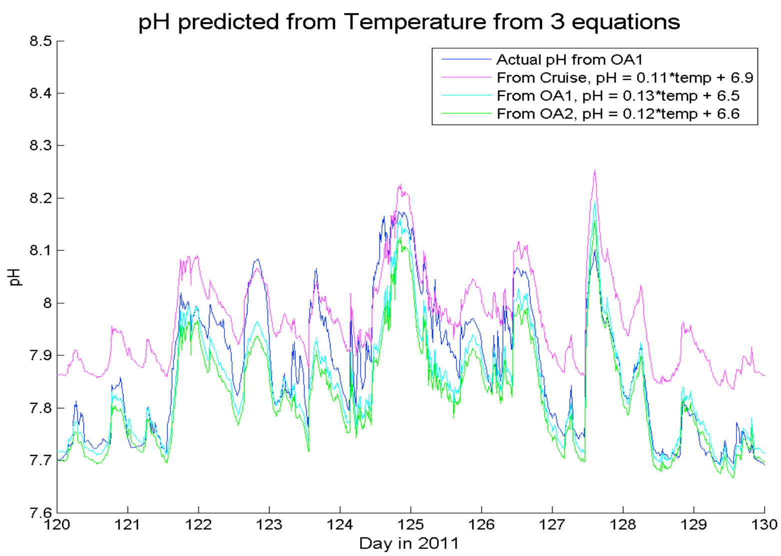


Figure 9: Top; Comparison of OA mooring 1 data (blue dots) with pH predictive equations from the OA mooring data (cyan and green lines), and from the PMEL cruise data (magenta lines). **Bottom:** Comparison of observed pH (blue line) to predicted pH. pH is predicted from temperature correlation equations from the PMEL cruise (magenta line), OA1 mooring (cyan line), and OA2 (green line).

Predictive equations were found from comparisons of temperature and pH at the OA moorings 1 and 2, and the PMEL cruise. (Table2) When tested against OA mooring temperature data, predict pH (from equations 1 and 2) was close to measured pH. (Figure 9, top figure) In comparison, the PMEL cruise line (equation 3) was 0.15 higher than measured pH. (Figure 9, bottom figure) Equation 3 overestimates pH by at most 0.15, but is a more spatially accurate predictor of potential pH from temperature.

Sea surface temperature can be observed from satellite, allowing for a large amount of data to be available over a large spatial area on a daily basis. The left maps in figure 10 show satellite sea surface temperature along the California coastline. On the right side of figure 10 are shown potential sea surface temperature. Potential sea surface temperature was predicted using equation 3. Equation 3 was chosen because it describes the relationship between temperature and pH along a large spatial area.

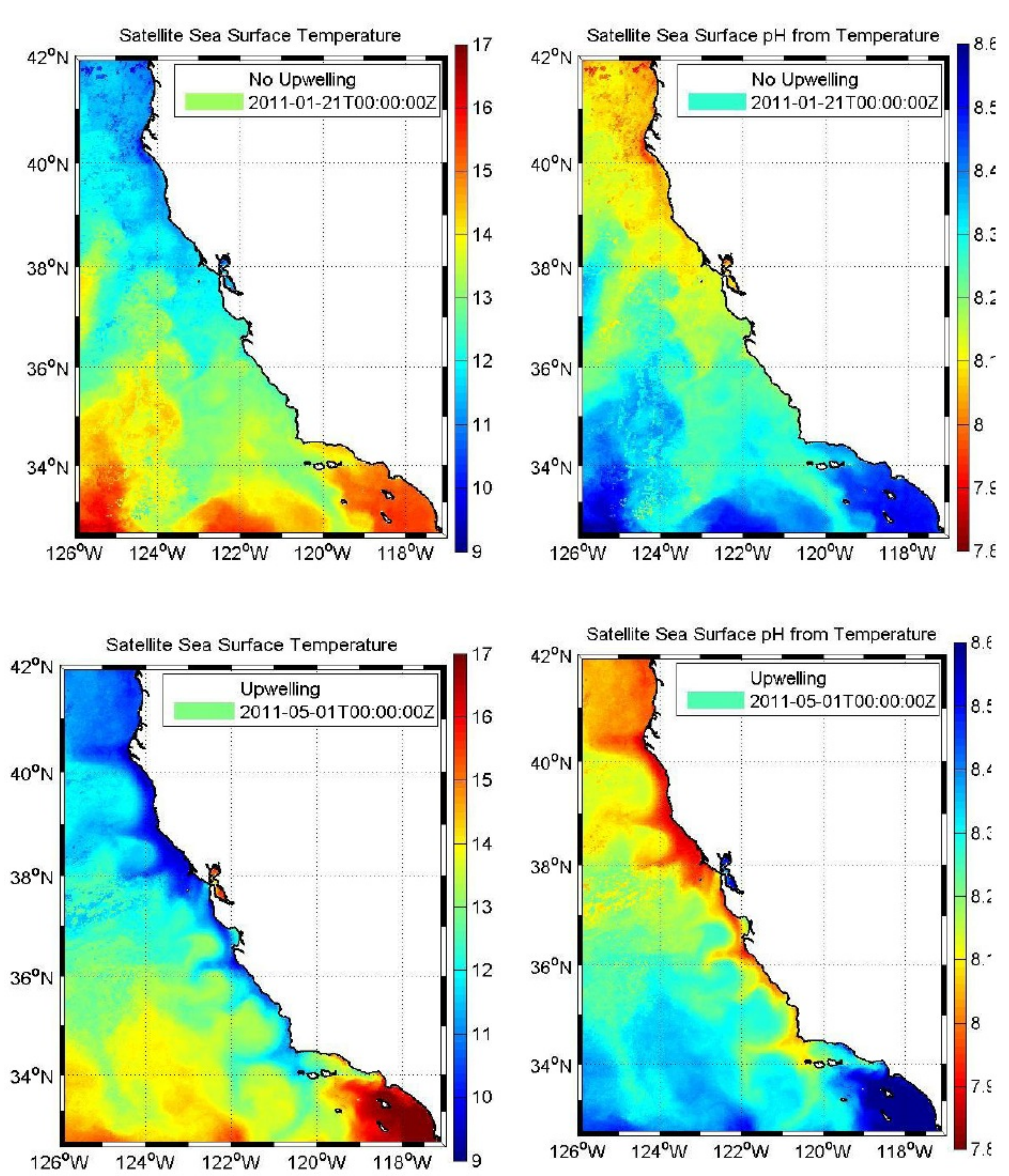


Figure 10: Map of satellite sea surface temperature (left) and potential pH (right) during a period of no upwelling (January 21st, 2011). Potential pH is converted from satellite sea surface temperature by applying the predictive relationship described by equation # 3.

DISCUSSION:

SPATIAL AND TEMPORAL DATA:

Temporal data was collected by the two MBARI ocean acidification moorings, OA1 and OA2. These moorings showed large variations in pH of up to 0.2 during the 2 month period of analysis. OA1 was closer to the upwelling center at Ano Nuevo, and thus had lower pH and temperature during upwelling periods. As the months of April and May are classically called upwelling season along the West Coast it was not surprising that a strong upwelling signal was seen at the OA moorings.

Spatially, pH was found to have the largest variation in upwelling regions. By converting temperature to potential pH it is possible to see the potential large scale variations in pH that exist along the California coastline. Though several linear equations were found relating temperature to pH at each mooring site (temporal data) and cruise station (spatial data), the slope and intercept of each equation varied less spatially than temporally. By choosing a temperature-pH equation that averaged a large number of spatial stations along the PMEL ocean acidification research cruise I was able to convert temperature to potential sea surface pH over a larger spatial than a local monitoring mooring is able to resolve.

COMMUNICATING SCIENCE:

Scientists and shellfish industry stakeholders have begun to recognize the need to work together to solve academic questions and to understand the current and future oceanic climate. An ocean acidification observation network is being established to address this need. In addition to developing an observation network through which data and information can be shared the fundamental differences in the needs of science and industry can be communicated. There is a spatial and temporal disconnect between how scientists collect data and the data the shellfish industry requires. Aquaculture farms are generally near shore, and need daily and hourly water quality updates, with future predictions on the day to year range, with a high degree of reliability but not necessarily a high degree of accuracy. Scientists collect highly accurate data in the continental shelf and oceanic environment, and model predictions on decadal scales. A network can be designed that incorporates the needs of both groups.

The Northwest Association of Networked Ocean Observing Systems (NANOOS) has piloted a project to communicate real time water quality data to shellfish growers in the Pacific Northwest. Research was conducted by NANOOS in 2006, surveying regional grower's needs and concerns from a communication network. Growers were found to be concerned about ocean acidification and the affect it will have on larvae. It was also found that growers wished for data to be communicated on an interactive website. NANOOS provided the platform to communicate these data. These data include real time salinity, temperature, oxygen, pH and Chlorophyll readings to warm fisherman and aquaculturists of algal bloom outbreaks, and low temperature, salinity and pH events. These data are used to investigate sudden mortalities, to forecast spawning based on water temperature and chlorophyll levels, to decide on optimal times to plant larval seed, and to predict future yields (Cathy, personal email). Currently NANOOS is developing a smart phone application to allow growers greater access to water quality data.

During the C-CAN planning workshop the benefits of ocean observing as related to ocean acidification were discussed:

1. Shellfish hatcheries will be able to make better informed decisions.
2. The linkage between exposure to low pH and biological effects can be better explored.
3. Politicians are interested in economics, and the shellfish industry provides that need.
4. Long and short-term trends will be better understood.
5. Collaboration enhances funding opportunities.
6. Forecast modeling and hindcast modeling will be more accurate.

By increasing scientific understanding of underlying Ocean Acidification mechanisms on all scales, the linkage between bio-physical-chemical coupling with resources, economics, impacts, trends and, patterns will become clearer. With an increase in this understanding will come better predictive models, and more cost effective data collection methods. Increasing understanding of bio-physical-chemical interactions will aid the shellfish industry, and prevent large economic losses to small coastal communities. And finally, as scientific understanding increases so will public understanding and awareness.

My impression of the discussion between scientists and stakeholders at the C-CAN meeting was that we need to develop a list of what scientists already know and a plan of the further study that needs to be conducted. Industry has very concise and well defined research questions, many of which could be easily borrowed by scientists. There is a need to communicate this knowledge to the people who can use it (the public, aquaculture industry, managers), and for the network to be updated continuously. We need to be able to tie the ecosystem together and illustrate the spatially and temporally dynamic environment that exists on the West Coast.

Recommendations for future CeNCOOS communication strategies:

1. Provide a network that texts, emails, or communicates via cell phone application to warn when upwelling will occur.
2. Provide introductions between interested graduate students in need of thesis ideas and concerned shellfish farmers in need of scientific assistance.
3. Provide an map of spatially variable pH, using a physical predictor
4. Suggest monitoring of marine protected areas located in upwelling 'hotspots'.
5. Ties need to be made between experts in biological, chemical and physical science and the areas of economic and social importance. CeNCOOS can create a network where interested parties can meet online (like an internet dating service).
6. Maintain active ties with the C-CAN network.

CONCLUSIONS:

For Shellfish farmers the future ocean is already here. Problems have been occurring in the last 5 years with larvae recruitment in shellfish hatcheries. Shellfish growers are already being forced to adapt to changing ocean acidification. Better predictions will help them make decisions on how to adapt to these changing conditions. For some this means investing in a better warning or mitigation system, for others it means moving the farm or the intake system to a different part of the bay.

Better communication of near real time data will assist shellfish growers to predict when larvae will recruit in the natural system, and when to pump water in a tanks system. Through an integrated west coast observational network, satellite sea surface temperature, ocean acidification buoys, and research cruise data can be pulled together into a cohesive program. A network of scientists and industry stakeholders providing and utilizing a near real time data network saves money and increases efficiency. It is not possible to prevent variability in temperature and pH, but increasing understanding will lead to more accurate predictions, and ultimately, better human adaptation to the harmful economic impacts of ocean acidification.

The development of an algorithm to predict potential sea surface pH from satellite observed sea surface temperature was developed to aid shellfish farmers. A map of potential pH is an effective way to visualize low pH events due to changes in short term oceanography such as seasonal upwelling patterns, and can be further utilized to predict ocean acidification ‘hotspots’.

As understanding of the coastal and global oceanic ecosystems has increased, so has the understanding of the interconnected nature of humans with the ocean and atmosphere. The ocean covers more than 70% of the earth, and is an irreplaceable resource for everything from food to oxygen, yet more funding is available to study outer space than our big wet backyard. As stakeholders have realized the variable nature of the ocean they have demanded a greater level of communication and a need to apply scientific research to resource management.

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APPENDIX 1: Survey Results.

	Carlsbad Aquafarms Inc. **Dennis Peterson.** **Carlsbad CA, Aqua Hedionda Lagoon.**	**Drakes Bay Oyster Company, Kevin Lunny** **Drakes Estero.**
What do you farm?	Mussels, oysters, abalones, macro algae.	Oysters.
What water quality issues are you most concerned about?	All.	Low pH and Algal blooms.
How do you currently get information on water quality?	Interactive website, monitor on the farm.	Interactive website.
What water properties do you monitor on your farm?	Temp, pH, salinity, Oxygen.	None.
What nearby buoys or station data are useful to you?	Temp., pH, Salinity, Chlorophyll, Oxygen, other.	Temp., pH, Salinity, Chlorophyll, Oxygen.
How would you prefer information to be communicated to you?	Interactive website.	Interactive website, email update.
How often would you like data to be communicated to you?	Daily.	Hourly, from own monitoring system.
How far into the future would you like data predicted?	Days to years.	Days.
What actions could you take to avoid low pH damaging your shellfish?	Shut down pumps.	Install monitoring equipment and sensors on farm. We could place the equipment in a building that would continuously measure the water from our seawater intake.
What time of year do you have the highest recruitment?	Spring and early summer.	Summer.
Anecdote of a time larvae recruitment failed or a strange event occurred.	Higher than normal temperatures occurred for an extended period of time, causing high oyster mortality.	Over the last two years we have had three events of almost complete loss of larvae during the settling operations. We do not know why this larvae mortality occurred.
Damage caused by failed larvae recruitment.	Loss of supply to meet demand.	~$25-30,000

	Hog Island Oyster Co., Tomales Bay. **Terry Sawyer**	**Penn Cove Shellfish, Kona Coast Shellfish** **Ian Jefferds.**
What do you farm?	5 species of oyster, mussels, clams.	Mussels and oysters
What water quality issues are you most concerned about?	Low pH, warmer water temperatures, low oxygen, algal blooms, nutrient loading from runoff.	Low pH, low O2, algal blooms.
How do you currently get information on water quality?	Email updates, phone calls, periodic report, on farm monitoring.	Interactive website, monitor on the farm.
What water properties do you monitor on your farm?	Temp, pH, Salinity, Oxygen.	Temp, pH, salinity, oxygen.
What nearby buoys or stations are useful to you?	pH and Chl-a, and temp, salinity and oxygen would be useful depending on location.	Temp, pH, salinity, chl, oxygen.
How would you prefer information to be communicated to you?	Interactive website, email update.	Interactive website, email update.
How often would you like data to be communicated to you?	Daily.	Daily.
How far into the future would you like data predicted?	Days to weeks.	Days to years.
What actions could you take to avoid low pH damaging your shellfish?	Shut off intake or adjust timing of 'open' mode.	At our hatcheries we can degas and mix with higher pH surface seawater.
What time of year do you have the highest recruitment?	Spring and summer.	May-June.
Anecdote of a time larvae recruitment failed or a strange event occurred.	Over the past 5 years we have had significant seed losses, some years worse than others. 2010 was a better year. Growth rates have fluctuated – diminished when 'normal' growth would have occurred. Seed size has decreased and we have had to purchase seeds from other hatcheries.	1994-95 we had poor natural recruitment but do not know why. 1997 we had a large mortality event of Gall provencialis which we attributed to low temperatures, spawning stress and low salinity.
Damage caused by failed larvae recruitment.	Large impacts; no inventory = jobs are lost and income potential decreases. The cost of buying seeds from an outside seller is lost, and	~ $60, 000

	seed selling companies have limited species availability so my business has lost the opportunity to sell those species.	

	Taylor Shellfish, Dabob Bay. **Benoit Eudeline.**	**Whiskey Creek Shellfish, Netarts Oregon.** **Sue Cudd.**
What do you farm?	Hatchery, oyster farm, geoducks, clams, mussels.	Shellfish hatchery.
What water quality issues are you most concerned about?	Low pH, low oxygen, algal blooms, pCO_2, aragonite saturation.	Low pH, low O_2, high CO_2.
How do you currently get information on water quality?	Farm monitoring.	Phone call, monitor on the farm.
What water properties do you monitor on your farm?	Temp, pH, Salinity, Chl, Oxygen.	Temp, pH, Salinity, Chl, Oxygen, pCO_2.
What nearby buoys or stations are useful to you?	Dabob Bay buoy is useful.	Temp, pH, salinity, chl, oxygen.
How would you prefer information to be communicated to you?	Interactive website, email update.	Interactive website.
How often would you like data to be communicated to you?	Hourly, daily.	Hourly
How far into the future would you like data predicted?	Days	Years
What actions could you take to avoid low pH damaging your shellfish?	Water treatment in the hatchery.	Avoid pumping the low pH water if there is real time monitoring, or can treat the water in the hatchery.
What time of year do you have the highest recruitment?	Summer	No production in December, best production in march/april.
Anecdote of a time larvae recruitment failed or a strange event occurred.	May – Sept 2008, 2009. Do not know why, were not monitoring at the time.	Since 2007 we have had sporadic problems correlated with low saturation state.
Damage caused by failed larvae recruitment.	Loss of 80% of the hatchery production.	In 2008 we produced on about 25% of normal and we lost a lot of money and customers.

	David Steele, Rock Point Oyster Company, Inc. **Puget Sound, WA.**	**Kate Cissna, Enetai LLC, Clam Frest, Best Fish Co, Crab Fresh.** **Totten Inlet and Oakland Bay,WA**
What do you farm?	Pacific Oysters and Manila Clams	Manila clams and Pacific Oysters
What water quality issues are you most concerned about?	Low pH, cold water, low oxygen.	Algal Blooms, pCO2, and pH.
How do you currently get information on water quality?	Interactive website, periodic report, monitor yourself.	Monitor on farm and email updates through the Sound Toxins group.
What water properties do you monitor on your farm?	Temp, pH, Salinity.	Temp, pH, Salinity, dOxygen.
What nearby buoys or stations are useful to you?	Temp, pH, Salinity, Chl, Oxygen.	Temp, pH, salinity, chl, pCO2, oxygen.
How would you prefer information to be communicated to you?	Interactive website, email update.	Interactive website.
How often would you like data to be communicated to you?	Weekly	Hourly
How far into the future would you like data predicted?	Days	Hours to Years.
What actions could you take to avoid low pH damaging your shellfish?	Natural set; can only anticipate low production and plan accordingly.	Schedule spawning and setting larvae based on the time of day, week, or month when conditions are good.
What time of year do you have the highest recruitment?	July/August.	
Anecdote of a time larvae recruitment failed or a strange event occurred.	Slow growth in Fall because of cold weather and colder than usual water. Slow growth in Spring due to cold weather and water with less algae for food.	Issues through the beginning of 2010 and 2011 getting larvae to set. Clutch tanks seem fine, but batch tanks and downwellers have trouble.

Damage caused by failed larvae recruitment.	Reduced future harvest.	$400 000 trying to get larvae to set repeatedly and grow big enough to get into the upweller tank. **
Contact	davesteele@comcast.net, 360 79- 7408	Kate: 360 427 4438, Brnedan 206 819 3474, Dave 206 819 3284

** Totten Inlet needs more information on how water is changing and what factors cause the changes; i.e. is it urban runoff and organic loading in the estuary mouths, or is it warm upwellings due to more global events? We know for sure that pH levels are a strong indicator for conditions needed for spawning and larvae in the first 6 weeks of life. We wish to have a 24 hour monitoring of conditions in Totten inlets pco2 and other parameters, at points above and in back of our farm. We only have $3500 water quality monitoring equipment right now that is being used within the hatchery, but we need additional equipment to monitor the inlet water at various depths, as well as the inhouse water. This would help us determine where to put our intake pipe and many other matters.

	Nick Wenzel **Seatle Shellfish LLC**	
What do you farm?	Geoduck	
What water quality issues are you most concerned about?	Low pH, low oxygen, algal blooms	
How do you currently get information on water quality?	Monitor yourself.	
What water properties do you monitor on your farm?	Temp, pH, salinity, oxygen.	
What nearby buoys or stations are useful to you?	Temp, pH, Salinity, Chl, Oxygen, DIN, dissolved nutrients.	
How would you prefer information to be communicated to you?	Interactive website.	
How often would you like data to be communicated to you?	Daily	
How far into the future would you like data predicted?	Weeks	
What actions could you take to avoid low pH damaging your shellfish?	Change practices seasonally to avoid activity during months of low pH. Use dolomite for shell building (?).	
What time of year do you have the	May – Sept (highest)	

highest recruitment?	Winter is lowest.	
Anecdote of a time larvae recruitment failed or a strange event occurred.	Large scale die-off in juveniles (<1 year) in late March, early April 2011. Suspect a toxic form of algae, but aren't sure.	
Damage caused by failed larvae recruitment.	Reduced future harvest by ~50 000	
Contact	wenzel24@gmail.com (Chlorophyll is of part. Interest)	