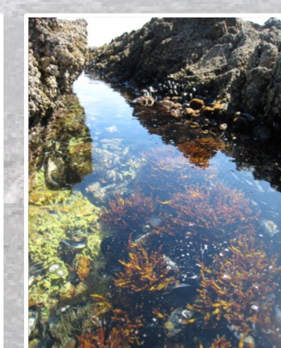
# California Current Acidification Network (C-CAN)

# Vision for Development of a West Coast Network for Monitoring Marine Acidification and Its Linkage to Biological Effects in the Nearshore Environment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# Contents

Vision Statement ........ 2

Chapter 1 — Introduction and Motivation ........ 3

Chapter 2 — Establish a Chemical Monitoring System ........ 6

Chapter 3 — Linkage to Biological Effects ........ 11

Chapter 4 — Causal Modeling ........ 14

Chapter 5 — Predictive Modeling ........ 16

Chapter 6 — Human Dimensions ........ 18

Chapter 7 — Communication ........ 19

## Vision Statement

The California Current Acidification Network (C-CAN) is a collaboration of interdisciplinary scientists, resource managers, industry and others from local, state, federal, and tribal levels dedicated to advancing the understanding of ocean acidification and its effects on biological resources of the US west coast. C-CAN's mission is to:

1) Coordinate and encourage the development of an ocean acidification monitoring network for the US west coast that serves publicly available data;
2) Improve understanding of linkages between oceanographic conditions and biological responses;
3) Facilitate and encourage the development of causal, predictive, and economic models that characterize these linkages and forecast effects; and
4) Facilitate communication and resource/data sharing among the many groups, organizations and entities that participate in C-CAN or utilize C-CAN as an informational resource.

Given the complexity of the emerging issue of ocean acidification and in recognition that growing our understanding of potential impacts will require a concerted community effort, C-CAN is committed to being the source for reliable, vetted scientific information for interested parties. C-CAN will identify and disseminate answers to pertinent questions, support ongoing and emerging efforts, and provide leveraged in-kind support toward the goal of adequately understanding this issue.

# CHAPTER 1 — INTRODUCTION AND MOTIVATION

Ocean acidification poses a threat to the health of the world's oceans and the significant benefits they provide. Globally, one-quarter of the carbon dioxide ($CO_2$) released into the atmosphere by anthropogenic activities is being absorbed by the oceans. When $CO_2$ dissolves in seawater, it lowers pH and reduces the concentration of available carbonate ions, a process called ocean acidification(OA). Water under-saturated with carbonate ions is corrosive to organisms that produce calcium carbonate exoskeletons, such as shellfish, corals, and some species of plankton that comprise the base of the marine food web.

The US west coast is particularly vulnerable to the effects of ocean acidification. Deep ocean waters are naturally undersaturated with calcium carbonate and corrosive to shelled organisms; the west coast has natural circulation patterns that periodically draw these deep waters into shallow coastal areas. The west coast shellfish industry has recently been experiencing dramatic declines in hatchery production and these declines have been correlated with upwelling events that bring low-pH, corrosive waters to shore.

Determining the effects of ocean acidification on nearshore ecosystems, including coastal and estuarine waters, is fundamentally difficult. In the open ocean, decades of monitoring having led to development of ocean models that improve understanding of how ocean chemistry and oceanographic conditions in the deep sea may change due to rising atmospheric $CO_2$. However, understanding the physical, chemical and ecological impacts of ocean acidification in the nearshore coastal environment is complicated by the interplay of numerous additional factors, such as freshwater inputs, tidal forcing, water stratification, and nutrient over-enrichment. Furthermore, development of models to understand the ecosystem effects of ocean acidification is hampered by a disconnect between carbon chemistry data and biological effects data. Most biological data are spatially located inshore (e.g., at shellfish hatcheries), whereas most physical and chemical measurements are taken offshore on moorings or during ship-based sampling events. Nearshore OA sampling is also less well-coordinated, with a lack of uniformity in the measured physical, chemical and biological parameters. Finally, the timescales over which data are integrated are fundamentally different. In the open ocean, the primary concern is predicting how large swaths of the ocean are changing over decadal scales; in the nearshore environment, stakeholders (e.g., shellfish harvesters, aquarium operators) need real-time data and predictive models that operate over a small segment of the coastline on daily to weekly timescales so they can adapt their operations.

**Meeting the Challenge**

Fully understanding the impact of ocean acidification along the west coast and developing adaptation strategies will require a level of coordination not seen before. Achieving this goal necessitates integration of ocean observing measurements, laboratory exposure studies, shellfish recruitment and production data, and field studies of organism performance in relation to ocean conditions. These data are currently collected by different sectors that have historically had limited interaction. However, observations by the shellfish industry that showed a correlation between declines in hatchery production with upwelling of lower-pH waters led to discussions between Sea Grant programs, Integrated Ocean Observing System (IOOS) managers and the shellfish industry, and ultimately to a 2010 workshop that brought together scientists and industry representatives to increase collective understanding of the effects of OA on the nearshore environment. Following this workshop the California-Current Acidification Network (C-CAN) was initiated to facilitate interaction among the diverse sectors affected by ocean acidification. C-CAN has since expanded to include many types of stakeholders affected by ocean acidification, such as other ocean-dependent industries, environmental advocacy groups, and regulatory agencies.

C-CAN is a collaboration that brings together these diverse perspectives to increase understanding about acidification of coastal, estuarine, and offshore waters, and its effects on biological resources. The overarching goal of C-CAN is to coordinate measurements, practices, and communication to define the effects of ocean acidification and develop strategies for adaptation. C-CAN is working to develop agreement on the various technical aspects of ocean acidification monitoring and lowering barriers to making seawater $CO_2$ measurements of sufficient quality to understand ecosystem effects of changing ocean chemistry. To this end, C-CAN will provide explicit guidance as to how best to make such measurements (i.e., identify specific parameters, required precision, and suggested instrumentation) and will develop the necessary data infrastructure (in collaboration with Regional Associations of the US Integrated Ocean Observing System) for combining the various individual data sets into a coherent network. C-CAN also aims to facilitate use of these network data in research required to develop tools that help determine the causes of ecosystem declines, as well as tools to predict future changes in ocean chemistry and biological communities. Finally, C-CAN will communicate the findings of the monitoring network to address management questions and promote the data products and tools developed by C-CAN partners.

Since its inception, C-CAN has coordinated a series of workshops designed to develop a network that integrates biological and chemical monitoring, with an eye towards developing adaptive practices and predictive modeling for the near-shore environment. Over the course of these workshops, C-CAN has reached agreement that this network should measure parameters that enable determination of the aragonite saturation state of seawater with an overall uncertainty of ± 0.2, and a complete description of the seawater $CO_2$ system, including $pCO_2$ and pH. Measurements should be concentrated on the waters along the coast and within estuaries, particularly in places where they can inform co-located biological studies, but should also be linked to mid-shelf and off-shelf monitoring. Specific requirements for participation in the network will be outlined in C-CAN's Core Principles document, which will detail the core monitoring parameters, precision required, and how chemical parameters should be linked to biological monitoring for different monitoring platforms. C-CAN is also in the process of developing guidance documents ("how-to" manuals) for several types of monitoring platforms: land-based-flow-through systems, ocean moorings, and ship based measurements. These documents provide detailed descriptions of recommended instrumentation, protocols, and quality assurance for each monitoring platform.

The purpose of this document is to outline C-CAN's vision for a U.S. west coast ocean acidification monitoring network. This document outlines C-CAN's roles in each of these areas:

- Establishing a Chemical Monitoring System (Chapter 2) — Development of a chemical monitoring network including desired sampling elements, protocols, training, and technical guidance to ensure data uniformity across users, expansion of the network's capacity, and access to a common data management structure;
- Linkage to Biological Effects (Chapter 3) — Linkage of physical and chemical data to biological data to develop relationships between ambient conditions and biological response;
- Support for Causal, Predictive, and Economic modeling (Chapters 4–6) — Facilitating use of C-CAN data, and knowledge of C-CAN participants, to assist development of models that determine the interaction of numerous stressors to forecast oceanographic conditions over a variety of spatial and temporal scales in the nearshore environment;
- Communication (Chapter 7) — Facilitation of communication among disparate interest groups that participate in C-CAN or are clients for its products.

C-CAN is set up as an enabling body. It will center efforts on training entities to collect data of sufficient quality to participate in the network. Based on C-CAN recommendations, individual monitoring programs have already begun to adapt their sampling activities, but much work remains to be done to increase capacity and begin data sharing and interpretation. The vision for C-CAN presented herein describes a fully functional west coast ocean acidification network that is achievable in the near term.

# Chapter 2 — Establish a Chemical Monitoring System

**Monitoring Biologically Significant Chemical Parameters-- Aragonite Saturation State**

Ocean acidification (OA) refers to the reduction in seawater pH associated with the global oceanic uptake of increasing atmospheric carbon dioxide ($CO_2$). However, pH (the measure of available hydrogen ions) itself is not the primary parameter of biological concern. A more relevant measure is disruption of carbonate equilibrium, which is only partly characterized by pH. After dissolving in seawater, $CO_2$ reacts with water and establishes a new equilibrium between carbonic acid, bicarbonate ions, carbonate ions and hydrogen ions. Ultimately, both carbonate ion concentration and pH decrease when $CO_2$ dissolves in the ocean. Those carbonate ions would otherwise be available to form calcium carbonate, a fundamental building block of exoskeletons in shellfish and other marine organisms.

Several measurable water quality parameters describe ocean acidification processes, but the unifying parameter that links them, and is thus the core indicator for the C-CAN monitoring network, is aragonite saturation state ($\Omega$). $\Omega$ is a measure of $CaCO_3$ available for organisms to make shells or other structures. When $\Omega$ is greater than 1, shells are more easily formed and when $\Omega$ is less than 1, mineral $CaCO_3$ dissolves. Organisms that produce shells made of $CaCO_3$, such oysters and clams, show negative responses to lowered $\Omega$ values. C-CAN has established as a founding principle, that its monitoring partners should determine changes in aragonite saturation state with an accuracy of ± 0.2, which is required to adequately characterize biologically-relevant changes in seawater chemistry.

**Formation of a Chemical Monitoring Network**

Organizations participating in the C-CAN monitoring network will agree to collect and share data that meets C-CAN data quality requirements. To facilitate this, C-CAN will develop guidance for ocean acidification monitoring, training in setting up a monitoring platform, and ongoing support to maintain monitoring activities into the future. This support will be provided through both technical manuals and hands-on training.

C-CAN recognizes that not all organizations possess equal levels of technical expertise and financial capability, but a lack of expertise or funding should not preclude participation in the network. Consequently, the guidance manuals will include three modes of data collection acceptable for inclusion in the network:

1) Cutting-Edge Mode: for those with a high level of technical expertise collecting continuous data on two or more carbonate chemistry parameters and working with prototype materials at the leading edge of technology;

2) Principal Mode: for those with a basic level of technical experience collecting data on two carbonate chemistry parameters and working with relatively reliable, commercially available, and supported materials;
3) Economy Mode: for those with limited resources or a minimal level of technical experience who can collect continuous data on at least one carbonate chemistry parameter using robust, commercially available, and supported materials.

Most C-CAN participants will fall into the principal mode. Whenever possible, C-CAN will assist participants in the economy mode with searching for support to upgrade to the principal mode. Participants in the cutting-edge mode are also critical to the overall program, as the technologies they develop are expected to improve monitoring and may be commercially adopted in the future for use in the principle mode.

Manuals **—**C-CAN plans to develop a series of technical manuals that will serve as "how-to" guides for at least three types of monitoring platforms: 1) flow-through systems for land-based monitoring operations at shellfish hatcheries and aquaria, 2) ship-based systems for collecting water column profiles, and 3) autonomous samplers for deployment on long-term moorings and gliders. These documents will provide detailed descriptions of the instrumentation, protocols, and quality assurance for each monitoring platform.

These documents will outline the instruments and samples that should be collected to adequately characterize aragonite saturation state with the required precision. Recognizing a wide variety of potential contributors to a C-CAN observing network, these manuals will be written as instructions on how to set up the sampling system on each type of monitoring platform. They will also provide quality assurance protocols, including the expected frequency of instrument calibration to reference materials and analysis of intercalibration samples. Lastly, the documents will describe data management protocols including descriptions of the data format required, how frequently data should be uploaded to the network, and what, if any, data synthesis should be done to make the data more useful to end users. Because monitoring technology is expected to improve and evolve over time, these manuals will be "living" documents. New versions will be produced and distributed to C-CAN network participants as needed.

Training **—** C-CAN will develop a comprehensive training program to help install monitoring systems at new organizations and ensure the data generated for the C-CAN network are collected with the highest quality standards practical at the time. A training program will be developed at a "Train-the-Trainers" workshop. This workshop will establish the protocols for training staff at new facilities on how to take the required ocean chemistry measurements and meet quality assurance and intercalibration requirements. The end result of this workshop will be a training manual that establishes uniform practices for trainers to develop ocean acidification monitoring systems.

Support — Chemical monitoring networks require some specialized and highly technical equipment, and deployment in a seawater environment is hard on even the most robust devices. Personnel at participating facilities will be trained to a level where they can handle routine maintenance, but would not be required to have the technical expertise to troubleshoot complex instrument problems . A regional expert (potentially associated with each IOOS Regional Association) will be established to help participating facilities troubleshoot technical problems related to instrument failure. The regional expert would be expected to have advanced technical knowledge of the instrumentation and would potentially work with the supplier's research and development arms to improve the products. As such, the instrumentation is expected to continue to evolve and improve. The regional expert would be expected to stay informed about recent advances and potential improvements to the existing platforms and relay this information to participating facilities in his or her region.

***Data Sharing and Management***

A key measure of C-CAN's success will be the wide-spread use of the data generated through its monitoring program. The goal of C-CAN is to not only provide chemical monitoring data for managers on current marine conditions, but to also provide data required to design and conduct relevant laboratory and field experiments to understand the effects of ocean acidification on susceptible organisms, and to develop causative and predictive models for determining ecosystem response. If the data are to be useful for these purposes, they must be shared and reported in a consistent and reliable manner. C-CAN's vision is to establish an integrated data management platform to serve this purpose.

The Integrated Ocean Observing System (IOOS) Regional Associations are the ideal candidates for data repository, collation, and sharing for the C-CAN network. The IOOS are already collecting data critical to interpretation of ocean acidification effects and have infrastructure in place for other parameters similar to those required for monitoring acidification. They can serve as C-CAN's chief collaborator in developing the network and data sharing design.

A data sharing platform for C-CAN must incorporate both real time and non-real-time data from monitoring units and observational studies, as well as experimental data. C-CAN will collaborate with the IOOS Regional Associations in expanding their capacity to collate these acidification data sources into an integrated network by developing data input structures and metadata requirements, as well as data visualization and access tools. A workshop will be held to address these needs. This workshop will produce a document defining the data format and metadata required by C-CAN participating facilities, how these data can be uploaded to the IOOS servers with minimum difficulty, expected data quality assurance and quality control checks, the types of data visualization tools required by different user groups (managers vs. researchers), and the design of data access portals for downloading and using data.

While the IOOS Regional Associations are expected to provide the primary data platform for storage and dissemination of ocean acidification network data, coordination with other relevant data platforms must be considered. C-CAN will facilitate integration with other data systems to ensure the network monitoring data are disseminated to the largest possible group of potential users. For example, C-CAN will cross-post data with other systems such as the California Environmental Data Exchange Network (CEDEN), as well as social networking sites such as OceanSpaces.

***Recruit Participants***

While the long-term aim of C-CAN is to build a chemical monitoring network by establishing monitoring sites where data gaps exist, its initial focus is to develop consistency and collaboration among locations where existing monitoring operations are underway. After this initial phase, C-CAN will focus on attracting new participants to the network. There are a number of organizations that conduct water quality monitoring as a part of their routine operations, but either do not measure acidification parameters or measure them in a way that limits value due to poor accuracy and precision. Incorporating these groups into the network has many benefits. The first is cost-effectiveness, in that they already have available personnel and facilities and only require better equipment, training, and some level of ongoing technical support. Second, many of these groups bring additional benefits to the network, either through co-located biological measurements or through links to education and outreach.

The first group of targeted organizations is shellfish hatcheries and harvest areas. Some of these facilities and locales are already set up for ocean acidification monitoring and can serve as a template for establishing similar systems at other shore-based locations. These facilities are high priority for C-CAN as they have the most complete biological data sets to establish a linkage between changing water chemistry and effects on organisms at different life stages. The partnership between shellfish hatchery owners and the C-CAN network is mutually beneficial. It offers scientists access to water chemistry and biological effects data while participants benefit from rigorous data analysis that allows the hatchery to minimize impacts on their operations.

The second group of targeted organizations is those that discharge into coastal waters (e.g., wastewater and stormwater dischargers). These organizations conduct regular monitoring (typically ship-based monitoring and sometimes monitoring at moorings) of parameters relevant to ocean acidification (e.g., temperature, salinity, dissolved oxygen, chlorophyll, biological oxygen demand, and nutrient concentrations). C-CAN will promote and incentivize the collection of additional data for the more biologically-relevant measurement of aragonite saturation state. As with the hatcheries, the partnership between C-CAN and dischargers is mutually beneficial; dischargers are better able to meet their discharge permit monitoring requirements and the C-CAN network is expanded to include additional monitoring locations.

The third group of targeted organizations is research reserves, coastal laboratories, and aquaria. The NOAA National Estuarine Research Reserves System (NEERS—five locations along the US west coast), the EPA National Estuary Program (NEP—six US west coast locations), NOAA Marine Sanctuary Program (five US west coast sanctuaries), are federally-supported programs whose core principles include long-term research, water quality monitoring, education, and coastal stewardship. These organizations are already conducting continuous monitoring of parameters relevant to ocean acidification (e.g., temperature, salinity, dissolved oxygen, chlorophyll), and some collect other biological data as well (e.g., nutrients, surveys of plants and organisms). C-CAN will promote and incentivize improvement of their water quality monitoring capacity to include measurement of parameters that allow determination of aragonite saturation state. Aquaria and coastal laboratories collect daily water samples as a part of their routine operations and test for a variety of other relevant parameters. Ocean acidification has already had demonstrable effects on aquaria collections. C-CAN can help them establish monitoring and response systems similar to those established for the hatcheries. Again, these partnerships are mutually beneficial; the NEERS groups, laboratories, and aquaria will have improved capacity for education and stewardship while the C-CAN network's available data increases.

# CHAPTER 3 — LINKAGE TO BIOLOGICAL EFFECTS

The coastal environment contains numerous stressors in addition to ocean acidification that affect ecological communities. Hypoxia, toxins, and outbreaks of disease have also been implicated as having adverse effects on nearshore organisms. Untangling the effects of these different stressors requires documenting the relationship between changes in ocean chemistry and changes in *in situ* biological communities. Laboratory exposure studies are also needed to determine if the changes observed in the environment correspond to the effects observed under controlled laboratory conditions.

Ocean acidification's adverse effects on species include reduced tolerance to temperature increases, impaired reproduction, inefficient cell function, impaired growth, larval shell dissolution, disease susceptibility, and higher mortality rates at early life stages. Generally, there is a higher "cost of living" for organisms subjected to a high-$CO_2$ marine environment, but different organisms have different sensitivities to ocean acidification. Furthermore, the same organism has different sensitivities at different life stages and the timing of acute acidification events can have implications for organism reproductive success. Options for populations of species faced with environmental stressors like ocean acidification include migration, acclimatization (tolerance), adaptation (which, if possible, may take generations), and extinction. Laboratory studies can help determine which of these avenues is likely for a variety of sensitive species under both current and future water quality conditions.

Ocean acidification not only has an effect on biological communities, but biological communities also influence ocean chemistry. As acidification affects biological communities, species shifts will result in changes in carbon and nutrient cycling. For instance, when algal blooms senesce, microbial communities consume and respire organic matter, which produces carbon dioxide and reduces oxygen concentrations. These types of biogeochemical processes influence the carbon budgets of coastal systems, affecting $pCO_2$ and pH in ways that are synergistic with the effects of ocean acidification.

**Prioritize Co-Location of Biological and Chemical Monitoring**

C-CAN will prioritize co-location of chemical monitoring with biological monitoring so that correlative relationships between chemistry and biology can be developed. The high quality ocean chemistry data set provided by the C-CAN monitoring network will aid in designing accurate laboratory studies, enabling production of controlled experimental data that defines the effects of ocean acidification on targeted organisms. A secondary priority is to conduct field and laboratory studies to understand the interaction between anthropogenic nutrient inputs and biological communities and ocean acidification. Integrating these data into causal and predictive models can help untangle the present and future effects of ocean acidification on the nearshore environment.

The first step in this process is to prioritize installation of prescribed chemical monitoring equipment at shellfish hatcheries and other locations where long-term biological monitoring programs exist. The second step is to develop a recommended set of biological measurements that should be made over an extended time period at multiple locations linked to chemical monitoring systems. These biological measurements will be designed to capture the episodic nature of settlement of a range of organisms. C-CAN will hold workshops to prioritize these measurements and then prepare protocols detailed in "how-to" manuals, defining recommended frequency and timing of sampling.

One strategy will be to focus research on sites where acute acidification effects on oyster larvae have already been demonstrated. Because of the strong signals from upwelling, the “noise” associated with other factors might be diminished, providing better data resolution to demonstrate the effects of changing carbonate chemistry. Paired biological, physical, and chemical data sets at these sites will greatly enhance the understanding of acidification impacts on sentinel populations.

**Establishing Linkage Experiments in the Field and Laboratory**

One of C-CAN's ultimate goals is to enable development of causal and predictive models of the ecosystem effects of ocean acidification in the coastal environment and controlled experiments are needed to parameterize these models. Data must be generated on sensitivity of life stages, critical timing and rates of effects, etc. Part of C-CAN's long-term vision is to facilitate and incentivize conduct of these types of experiments in both field and laboratory settings.

C-CAN will organize a workshop to facilitate use of the monitoring network data and identify the critical test conditions best suited to inform model development. The result of this workshop will be a road map outlining targeted species and experiments that must be conducted to establish critical thresholds for individual species, life stage sensitivity, rates of decline, etc. Workshop participants will include modelers and biological oceanographers to open the lines of communication regarding model needs and how researchers can provide the necessary data inputs.

**Understanding the Effects of Biological Communities on Ocean Acidification**

Understanding the effects of ocean acidification on biological communities alone is not sufficient to fully understand ocean acidification impacts on coastal and estuarine waters. Other factors, such as nutrient pollution and increased primary production (eutrophication) are expected to have synergistic effects with ocean acidification. For example, increased $pCO_2$ and decreased dissolved oxygen would add to biological stress beyond what would be expected from global ocean acidification alone.

To support the understanding of synergistic interactions, C-CAN will facilitate field and laboratory studies designed to produce data on critical rates and feedback processes that affect coastal ocean chemistry and biology. To start, some basic oceanographic measurements can be collected to understand these interactions, chiefly, autonomous chlorophyll and dissolved oxygen measurements, which can be used to understand changes in ecosystem metabolism over different timescales (daily, monthly, seasonally, interannually). Field studies compiling large amounts of monitoring data over several years can be used to compare patterns in nutrient loading, algal blooms, hypoxia, and acidification events. In the coastal zone, the effects of ocean acidification are thought to be exacerbated by nearshore processes, but little is known about how they are changing in parallel. Collaborative regional monitoring programs such as the Southern California Bight Regional Monitoring Program and California Cooperative Oceanic Fisheries Investigations (CalCOFI) provide an opportunity to look at these issues in unison and pull out synergisms on local and regional scales.

Autonomous or discrete measurements of nutrient concentrations as well as nutrient loading from watersheds to coastal and estuarine waters could aid in understanding the role of nutrient enrichment in development of eutrophication. Additional field studies targeted at understanding nutrient uptake kinetics and changes in microbial nutrient cycling can also be conducted to understand the biological and chemical interactions in the coastal zone and fill out carbon budgets for the nearshore environment. These measurements and studies close the loop between understanding how ocean chemistry affects biology and, in turn, how biology affects ocean chemistry.

# CHAPTER 4 — CAUSAL MODELING

The ultimate goal of C-CAN is not just data collection, but establishing a network of experts working collectively towards use of that data for decision-making. In the case of the shellfish industry, these decisions will focus on optimizing operations that ameliorate or adapt to changing acidification conditions. At the water quality management level, these decisions will focus on what steps can be taken to lessen the pace of acidification. At the resource management level, decisions will focus on managing adaptively to build promote sustainability of coastal resources or conduct spatial planning so that sensitive biological systems are located in areas least susceptible to acidification.

C-CAN will seek to achieve this objective by working to support the development of models that integrate the data from its monitoring program to address three key questions:

1) What factors contribute to coastal ocean acidification and ecosystem response and how effective will limiting these factors be individually or collectively?
2) What is the anticipated rate of change for acidification, both to help with short-term decisions made at the hatchery operation level and in the long-term to assist with spatial planning?
3) What are the potential social and economic impacts of changing ocean chemistry on coastal communities?

This chapter describes C-CAN's plans for addressing the first question, Chapter 5 provides the approach for addressing the second, and Chapter 6 addresses the third.

**Developing Causal Models for the Nearshore Environment**

The primary driver for acidification on the US West Coast is upwelling of deep ocean waters affected by increased global oceanic absorption of atmospheric $CO_2$. However, the coast is also subject to urban and agricultural discharges containing biologically-important nutrients that can exacerbate the problem locally. Differentiating locally-triggered eutrophication from that tied to upwelling of deep waters onto the coastal shelf is challenging. Furthermore, these processes are embedded in a complex circulation pattern modulated by large interannual and decadal fluctuations (e.g., El Niño Southern Oscillation, the Pacific Decadal Oscillation, climate change, etc.) in combination with strong local intrinsic variability. Measurement programs alone are not sufficient to establish material budgets and assess the fate and transport of biological tracers or contaminants.

The first step in developing causal models is reaching broad agreement on what models to use as the basis for further development. Efforts are already in motion to fulfill this need, including a workshop that will convene managers, expert scientists, and modelers to determine how existing models can be improved to best answer management questions. C-CAN will take an active role in this effort to ensure C-CAN data are incorporated into the chosen models and the monitoring system is refined (if the necessary parameters are not already being collecting) to enable a full understanding of the effects of changing ocean chemistry on coastal and estuarine habitats.

The second step is to act on the workshop findings to expand the capability of the existing models and enable a more comprehensive and consistent evaluation of both anthropogenic and climatic perturbations on nearshore physical, chemical, and biological conditions. Developing these models requires newly developed chemical/biological subsystems integrated with physics on the regional scales useful to managers; however, existing biogeochemical and physical models are insufficient for understanding the complexity of ocean acidification effects on nearshore and estuarine habitats. Biogeochemical models must be expanded to include a wider diversity of species, environmental effects on physiology, ecosystems interactions among trophic levels, and feedback loops between biological communities and ocean chemistry. Physical models must be expanded to include processes that affect shallow nearshore environments. Coupled physical and biogeochemical models must incorporate anthropogenic and natural fluxes of terrestrial nutrients and pollutants from atmospheric deposition, rivers, and urban discharges.

The third step is to conduct field and laboratory studies to calibrate and validate the models. C-CAN will work with partners to facilitate gathering of data on key rate processes that can be used to parameterize the models, as well as provide data for model validation. These validations are critical for testing the models and attributing observed data trends. Most critical to validation are large data sets representing "snapshots" of coastal waters (e.g., California Cooperative Oceanic Fisheries Investigations, Southern California Bight Regional Monitoring Program), which provide the best opportunity to test the new models. Model results validated with these data sets offer the best way of converting empirical data from major field campaigns into regional balances of important properties such as nutrients, oxygen, carbon, and acidity (pH). Historical time series can also be used to assess the drivers of both interannual and long-term change using hindcast model simulations.

The final step is analyzing vast quantities of model output to distill model results into regional budgets and discern the major controls and causes of change over time. These model results can then be used by environmental managers to determine best management practices to minimize stressors, identify critical habitat, and track ecosystem changes through time.

# Chapter 5 — Predictive Modeling

**Forecasting Future Changes**

Impacts of ocean acidification to ecosystem processes and overall productivity are mostly unknown, but are poised to affect whole ecosystems. Consequently, this issue has raised concerns across scientific and resource management communities as to possible ecological, economic, and societal impacts. In addition to developing models that enable understanding of the fundamental causes of ecosystem change at a variety of spatial scales, it is also imperative to be able to predict future changes.

C-CAN's vision is that its monitoring network will provide the foundation for development of predictive tools that forecast future ocean chemistry shifts and the subsequent effects on biological communities, with an eye towards improving the ability of industry, managers, and policymakers to modify their practices to best mitigate the effects of ocean acidification. These models will build on causal models and incorporate forecasting capacity at a variety of temporal and spatial scales. Current predictive models mostly focus on ocean basin-level changes and decadal scales. C-CAN will facilitate extension of those models to the coastal zone and to spatiotemporal scales relevant to coastal managers. For example, predictive tools that forecast shorter-term acidification events could be used by the shellfish industry to modify their operations. Predictive tools will also assist in spatial planning, enabling resource managers to assess alternative management strategies to prevent degraded ecosystems.

**Developing Predictive Models for the Nearshore Environment**

C-CAN will promote development of two tiers of predictive models for the nearshore environment. The first type is "climate" models, which will be used to predict long-term changes in carbonate chemistry over multi-decadal timescales. Such models could be used by the resource management community to characterize ecosystem vulnerability, identify sensitive habitat, narrow the best locations for marine protected areas, and plan restoration efforts. They could also be used by the shellfish industry for guiding placement of hatcheries.

The second type of predictive models is "weather" models, which will be used to identify small-scale spatial and temporal variations in carbonate chemistry. These types of models will primarily be used by the shellfish industry and aquaria for planning their day-to-day operations in the short term. They will provide forecasts of oceanographic conditions, predicting arrival of corrosive water weeks or months before it is expected to hit the shoreline. Such forecasts could enable hatcheries and aquaria to plan ahead and minimize the impacts of acute acidification events on the health of their collections.

Once the predictive models are established, C-CAN will facilitate development of an online web portal allowing prospective users to obtain predictions on a spatial and temporal scale of their choosing. Model output will be collated and assembled by region on multiple timescales, allowing users to zoom in and view predictions for oceanographic conditions in multiple areas on weekly, monthly, and yearly timescales.

# CHAPTER 6 — HUMAN DIMENSIONS

**Link Ocean Acidification to Economic and Social Outcomes**

The California Current ecosystem supports commercial shellfish aquaculture, commercial wild-caught fisheries, recreational fisheries, and a healthy nearshore ecosystem that contributes to economic revenues, culture, and social values of coastal communities. Ocean acidification can potentially affect a number of different species that support these uses. Economically-valuable shellfish will likely be affected, and organisms that prey on shellfish may be indirectly affected, as will other components of the interconnected ecosystem. Changes in ocean chemistry and the resulting biological impacts could have substantial economic impacts on marine-based businesses and acute impacts on small coastal communities that depend on these industries.

C-CAN's envisions that its data network will also be used to help understand how changes in ocean chemistry and biological responses affect human communities. Connecting ocean acidification with “human dimensions” research can be used to help inform policy and other management decisions aimed at helping society cope with, prepare for, and adapt to the expected changes in ocean chemistry.

C-CAN will support the work of social scientists who can evaluate the social and economic costs of ocean acidification. C-CAN will promote using west coast communities to serve as a test case for social science research and will facilitate similar studies of economic and social impacts along the west coast. The California Current is an ideal place to link ocean acidification to social repercussions because of its historically productive fisheries and aquaculture industry, and the strong ties of coastal communities and tribes to these  ocean resources. C-CAN is well positioned to serve as a boundary organization that connects social scientists with environmental scientists, managers, regulators, and industry. C-CAN will supply social scientists with data to support their analyses, as well as an opportunity to participate in workshops that connect them to members of the C-CAN community who can assist with identification and quantification of social and economic impacts. Specifically, C-CAN will collaborate with the National Science Foundation’s Socio-Environmental Synthesis Center (SESYNC), which is bringing together scientists and policy makers to identify “hotspots of human vulnerability” to ocean acidification.

# CHAPTER 7 — COMMUNICATION

Collection of ocean acidification data is fruitless if the results are not shared and used. Sharing of data and experience is one of C-CAN's core principles and will be formalized through a "Declaration of Interdependence" which outlines the responsibilities of C-CAN network participants. Moreover, a key measure of C-CAN's success will be access and use of the data collected in the monitoring network by scientists, industry, managers, and policy makers.

One of C-CAN's strengths in meeting this goal is the diversity of participants. Communication of different data types and experience among the disparate groups that comprise C-CAN will advance the collective understanding of ocean acidification impacts, facilitating development and implementation of mitigation strategies at a rate much faster than if individuals were working in isolation. C-CAN's communication strategy focuses on achieving two distinct and equally important outcomes: 1) leveraging knowledge and data to improve the scope and quality of ocean acidification data sets and models, and 2) communicating key messages to the larger community about impacts of ocean acidification and steps that can be taken to address it.

**Leveraging Knowledge**

C-CAN scientists cover a wide array of specializations, spanning chemistry, physics, mathematics, and biology. One focus of the C-CAN communication strategy will be to facilitate interaction among these specialists, allowing them to leverage their individual resources to produce better collaborative science. Biological oceanographers given chemical monitoring data can design better laboratory experiments that test stressors in conditions matching the natural environment. Results of the laboratory experiments can then be used to inform surveys that look for evidence of the same patterns in the field. These, in turn, can be used by chemical oceanographers to help interpret chemical monitoring data sets.

C-CAN will also serve as a point of interaction between data-collecting research groups and the modeling community. Development of accurate models hinges on communicating modeling data needs to the groups best suited to fulfill them. Understanding the requirements for key rates and processes used to parameterize models will allow monitoring entities to design appropriate field and laboratory studies.

Knowledge gained in implementing the monitoring network will also be leveraged among participants. The network is expected to generate a wealth of experience with new technology and an understanding of what works for a specified set of circumstances and what does not. This experience will be shared and documented through a series of workshops that continue to enhance the capabilities and quality of the monitoring network. These hands-on workshops will be designed to keep C-CAN participants up-to-date on the latest technologies and recent scientific advancements in monitoring. Different facilities can also share their experiences, commonly-encountered problems with the instruments, and approaches for addressing them. As data tools are developed for visualization and prediction, these meetings can also serve as a means for data users to “beta test” their performance. Input from beta-testers can be used for troubleshooting, to make improvements to the tools, and to elicit recommendations for how they can be refined to better meet specific needs, thus making the tools as valuable to the end users as possible.

Beyond meetings, C-CAN will employ a digital communication strategy to enhance interaction among its members. The C-CAN website will be used primarily as a means to communicate activities with the outside world. Internal communication among C-CAN participants will be enhanced through use of an e-mail listserv and wiki-based discussion forums. These online discussion forums will allow monitoring network participants to post questions and/or notes on their experiences with new and evolving monitoring technologies and receive answers in real time. Such a forum will help facilities troubleshoot minor problems or explore technological advances when they first become available, as well as to share the latest news.

**Disseminating Findings**

The diversity of C-CAN participants facilitates and strengthens dissemination of research findings to a wide array of audiences. Scientists often have difficulty communicating their findings because they do not speak at the same technical level as the audiences they want to reach. Worse, they are sometimes viewed as highlighting issues to gather additional research dollars to support their work, rather than communicating highly relevant findings to society. Industry and NGOs often have entry points and share a common language level with these same audiences, but can be viewed as speaking without technical authority in the topic area. C-CAN’s diversity of participants allows it to merge these strengths to provide a common and more effective voice that will be collectively welcomed into a larger number of venues.

To achieve a collective voice, C-CAN’s diversity of participants must develop consensus about ocean acidification science. C-CAN has the ability to generate broad consensus, not only on how and what to monitor, but also on data interpretation. C-CAN will hold annual meetings in which industry representatives, scientists and managers  discuss ocean acidification science. These meetings will promote discussions on what information is available to answer participants’ questions, what level of consensus can be achieved based on existing data, and (when consensus cannot be achieved) what data still need to be collected.

C-CAN will use a variety of approaches to communicate agreed-upon messages in areas where consensus has been achieved. First, C-CAN‘s website already provides access to a variety of resources and will be expanded to provide more. Second, C-CAN will develop products that allow its members to speak with a common voice. For instance, C-CAN will produce PowerPoint presentations that summarize the latest ocean acidification findings, as vetted by the C-CAN community, as a starting point for C-CAN members asked to give ocean acidification talks to different audiences. These won't replace the personal knowledge and experience of C-CAN's many experts, but will provide a common starting point describing areas where consensus has been achieved. . Third, C-CAN will develop fact sheets that can be shared with audiences as a take-home reference when presentations are given. Fourth, as a resource for external groups looking for more information, C-CAN will establish a "speakers bureau" by developing a list of its members that have interest and expertise to give talks to a variety of groups on an array of ocean acidification topics. Finally, C-CAN will publish a newsletter, at a minimum annually, whose target audience will be industry, resource managers, decision makers and the public. This newsletter will summarize, in nontechnical language, scientific advancements and discoveries related to ocean acidification, and the status of the coastal ocean with respect to ocean acidification (as vetted by the C-CAN network).