

Developing an Global Ocean Acidification Observation Network

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Abstract

Since the beginning of industrialization, the increase in atmospheric carbon dioxide (CO_2), originated largely from human fossil fuel combustion and deforestation, is causing a decrease in ocean pH and shifts in seawater carbonate chemistry. This process called ocean acidification is well established from field data, and the rate of change in ocean pH and carbon chemistry is expected to accelerate over this century unless future CO_2 emissions are restricted radically. The rate of CO_2 increase is at least an order of magnitude faster than experienced by the Earth for millions of years and the current concentration is estimated to be the highest in, at least, the past 800,000 years. Central to the atmospheric CO_2 inventory over the next century will be the adjustments in the ocean uptake of anthropogenic CO_2 and seasonal and interannual uncertainties in the natural CO_2 exchange flux. To quantify these changes on a global scale, an integrated international interdisciplinary program of ship-based hydrography, time-series moorings, floats and gliders with carbon system, pH and oxygen sensors, and ecological surveys is already underway. This program will determine the extent of the large-scale changes in the carbon chemistry of seawater and the associated biological responses to ocean acidification in both open ocean and coastal environments. Many countries are presently engaged in ocean acidification research and monitoring activities. Some examples include European projects such as EPOCA and BIOACID and emerging programs in the UK and USA funded by NERC and the NSF. The proposed activities will require a coordinated

international research effort that is closely linked with other international carbon research programs, such as the CLIVAR/ CO_2 Repeat Hydrography Program. The global ocean acidification observation network will benefit from and interface with the data synthesis activities, data archiving and international data management activities of the carbon and ocean acidification programs.

Introduction

Human activities from the beginning of industrialization have resulted in the accelerated increase in carbon dioxide partial pressure ($p\text{CO}_2$) increasing from approximately 280 parts per million volume (p.p.m.V.) at the end of the 19th century to the current levels of 387 p.p.m.V. During this time, the oceans have absorbed about one-third of the anthropogenic carbon emissions. This is of great benefit to humans because the ocean uptake of gases balancing the increase in greenhouse gas levels in the atmosphere, thereby partly minimizing global warming. When CO_2 enters seawater, the $p\text{CO}_2$ in seawater increases and both the seawater pH and the concentration of carbonate ions (CO_3^{2-}) decrease. This process is referred to as ocean acidification (Figure 1). As a result, the pH of ocean surface waters has already decreased by about 0.1 unit since the beginning of industrialization (Caldeira and Wickett, 2003; 2005), with a decrease of $\sim 0.0018 \text{ yr}^{-1}$ observed over the last quarter century at several open ocean time-series sites (Bates, 2007; Bates and Peters, 2007; Santana-Casiano et al., 2007). The continuing process of ocean acidification has long been documented (Bacastow and Keeling, 1973; Broecker et al., 1971; Broecker and

Takahashi, 1966; Feely and Chen, 1982; Feely et al., 1988) but the ecological implications of such chemical changes have only recently been examined.

The current levels of $p\text{CO}_2$ are not unprecedented in the history of Earth although today's CO_2 levels are thought to be the highest for at least the last 800,000 years. However, the rate of increase in $p\text{CO}_2$ is thought to be at least an order of magnitude faster than has occurred for millions of years. The rate of increase in $p\text{CO}_2$ (and the associated chemical changes) will undoubtedly impact upon marine life but how marine biota will adapt to ocean acidification remains an open question. Increasing ocean acidification also reduces the availability of carbonate ions (CO_3^{2-}) in seawater. These are important building blocks for marine plants and animals that produce calcium carbonate (CaCO_3) and, therefore, their fate in future surface under-saturated waters could be compromised by the year 2032 in the Arctic Ocean, and by 2050 in the Southern Ocean with potential disruptions to many components of the marine food web (McNeil and Matear 2008; Steinacher et al., 2009). In addition to the changes in pH, if CO_2 levels continue to rise, this will lead to significant temperature increases in the atmosphere and the ocean surface in the coming decades. These synergistic effects of CO_2 and temperature (and other climate change-related variables) are however unknown. Other unanswered questions are what are the reciprocal interactions between biota and water chemistry, what are the effects of ocean acidification on marine calcifiers, what determines the capacity of organisms to adapt to ocean acidification, and what are the threshold levels for physiological tolerance (tipping points) at the organism and community levels. This information is required to predict the socio-economic impact of ocean acidification and to design CO_2 emission mitigation strategies.

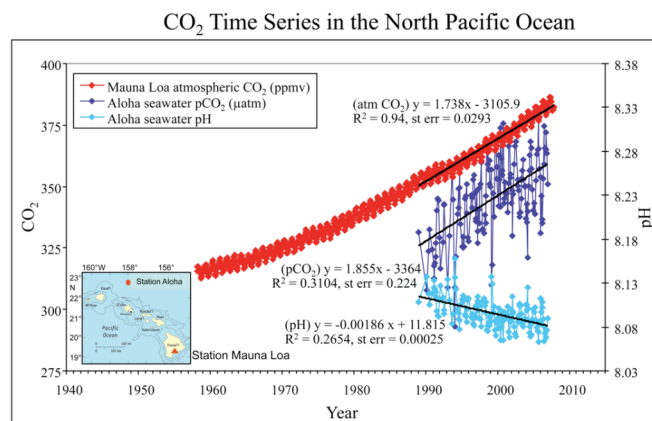
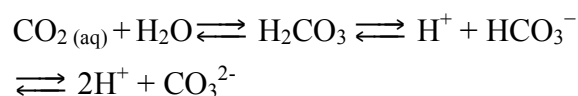


Figure 1: Time series of atmospheric CO_2 at Mauna Loa (in p.p.m.V.) and surface ocean pH and $p\text{CO}_2$ (μatm) at Ocean Station Aloha in the subtropical North Pacific Ocean. Note that the increase in oceanic CO_2 over the last 17 years is consistent with the atmospheric increase within the statistical limits of the measurements. Mauna Loa data: Dr. Pieter Tans, NOAA/ESRL (<http://www.esrl.noaa.gov/gmd/ccgg/trends/>); HOTS/Aloha data: Dr. David Karl, University of Hawaii (<http://hahana.soest.hawaii.edu>) (modified after Feely, 2008).

Some facts about ocean acidification

Results from the global ocean CO_2 surveys over the past two decades have shown that ocean acidification is well documented and a predictable consequence of rising atmospheric CO_2 . Seawater carbonate chemistry is controlled by a series of chemical exchange, dissolution and precipitation reactions. Atmospheric CO_2 equilibrates with dissolved CO_2 in seawater [$\text{CO}_2(\text{atmos}) \rightleftharpoons \text{CO}_2(\text{aq})$] and any increases in the atmosphere reach equilibration with the seawater phase in a time scale of a year. Since CO_2 is a weak acid, it reacts with seawater to form carbonic acid (H_2CO_3). A major fraction of the H_2CO_3 dissociates into hydrogen ions (H^+) and bicarbonate ions (HCO_3^-). A small portion of the H^+ reacts with carbonate ion (CO_3^{2-}) to produce HCO_3^- ions. As a result, CO_2 uptake by the oceans causes a increase in H^+ , and a decrease in pH and CO_3^{2-} concentrations:



These reactions are extremely fast, and inorganic carbonate species can be assumed to be in equilibrium. The formation of H_2CO_3 occurs within 10s of seconds and the

interconversion of HCO_3^- and CO_3^{2-} takes place within microseconds. For surface open ocean conditions, about 90% of the total carbon is in the form of the bicarbonate anion (HCO_3^-), ~9% as carbonate (CO_3^{2-}), and ~1% remains as undissociated $\text{CO}_2(\text{aq})$ and H_2CO_3 .

Another process that impacts upon the equilibria of the carbonate species is biotic calcification: $[\text{Ca}^{2+}] + [\text{CO}_3^{2-}] \rightleftharpoons \text{CaCO}_3(\text{s})$. The term 'saturation state' (Ω) of calcium carbonate is defined by $\Omega = [\text{Ca}^{2+}][\text{CO}_3^{2-}] / K'_{\text{sp}}$, and differs for different mineral forms of the precipitating carbonate and different contribution of metals to the carbonate fraction (e.g., MgCO_3 versus CaCO_3). Organisms producing skeletons or body parts of solid-phase CaCO_3 are critically dependent on the availability of CO_3^{2-} . Most surface waters in the global ocean are currently supersaturated ($\Omega > 1$; e.g., 2-4 for aragonite and 4-6 for calcite), yet a decrease in these values will affect organisms with optimal carbonate precipitation rates above these saturation states.

Two biotic processes affect the direction of CO_2 fluxes between the upper ocean and the atmosphere: photosynthesis utilizes CO_2 at the surface and thus increases the seawater pH, and respiration releases CO_2 in the surface and through the water column: $\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{CH}_2\text{O} + \text{O}_2$. Photosynthesis also produces a large fraction of the annual global supply of oxygen (and consumes nutrients such as nitrate, phosphate, and iron, all of which can be limiting in different parts of the ocean). The downward flux of organic matter from the ocean subsurface to the deep sea is re-oxidized by respiration back to CO_2 , thereby sequestering CO_2 from the atmosphere but also acidifying the deep sea. While the focus of monitoring programs is on measuring CO_2 , oxygen measurements are required particularly when investigating the effect of ocean acidification on biologically-relevant processes involving the cycling of CO_2 and O_2 . For example, the most abundant protein on Earth, RuBisCO (ribulose-1,5-bisphosphate carboxylase oxygenase)

catalyses either the carboxylation or the oxygenation of ribulose-1,5-bisphosphate with CO_2 or O_2 . Therefore, monitoring both CO_2 and O_2 is key to understanding the effect of processes like ocean acidification on biological activities of biogeochemical relevance.

Natural fluctuations in pH

The effects of ocean acidification are well verified from models, open-ocean hydrographic surveys, and time series data (Bates, 2007; Bates and Peters, 2007; Caldeira and Wickett, 2003; Caldeira and Wickett, 2005; Chung et al., 2003; Feely et al., 2008; Feely et al., 2004; Feely et al., 2002; Orr et al., 2005; Sabine and Feely, 2007). At the Hawaii Ocean Time-Series (HOT) station ALOHA the increases of surface water $p\text{CO}_2$ and atmospheric CO_2 agree well (Figure 1), indicating uptake of anthropogenic CO_2 as the major cause for long-term increases in dissolved inorganic carbon (DIC) and decreases in CaCO_3 saturation state (Doney et al., 2009). However, while ocean acidification is a global-scale phenomenon, there are areas that already have naturally low pH conditions; e.g., modelling studies have suggested that the high latitude oceans (Arctic and Southern Oceans) will experience aragonite undersaturation by the middle of the century (Cao and Caldeira, 2008; Gehlen et al., 2007; Orr et al., 2005). Steinacher et al., (2009) argue that the surface Arctic will start experiencing localized aragonite undersaturation within the next decade.

In a recent study, Feely et al. (Feely et al., 2008) presented new observations to show that organisms growing in coastal upwelling events along the continental shelf of the west coast of North America may already be experiencing significant biological effects resulting from the combined impacts of coastal upwelling and ocean acidification (Figure 2). Here the seasonal upwelling of subsurface waters along the coast brings CO_2 -enriched waters onto the shelf and, in some

instances, into the surface ocean. It appears that this water, in addition to its original high level of CO₂ resulting from natural respiration processes in the subsurface layers, is also significantly enriched with anthropogenic CO₂. An immediate consequence of this additional CO₂ is that the CO₂ concentration in these upwelled waters is significantly greater than what it would have been in pre-industrial times. Since these “acidified” upwelled waters are undersaturated with respect to aragonite they are already a potential threat to many of the calcifying aragonitic species that live in these coastal regions. Because seasonal upwelling is a common phenomenon in many coastal regions, this process may be affecting coastal ecosystems in other locations as well.

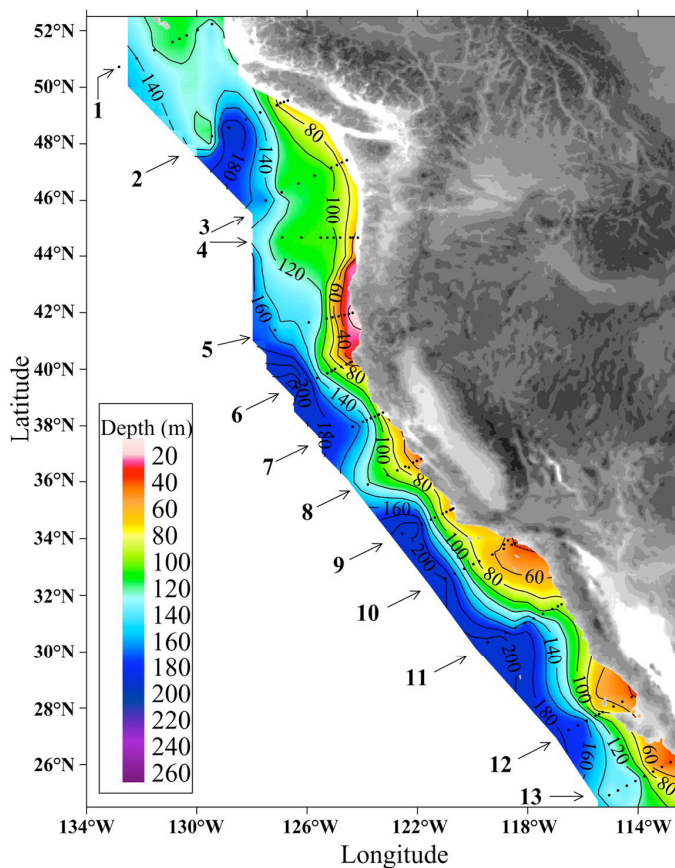


Figure 2. Distribution of the depths of the undersaturated water (aragonite saturation < 1.0; pH < 7.75) on the continental shelf of western North America from Queen Charlotte Sound, Canada to San Gregorio Baja California Sur, Mexico. On transect lines 5 the corrosive water reaches all the way to the surface in the inshore waters near the coast. The black dots represent station locations (Feely et al., 2008).

Shoaling of undersaturated waters has been observed in the North Pacific (Feely et al., 1988), and Chukchi Sea of the Arctic (Bates et al., 2009) where the biological pump enhances the seasonal undersaturation of carbonate minerals in subsurface waters.

Adaptation of marine biota to ocean acidification

By the end of this century atmospheric carbon dioxide levels could reach more than 800 p.p.m.V. (Orr et al., 2005), which means that, by 2100, the ocean would increase acidity by about 150% relative to the beginning of the industrial revolution. The big question facing biologists is whether marine animals and plants will be able to adapt to the fast rate of change. Primary producers including diatoms (Tortell et al., 2000) and coccolithophores (Riebesell et al., 2000; Iglesias-Rodriguez et al., 2008; Shi et al., 2008) seem to respond to ocean acidification by increasing photosynthetic carbon fixation. Nitrogen-fixation by *Trichodesmium* is enhanced by elevated CO₂ (Hutchins et al., 2007). Growth and light-saturated photosynthetic rates of seagrasses are also increased under high CO₂ conditions (Palacios and Zimmerman, 2007; Zimmerman et al., 1997). Of particular concern is the group of shelf-forming organisms for which carbonate ions are the basic building blocks, e.g., corals, shellfish, and marine plankton (Fabry et al., 2008; Feely et al., 2004; Feely et al., 2002; Gattuso et al., 1998; 1995; Gazeau et al., 2007; Guinotte et al., 2003; Guinotte and Fabry, 2008; Guinotte et al., 2006; Hall-Spencer et al., 2008; Kleypas et al., 1999; Kleypas et al., 2001; Kleypas et al., 2006; Langdon and Atkinson, 2005; Langdon et al., 2003; Leclercq et al., 2000; Leclercq et al., 2002; Riebesell et al., 2000; Zondervan, 2007; Zondervan et al., 2002; Zondervan et al., 2001).

In the marine environment, calcification involves the transport of calcium ions, which is ubiquitous in eukaryotic organisms (Knoll, 2003). Calcification involves the formation of

organic matrices in intimate association with the biomineralization process (Cuif and Dauphin, 2005), which gives protection against CaCO_3 dissolution as particles sink to the seabed in addition to their mineral form. In terms of the carbon chemistry of the upper water column and hence the potential to drawdown atmospheric CO_2 , autotrophs and heterotrophs clearly contribute in different ways. While autotrophs produce POC and can also produce PIC, heterotrophs do not produce POC *de novo* and hence only serve to increase $p\text{CO}_2$ and, if near the surface, to reduce uptake from the atmosphere. The sedimentary record, which has been so well studied and integrates over time and space, provides conflicting evidence. Part of this may be due to selective post depositional changes such as the dissolution of foraminifera above the lysocline or a consequence of lowered pH at the sediment water interface (de Villiers 2005). In addition, the particular vehicles by which the material settles (e.g., marine snow, fecal pellets) and the protection of biominerals with an organic layer which affects the rate of dissolution are central to the preservation of sedimentary material. Also, the chemistry of biomineralization appears to be specific to physiological stages. For example, in some strains of coccolithophore cells were found to increase in volume under phosphate limitation (Müller et al., 2008) and elevated CO_2 (Iglesias-Rodriguez et al., 2008a), but cells decreased in volume under nitrate limitation (Müller et al., 2008). Compartmentalization of calcification and packaging of the biomineral are important factors to consider. In coccolithophore cells, the calcite crystals produced intracellularly and extruded to the plasma membrane are protected by an organic film of polysaccharides that are also in the base plate (Paasche, 2002). This protective 'skin' can be argued to protect calcium carbonate from dissolution under conditions of decreased pH caused by elevated $p\text{CO}_2$. This intracellular biomineralization and protective layer may partly explain the resilience of coccoliths to changes in the carbonate chemistry through geological time.

This control may also apply to corals, in which an organic matrix has been found to be essential in the control of CaCO_3 crystals (Allemand et al., 2004).

The life cycle of calcifying organisms is accompanied by dramatic alterations in mineral chemistry and the carbonate 'carrying capacity'. One striking example is the transition from calcifying coccolith-bearing vegetative cells to scale-bearing cells and gametes, which lack coccoliths and are surrounded instead by organic scales (Klaveness, 1972; Green, 1996) and the switch from calcifying vegetative cells to non-calcifying gametes in response to a viral infection (Frada et al., 2008). Another example are spicules of echinoderm larvae undergoing transformation of amorphous calcium carbonate into calcite (Addadi et al., 2003; Politi et al., 2008). In molluscs, the transition between aragonite and calcite is dependent upon the growth stage of the organism (Zaremba et al., 1996). These short-term switches in physiology associated with environment and developmental change suggest an evolutionary advantage from a complex genetic make up that enables switching between different mineralogies and associated processes to the maintenance of the biomineral.

Since the sum of the molar concentration of all forms of DIC in seawater (<2.5 mM) is less than one-quarter the molar concentration of Ca^{2+} in seawater (~10.2 mM), carbon is likely the limiting substrate in marine calcification. And since the concentration of CO_3^{2-} in seawater (~0.23 mM) is approximately one-eighth the concentration of HCO_3^- in seawater (~1.9 mM), it is perhaps expected that the ability to utilize HCO_3^- in calcification would have been rapidly selected for in the evolution of calcifying marine organisms. Increased CO_2 and its subsequent changes in ocean chemistry may alter not only the physiology of organisms but species composition and succession. Thus ocean acidification could have profound impacts on important marine biogeochemical and

biological processes in the coming decades. In addition to ocean acidification, predicted increases in temperature will undoubtedly impact upon metabolic rates and organism health. For example, a decline in coral reef accretion rates due to simultaneous increases in temperature and decreases in carbonate ion concentration (Silverman et al., 2009) would have negative impacts on fisheries, tourism, coastal protection, and carbon processes. The increase in $p\text{CO}_2$ can also impact the physiology of marine biota through acid-base imbalance and reduced oxygen transport capacity (Fabry et al., 2008; Rosa and Seibel, 2006). The extent to which an organism will adapt to selection pressure depends upon its genetic make up such that groups with active proton pumps, mechanisms for active uptake of bicarbonate and conversion into carbonate when carbonate ions are scarce will have an advantage with respect to obligate carbonate users. The question remains what ecological and societal consequences will arise from the loss of functional groups, and how the new dominant groups will impact upon ecosystems, biogeochemical cycles and the economy. This could have particular implications in fisheries resource management communities.

An Ocean Acidification Observation network

A coordinated multidisciplinary approach to observations and modelling is key to achieving a successful research strategy for ocean acidification. This will facilitate the development of our capability to represent and predict future responses of marine biota, ecosystem processes, and biogeochemistry (Fabry et al., 2008). Experiments to date have showed different responses of marine calcifiers to ocean acidification. These range from enhanced, suppressed and no effect on physiological properties (Figure 3) (Doney, 2008). These range from lab experiments, which are ideal to establish the physiological processes underlying acclimation in individual species, through mesocosm

experiments and field manipulations, which address the biological complexity in the response. However, all the manipulation experiments have been conducted in time scales that do not address long-term adaptation, and the modification of the carbonate chemistry is abrupt, i.e., organisms are exposed to the new condition in one single step rather than in incremental pulses. Therefore, while these experimental approaches can provide valuable information on the physiological mechanistics of adaptation to ocean acidification, assessing the long-term adaptation and the susceptibility to ocean acidification is questionable with this approach. Abrupt exposures to corrosive waters occur seasonally (Feely et al., 2008) so these are ideal areas to test acclimation to abrupt exposure (change in physiological performance) and adaptation (selection at the population and community levels over time). Building an ocean observation network targeting both coastal and open ocean regions of different susceptibilities to ocean

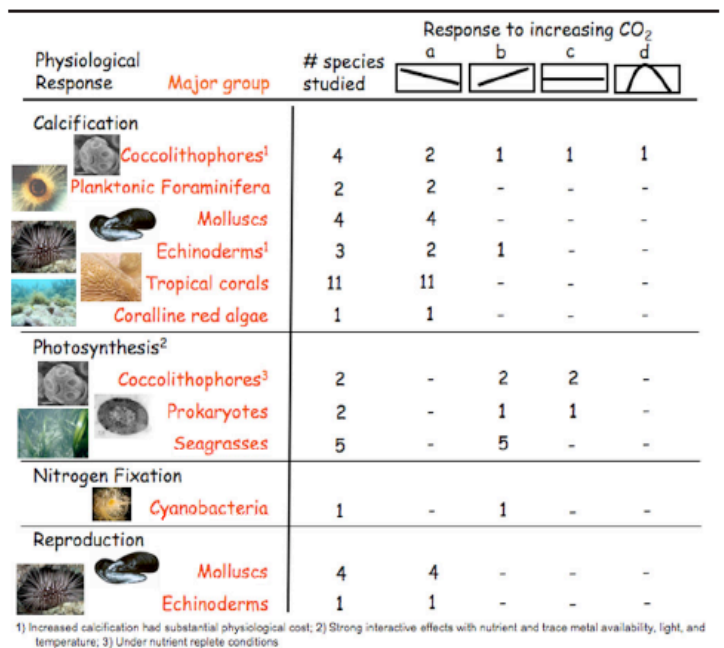


Figure 3. Responses of groups of marine organisms to ocean acidification. The response curves on the right indicate four cases: (a) linear negative, (b) linear positive, (c) level, and (d) non-linear parabolic responses to increasing levels of seawater partial pressure of CO_2 for each of the groups (from Doney, 2009).

acidification will assess the extent of changes in water chemistry over time and will measure impacts at several levels of organization – from chemical to biological. This approach will also take account of the biological complexity and how changes occur at the population and community levels. It will also measure the effect of any changes in functional group dominance and the effect on biogeochemistry.

Our present understanding of the long-term changes in the carbonate system comes from the repeat sections and time series measurements (Bates, 2007; Feely et al., 2008; Feely et al., 2004). Supporting these activities and expanding the global time-series network and the emerging Ocean Observation Initiative with new carbon and pH sensors will provide important information on the changing conditions in open-ocean and coastal environments that are presently undersampled. At present, most of the current moored carbon observatories only accommodate measurements of $p\text{CO}_2$, which is insufficient to fully constrain the carbon system necessary for effective monitoring and forecasting of ocean acidification and the parallel biological effects. Ideally, this network would also have the capability to measure CaCO_3 saturation states and rate of CaCO_3 production- and dissolutions. Sensors

for dissolved inorganic carbon and total alkalinity are desirable for detecting changes in the marine inorganic carbon system and deposition of other non- CO_2 sources of acidification, particularly in coastal regions (Doney et al., 2007; Ilyina et al., 2009). Measurements of net primary production, either directly or from nutrient or oxygen inventories along with hydrodynamic considerations in coastal zones, are also important for identifying and interpreting physical and biological responses to ocean acidification. These additional measurements are needed to predict ecosystem responses to ocean acidification. Leveraging existing infrastructure and monitoring programs will enable research to be conducted efficiently and quickly. For example, additional inorganic carbon system measurements and process studies could be conducted at the OceanSITES time series stations (Figure 4) and in areas particularly susceptible to ocean acidification such as the Long-Term Ecological Research in the California Current, Palmer West Peninsula Antarctica and at Moorea. Additional time series stations, repeat surveys, intensified process studies: e.g. open ocean mesocosm experiments, coastal mesoscale CO_2 release experiments, and underway measurements are also urgently needed in other open-ocean and coastal regions.

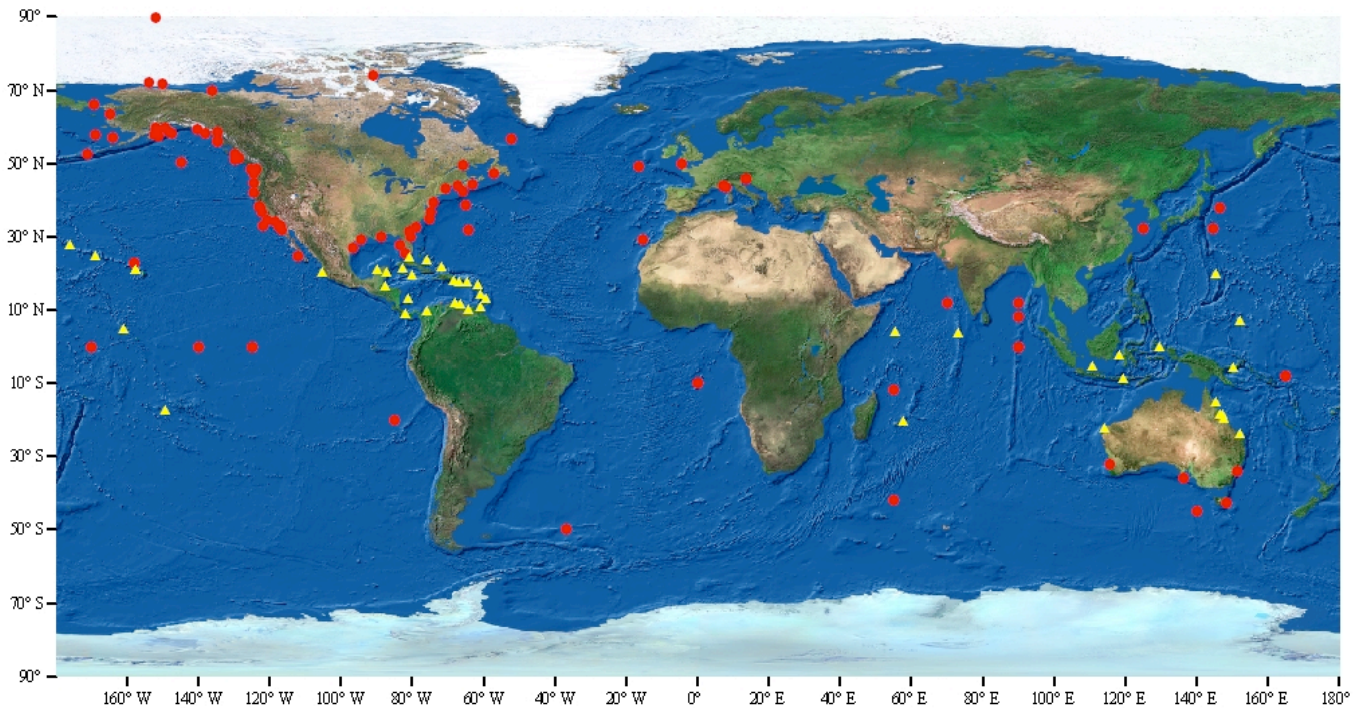


Figure 4. OceanSITES proposed sites for ocean acidification monitoring (red) and specific sites for coral reef monitoring (yellow).

In coastal regions, the effect of upwelling and riverine input will be assessed for implementation into biogeochemical models that address specifically ocean acidification. Consequently, new moored buoys equipped with carbon system sensors and ancillary technologies (e.g. autonomous water samplers, nutrient analyzers) for ocean acidification should be added to the present carbon network. These open ocean monitoring systems will provide verification for open ocean large-scale biogeochemical

models and coastal data will verify nested high resolution coastal models. Carbon system sensors could also be deployed on floats and gliders to resolve shorter space-time scale variability of the upper ocean. Sites which also deploy deep sediment traps offer additional advantages, in allowing the links between calcification and biological carbon sequestration to the deep to be evaluated (Oschlies et al., 2008), and by providing seasonally resolved sampling of biogenic carbonate forming organisms, such as foraminifera which have been shown to exhibit reduced shell thicknesses in response to acidification (Moy et al., 2009).

In addition to the network of ocean observatories, the present ocean acidification monitoring network could profit from measurements on ships (Figure 5) equipped with carbon system sensors and ancillary technologies (e.g. autonomous water samplers, nutrient analyzers). These moving

CaCO₃ mineral saturation state levels) that will lead to irreversible effects on species and ecosystems over the next few decades? Can we develop new biological methodologies to determine whether organisms and ecosystems can adapt sufficiently to changing seawater chemistry in ways that will reduce potential

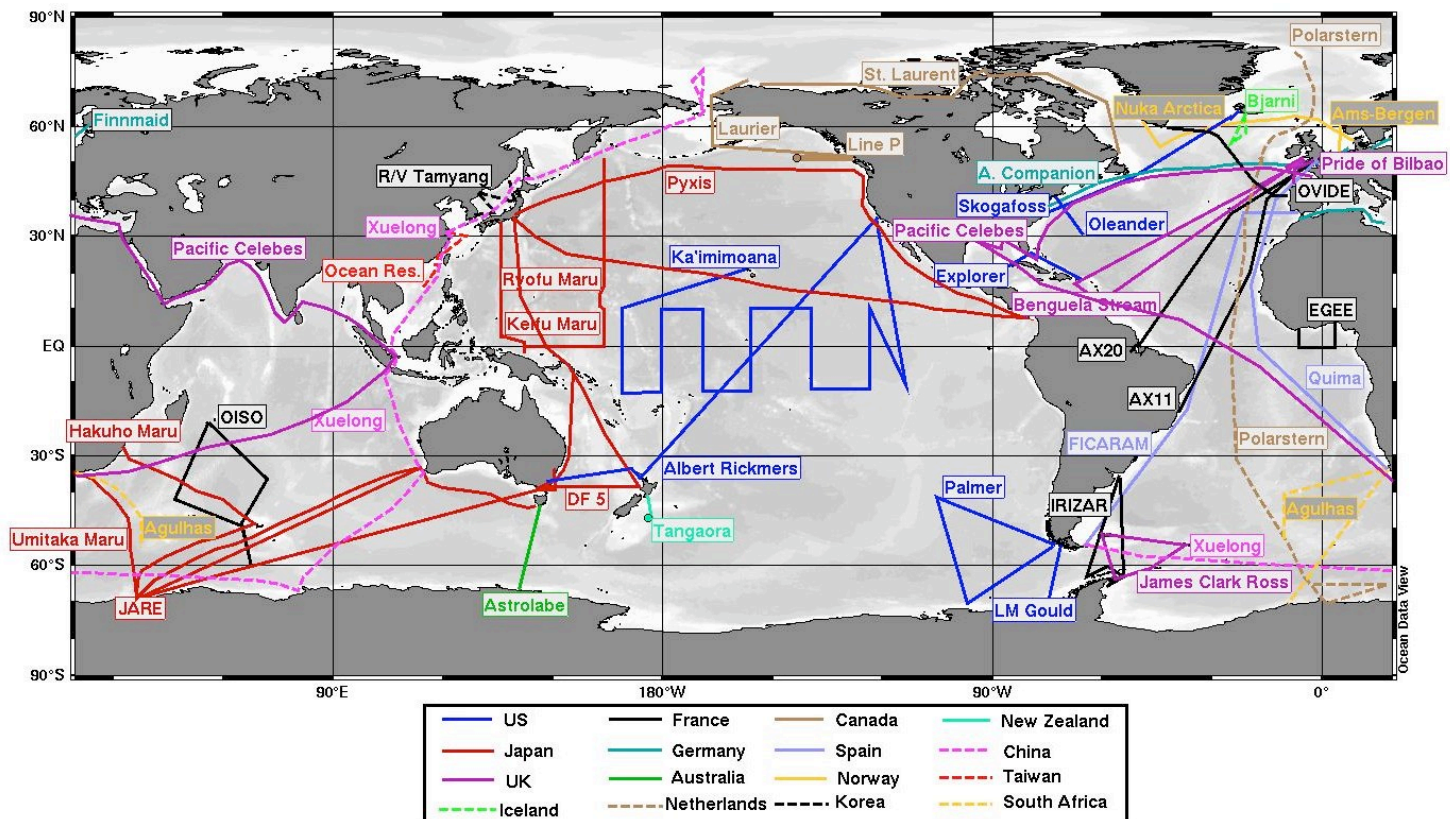


Figure 5. Underway Volunteer Observing Ship Network.

platforms will add to the existing carbon network and should be supported with technology to study OA (DNA sensors, particulate inorganic and organic carbon production rates, supported by satellite measurements).

Critical research elements require regional and global networks of observations and process studies, manipulative experiments involving a suite of organisms in laboratory experiments, mesocosm and field studies, technological advances, and new modelling approaches. One of the key questions regarding responses to ocean acidification is whether or not there are geochemical thresholds for ocean acidification (e.g.,

negative impacts of ocean acidification? Indices for ocean acidification beyond basic water-column physics and chemistry have yet to be adequately developed. Parameters that can be measured routinely onboard ships include temperature, salinity, oxygen, nutrients, CO₂ partial pressure (*p*CO₂), pH, total alkalinity (TA), dissolved inorganic carbon (DIC), dissolved organic carbon (DOC) and particulate organic- and inorganic carbon (POC, PIC). While some of these chemical species now can be measured on moorings they are not yet broadly utilized on a global scale. Moreover, new method development is required for routine measurements of DIC and TA and proxies that may indicate stress on biological organisms. This paper provides a community-based plan to address a strategy for a global ocean acidification observing system in the major ocean basins and

marginal seas, warm water coral reefs, coastal margins, tropical to subtropical open-ocean regions, and high-latitude regions.

The emerging ‘-omics’ technology

Research on the effect of climate change on the variability in the biological pump is restricted to time-series observations in specific regions, primarily in the low and mid-latitudes or to “snapshots” from isolated studies. Many gaps exist, particularly for the high latitude oceans, where climate-driven shifts in oceanic productivity may take place first, and in a more pronounced way. Most measurements address single responses in strains (e.g., lab studies) or populations (mesocosm studies, deck incubations) but to dissect the individual signal from the components of the community and to measure changes in population functionality represent a challenge with the traditional approaches used in oceanographic research.

The application of molecular tools traditionally used in the biomedical field is revolutionizing the field of oceanography. Genomics, proteomics and transcriptomics are rapidly transforming marine biology and biogeochemical studies (Figure 6). Shotgun methods have enabled assessing the diversity of populations, the most striking example being Venter’s elegant metagenomics approach to dissecting the population structure of microbial populations in the Sargasso Sea (Venter et al., 2004; DeLong et al. 2006, Sogin et al. 2006 and references therein). Research has transitioned from static descriptive studies of single genes, proteins or metabolites to a more ecological approach, involving the simultaneous study of many levels of organization (from molecules represented in the mixed cell suspension (shotgun approach) through to whole organisms, populations and communities) (Hollywood et al., 2006, Joyce & Palsson 2006). However, in order to achieve the full potential, an integration of these molecular data with traditional ecological and biogeochemical approaches is required.

Another limitation is the access to the appropriate bioinformatics resources and the training required for data interpretation. In the immediate future, marine scientists dealing with biological systems will need these skills and thus appropriate training.

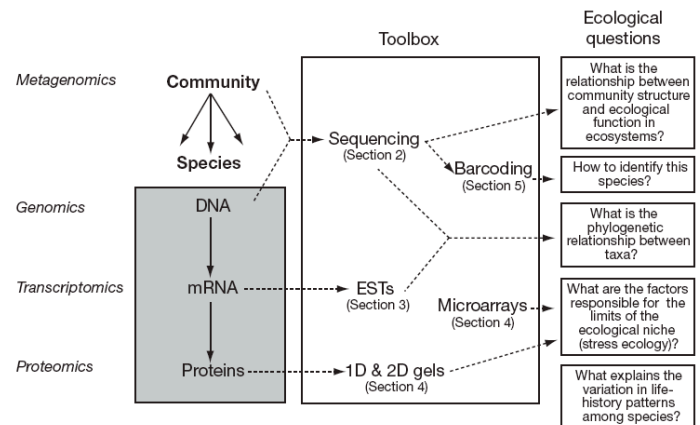


Figure 6. The application of ‘-omics’ tools to ecological questions (Dupont et al., 2007).

Future challenges

One of the biggest challenges facing the community is to unveil the mechanisms behind adaptation over realistic time frames. The experimental approaches used to date only address physiological responses to environmental selection pressure but do not address long-term adaptation. There is an urgent need to work within generation times and environmental change at rates representative of those experienced by biota in the field. Monitoring adaptation in real time in the field, particularly in those areas of high susceptibility to ocean acidification (polar latitudes, upwelling zones) will provide information central to representing and forecasting the effect of ocean acidification and will act as platforms to calibrate the findings in the lab/mesocosms with strains/populations. A global observation network will assess any shift in the contribution of functional groups or in their physiological performance. Data repositories of detailed carbonate chemistry, biological performance and molecular adaptation to environmental selection pressure will not only provide first hand information about natural

selection processes in real time but will also answer fundamental questions of how changes in carbon chemistry alter the abundance and physiology of functional groups. While work with single strains/species provides information about regulation of processes (e.g., changes in gene/protein expression, cell volume, photosynthetic rates, calcification rates, nitrogen fixation rates), it does not account for the complexity of natural populations, physical transport effect, interactions between bacteria and viruses and eukaryotic phytoplankton, mortality, etc).

Many countries are presently engaged in ocean acidification research and monitoring activities, for example, the European projects EPOCA and BIOACID and emerging programs in the UK and USA funded by NERC and the NSF. The proposed activities will require a coordinated international research effort that is closely linked with other international carbon research programs, such as the CLIVAR/CO₂ Repeat Hydrography Program. The global ocean acidification observation network will benefit from and interface with the data synthesis activities, data archiving and international data management activities of the carbon and ocean acidification programs. The main role of the global ocean acidification observatory is to gain a robust understanding of the chemical and biological impacts of ocean acidification by conducting time-series measurements at several levels of organization from molecular to ecosystem level and building upon the advanced, long-term, monitoring platforms available. Evidently, genomic, transcriptomic and proteomic approaches to studying oceanic ecosystem is essential to understanding the organisms control on elemental cycles through time. Robotic *in situ* devices deployed on moorings can be powerful tools and are now available as autonomous samplers, to report on genomic data of microbial community composition (Greenfield et al., 2006; 2008; Scholin et al, 2008). Building a global time series to assess changes in chemistry and

biology will improve coupling between biogeochemistry, physiology, and modelling. The total cost of the present observational efforts for ocean acidification is estimated at about \$10 Million US dollars per year. We estimate that the cost of an expanded international observational program as described below to be approximately \$50 Million US dollars per year.

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