A GLOBAL SEA SURFACE CARBON OBSERVING SYSTEM: INORGANIC AND ORGANIC CARBON DYNAMICS IN COASTAL OCEANS

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EXECUTIVE SUMMARY

Coastal environments are an important component of the global carbon cycle, and probably more vulnerable than the open ocean to anthropogenic forcings. Due to strong spatial heterogeneity and temporal variability, carbon flows in coastal environments are poorly constrained. Hence, an integrated, international, and interdisciplinary program of ship-based hydrography, Voluntary Observing Ship (VOS) lines, time-series moorings, floats, gliders, and autonomous surface vessels with sensors for pCO_2 and ancillary variables are recommended to better understand present day carbon cycle dynamics, quantify air-sea CO_2 fluxes, and determine future long-term trends of CO_2 in response to global change forcings (changes in river inputs, in the hydrological cycle, in circulation, sea-ice retreat, expanding oxygen minimum zones, ocean acidification, …) in the coastal oceans. Integration at the international level is also required for data archiving, management, and synthesis that will require multi-scale approaches including the development of biogeochemical models and use of remotely sensed parameters. The total cost of these observational efforts is estimated at about 50 million US dollars per year.

1. INTRODUCTION

1.1. Carbon fluxes in the coastal oceans

Continental shelf sea environments are an important component of the global carbon (C) cycle (Fig. 1), and more vulnerable than the open ocean to anthropogenic forcings. Continental shelf seas constitute one of the most biogeochemically active areas of the biosphere. They receive massive inputs of organic matter and nutrients from land and exchange large amounts of matter and energy with the open ocean across continental slopes. Globally, these transition zones support between ~15% and ~30% of oceanic primary

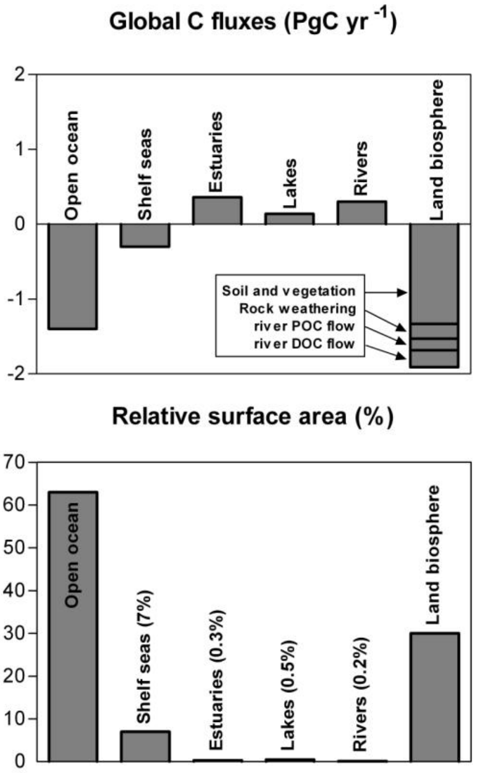

Figure 1 Global CO_2 exchanges with the atmosphere ($PgC\ yr^{-1}$) in the open ocean (Takahashi et al. 2009), continental shelf seas and estuaries (Chen and Borges 2009), rivers (Cole and Caraco 2001), lakes (Cole et al. 1994), and land biosphere (vegetation and soils (Cole et al. 2007), rock weathering (Ludwig et al. 1996a), the export of DOC (Dissolved Organic Carbon) and POC (Particulate Organic Carbon) by rivers from land to ocean (Ludwig et al. 1996b)), and the relative surface area of continental shelf seas (Walsh 1988), estuaries (Woodwell et al. 1973) and rivers and lakes (Lehner and Doll 2004). Note that the export of DOC and POC by rivers from land to ocean is a sink of atmospheric CO_2 for the land biosphere and source of CO_2 from the coastal and open oceans (assuming remineralization to maintain steady state). Note that rock weathering is a sink of atmospheric CO_2 for the land biosphere and source of CO_2 from the coastal and open oceans (assuming marine calcification to maintain steady state).

production and ~80% of oceanic organic matter burial (e.g. Gattuso et al. 1998a). In addition, they host most of the benthic marine $CaCO_3$ production, ~20% of surface pelagic oceanic $CaCO_3$ stock (Balch et al. 2005), and ~50% of oceanic $CaCO_3$ deposition (Gattuso et al. 1998a). Hence, flows of carbon and nutrients are disproportionately high in comparison with the surface area (<7% of total oceanic surface area). Based on literature compilations, the contemporary sink of CO_2 has been estimated to range between 0.2 and 0.4 $PgC\ yr^{-1}$ (Borges 2005, Borges et al. 2005, Cai et al. 2006, and Chen & Borges 2009).

This sink corresponds to 14% to 29% of the most recent estimate of the contemporary open ocean sink for atmospheric CO_2 of 1.4 $PgC\ yr^{-1}$ (Takahashi et al. 2009). However, to date, available estimates of present day air-sea CO_2 fluxes in the coastal oceans suffer from several caveats (see Sect. 2.1). The net air-sea exchange of CO_2 is the small difference among several much larger input and output gross fluxes of carbon to the coastal oceans (river inputs, export to the open ocean, exchange with the sediments, etc.) (Vlahos et al 2002). Global change forcings that result in changes to any of these larger coastal carbon fluxes may thus result in proportionally larger changes to the global net air-sea CO_2 exchange in coastal oceans. It is critical to better constrain the magnitude and controls on the major coastal ocean carbon fluxes to improve our ability to predict future changes to CO_2 fluxes in coastal oceans based on a process-level understanding.

Carbon dioxide (CO_2) is the form of dissolved inorganic carbon (DIC = $[CO_2]+[HCO_3^-]+[CO_3^{2-}]$) used in photosynthesis by autotrophs, remineralized by heterotrophs and exchanged across the air-sea interface. It is essential to improve our understanding of the dynamics of the DIC system, and the quantification of air-sea CO_2 fluxes over daily, to seasonal, to inter-annual and decadal time-scales. Synoptic estimates based on field data using a variety of platforms, based on remotely sensed data and on modelling of the full spatial extent of the coastal ocean are necessary to understand the diversity of biogeochemical C cycling related to extremely varied physical and biogeochemical settings. The dynamic, rapidly evolving nature of these environments presents a major challenge for the development of appropriate observing systems.

Carbon cycle dynamics in coastal environments can shift rapidly, particularly in response to changes in nutrient and organic matter inputs that may lead to long-term changes in CO_2 sequestration (e.g. Mackenzie et al. 2004) or to rapid decadal shifts in source or sink status for atmospheric CO_2 (Gypens et al. 2009). So far, due to lack of adequate data-sets, long-term changes in CO_2 dynamics in coastal environments have only been investigated through a few relatively simple numerical models (Mackenzie et al. 2004; Gypens et al. 2009), and a few data-based studies (Bering and Okhotsk Seas: Murata (2006); Takahashi et al. (2006); Barents Sea: Omar et al. (2003); North Sea: Thomas et al. (2007); California Current: Fig. 2).

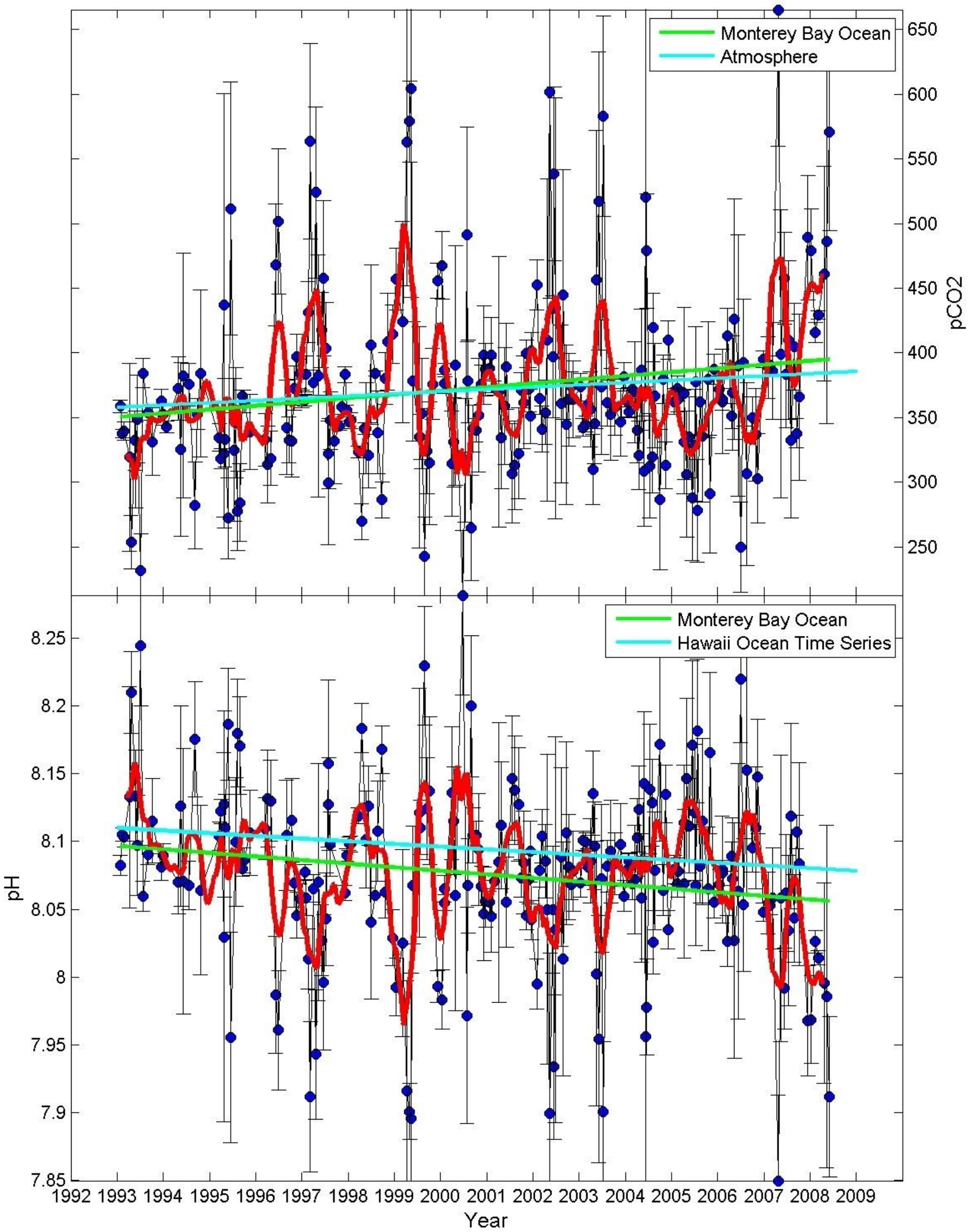

Figure 2 Time-series of sea surface pCO_2 and pH from Monterey Bay, California (F.P. Chavez, unpublished). The blue dots are averages of a 50 km underway transit. The red line is interpolated and smoothed. The green line is the trend. In light blue are the regression lines for atmospheric pCO_2 from Mauna Loa and sea surface pH from the Hawaii Ocean Time series (HOT) published in Doney et al. (2009). The slow and steady uptake of atmospheric CO_2 by the oceans has been observed in the open-ocean time series off Hawaii but now it can clearly be detected in Monterey Bay—a surprise given the strong variability on daily to interannual time scales in ocean pCO_2 due to coastal upwelling and the resulting biological production. Multi-decadal variations are driving an increase of subsurface pCO_2, thereby accelerating the rate of increase of pCO_2 relative to the atmosphere. As a result pH is decreasing faster than in the open ocean.

Very similar dynamic ranges and spatiotemporal variability have been observed in the carbon cycles of island coastal environments not associated with continental shelf settings (Bates 2002; Fagan and Mackenzie 2007; Paquay et al. 2007). While these island coast environments have not typically been included in large-scale or global carbon cycle syntheses, many are also substantially more prone to anthropogenic impacts than remote open ocean ecosystems by virtue of proximity to population centers and relatively restricted circulation. We include the requirements of island coastal settings with respect to global carbon cycle observations in this community white paper to acknowledge that many of the same global change factors apply to carbon cycles processes in both island and continental shelf environments, although we anticipate that a distinction will be made between island and continental margin observational resources in how they will be used for future synthesis and monitoring efforts.

1.2. Vulnerability and possible future evolution

The coastal oceans are more vulnerable to anthropogenic forcings than the open ocean. Potential feedbacks between marine organisms and communities and anthropogenic CO_2 forcing are expected to be disproportionately important in the coastal ocean compared to the open ocean, due to the larger fluxes of organic and inorganic carbon. These diverse anthropogenic forcings are considered as follows:

- Changes in circulation and stratification. It has been hypothesized (Bakun 1990) and modelled (Snyder et al. 2003; Diffenbaugh et al. 2004) that the intensity and duration of coastal upwelling will increase in the future due to climate change. This has to some extent been confirmed by observations in some (McGregor et al. 2007) but not all (Di Lorenzo et al. 2005; Field et al. 2006) coastal upwelling systems. The response of air-sea CO_2 fluxes to increased upwelling is difficult to predict and can go both ways. Stronger vertical inputs of DIC would drive the system to emit more CO_2 to the atmosphere, while enhanced nutrient inputs would drive higher primary production, export production and a sink for atmospheric CO_2. Long-term observations such as in the California Current (Fig. 2) are needed to unravel the response of coastal upwelling systems to global changes.

- Climate change is expected to lead to a future decrease of oxygen (O_2) content in the oceans due to thermohaline circulation slowing down and the decreasing solubility of O_2 with surface warming of the source waters from intermediate and deep layers (e.g., Bopp et al. 2002; Matear and Hirst 2003). This will lead to the expansion of oxygen minimum zones (OMZ) as confirmed by historical observations (Bograd et al. 2008; Stramma et al. 2008). OMZ are associated with major coastal upwelling regions that act as sources of CO_2 to the atmosphere because denitrification leads to low concentrations of nitrate and an excess of DIC relative to nitrogen (Friederich et al. 2008; Paulmier et al. 2008). Coastal upwelling areas without OMZ such as the Iberian coastal upwelling system (Borges and Frankignoulle 2002a) or with deep OMZ such as the Oregon coast (Hales et al. 2005) are currently sinks for atmospheric CO_2. However, the future horizontal and vertical expansion of OMZ is expected to provide positive feedback on increasing atmospheric CO_2 due to enhanced CO_2 emissions from coastal upwelling systems.

- Retreat of sea-ice in the Arctic Ocean. Coastal waters in the Arctic Ocean are known to act as a strong sink for atmospheric CO_2 due to low temperature (Murata and Takizawa 2002) and high primary production (Bates 2006). The physical and biogeochemical conditions driving the CO_2 sink are affected by spatial and temporal variations of sea-ice distributions. Thus, future sea-ice loss will impact air-sea exchange of CO_2.

- Land-use activities (agriculture, deforestation, urbanization) are changing the fluxes to the coastal ocean of suspended sediments (Milliman 1991; Vörösmarty et al. 2003), organic carbon (Meybeck 1993), total alkalinity (Raymond and Cole 2003; Cai et al. 2008) and nutrients (Smith et al. 2003). These fluxes to the coastal ocean will be further modified by changes in river discharge that are forced by climate change impacts on the hydrological cycle (e.g. Manabe et al. 2004, Peterson et al. 2006), and dam-building and river diversion activities (Vörösmarty and Sahagian 2000). Existing numerical models (Mackenzie et al. 2004; Gypens et al. 2009) suggest these changes in inputs have already changed and will continue to change air-sea CO_2 fluxes on decadal and longer time scales.

- Key species and communities in many coastal ecosystems are threatened by direct and indirect human impacts, with implications for net carbon fluxes in these environments. For instance, losses in seagrass (Short and Neckles 1999; Duarte 2002) and coral reef ecosystems (Hughes et al. 2003) have been observed and are predicted to continue due to mechanical damage (dredging and anchoring), as well as eutrophication and siltation, with the latter two leading to light limitation. Negative indirect human impacts on seagrass and coral ecosystems include increases of erosion by sea level rise, frequency and intensity of extreme weather events, ultraviolet irradiance, and water temperature. Other coastal ecosystems, such as mangrove forests or salt-marshes, are relatively resilient to present and future hydrological changes, pollution, and global warming, but in some parts of the world they are being cleared for urban development and aquaculture (Alongi 2002).

- The increase of surface water DIC due to the invasion of anthropogenic CO_2 will generally decrease the $CaCO_3$ saturation state with potential decline of $CaCO_3$ production in benthic (Gattuso et al. 1998b; Kleypas et al. 1999) and planktonic (Riebesell et al. 2000; Zondervan et al. 2002; Delille et al. 2005) communities and enhancement of shallow-water $CaCO_3$ dissolution (Andersson and Mackenzie 2004). The increase of seawater CO_2 concentration due to the invasion of anthropogenic CO_2 could also enhance primary production for at least some phytoplanktonic species, as reviewed by Wolf-Gladrow et al. (1999). Anthropogenic CO_2 uptake may also affect pelagic carbon export by stimulating the production of transparent exopolymer particles (e.g., Engel et al. 2004) or altering the elemental stoichiometry of uptake, accumulation, and loss processes (e.g., Riebesell et al. 2007).

- In coastal environments, the acidification of surface waters could be enhanced compared to the open ocean due to anthropogenic atmospheric nitrogen and sulfur deposition (Doney et al. 2007), upwelling of anthropogenically "acidified" DIC-rich waters (Feely et al. 2008), or river inputs (Salisbury et al. 2008; Chierici and Fransson, 2009). On the other hand, the effect of acidification on surface water carbonate chemistry could be modulated by enhanced primary production related to eutrophication (Gypens et al. 2009) or by the increase of the buffering capacity of seawater related to enhanced total alkalinity fluxes from rivers (Raymond and Cole 2003; Cai et al. 2008; Raymond et al. 2008).

- In some coastal environments, the high levels of organic matter present in sediments support anaerobic degradation processes, which increase the total alkalinity of the overlying water and increase the potential for carbon storage (Chen 2002; Thomas et al. 2009). This may also be true for salt-marsh surrounded estuaries and shelves where total alkalinity production is significant (Cai and Wang 1998; Cai et al. 2003). This increase of total alkalinity is mainly related to dentrification, and the impact of reduced primary production due to the removal of nitrate does not compensate for the increase of total alkalinity in terms of air-sea CO_2 fluxes (Fennel et al. 2008).

2. SCIENTIFIC OBJECTIVES AND RATIONALE

The principal scientific objectives for a sustained coastal carbon observational network are:

1. to improve estimates of spatial and temporal variability of carbon fluxes in coastal oceans;

2. to understand the processes controlling coastal carbon balance and how these processes are affected by natural and anthropogenic drivers; and

3. to develop the detection and prediction capacity to forecast long-term changes of CO_2 dynamics in coastal oceans in response to global changes (changes in river inputs, in the hydrological cycle, in circulation, sea-ice retreat, expanding oxygen minimum zones, ocean acidification, …).

To achieve these objectives the community needs to:

1. improve existing technology and develop new methodology for measurements of CO_2 and ancillary variables;

2. develop an observational network using a multitude of platforms : VOS lines, moorings, drifters, gliders, autonomous surface vessels, and process-oriented research cruises;

3. bank and manage quality checked data; and

4. synthesize data using several approaches such as biogeochemical models and use of remotely sensed products.

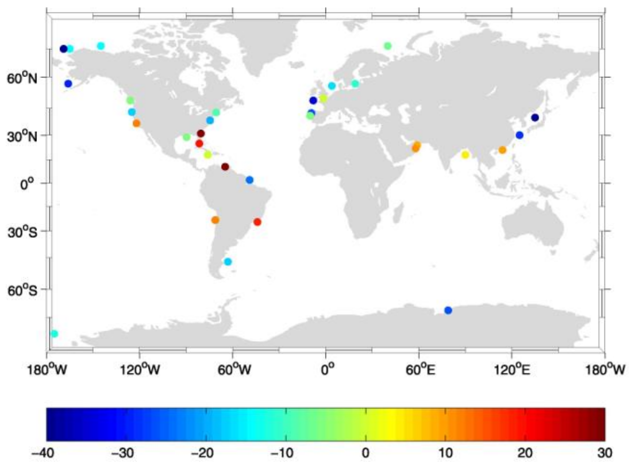

Figure 3 Distribution of sites used in the compilation of coastal air-sea CO_2 fluxes (g C m^{-2} yr^{-1}) by Cai et al. (2006). Data coverage and distribution is similar to the other literature compilations by Borges (2005), Borges et al. (2005) and Chen & Borges (2009).

2.1. Observational needs for improving estimates of net global air-sea exchange in coastal oceans

To date, available estimates of present-day air-sea CO_2 fluxes in the coastal oceans suffer from several limitations:

- Literature data compilations are based on pCO_2 data sets that are not necessarily quality checked and at the standards of present day standard operating procedures (SOP). Published air-sea CO_2 flux estimates have been computed using different parameterizations of gas transfer velocity as a function of wind speed and different sources of wind speed data.
- Published studies also lack sufficient data coverage to adequately characterize the spatial and ecosystem variability of coastal environments (Fig. 3). In particular, coastlines of the Russian Arctic, western South America, eastern Africa, large sections of western Africa, and most of Antarctica are dramatically under-sampled.
- Due to the large temporal and spatial variations of the partial pressure of CO_2 (pCO_2) in coastal environments (Fig. 4), air-sea CO_2 fluxes can be biased by inadequate spatial or temporal coverage. The relative inadequacy of spatial and temporal coverage exists even for many shelves that have already been surveyed, i.e. in the East China Sea (Zhai and Dai, 2009), in the Southern Bight of the North Sea (Thomas et al. 2004; Schiettecatte et al. 2007), or the U.S. South Atlantic Bight (Cai et al. 2003; Jiang et al. 2008).
- Temporal scales range from diurnal (Dai et al., 2009) to inter-annual variations of air-sea CO_2 fluxes due to global climate oscillations (El Niño-Southern Oscillation: Friederich et al. 2002; Southern Annular Mode: Borges et al. 2008a). In near-shore ecosystems, variable river influence (Borges et al. 2008b; Gledhill et al. 2008; Salisbury et al. 2009) can also be particularly important in driving inter-annual variability of air-sea CO_2 fluxes.

Overall, adequate data-sets generally do not exist to quantify the true scale of processes both regionally and globally. Recommendations to overcome these issues are addressed in Sect. 3.

2.2. Extrapolating surface carbon observations through remote sensing and synthesis methods

Remote sensing techniques have been successfully applied in the open ocean to extend surface pCO_2 observations and evaluate air-sea CO_2 fluxes (e.g., Lefèvre et al. 2002; 2004; Rangama et al. 2005; Friedrich and Oschlies 2009; Telszewski et al. 2009). Algorithms are typically based on remotely sensed chlorophyll-a and sea surface temperature (SST), occasionally also based on modeled or climatological mixed layer depth or geographical position (latitude and longitude). These algorithms use multiple linear regression (Lefèvre et al. 2002; 2004; Rangama et al. 2005) or more recently neural network techniques (Lefèvre et al. 2005; Jamet et al. 2007; Friedrich & Oschlies 2009; Telszewski et al. 2009). In coastal waters, remote sensing techniques have been used on a few studies to evaluate pCO_2 (Salisbury et al. 2008), air-sea CO_2 fluxes (Olsen et al. 2004; Lohrenz and Cai 2006), and carbonate chemistry (Gledhill et al. 2008). Yet, in coastal waters, particularly in near-shore areas, the use of remote sensing techniques is more complex than in the open ocean:

- Coastal waters have more complex optical properties due to interference from suspended matter and colored dissolved organic matter (CDOM), and usually require specific atmospheric corrections due to the presence of neighboring land masses (e.g., Ruddick et al. 2000).

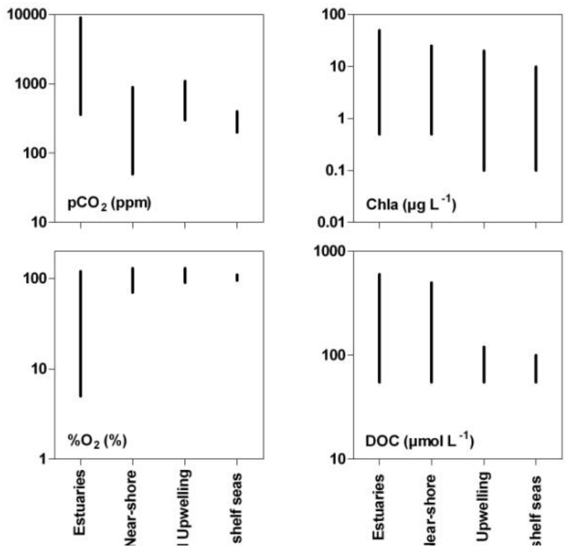

Figure 4 Range of spatio-temporal variability across different coastal environments of the partial pressure of CO_2 (pCO_2), oxygen saturation level ($\%O_2$ %), chlorophyll-a (Chla) and dissolved organic carbon (DOC) based on Borges & Frankignoulle (2002a; b; c), Bouillon et al. (2003), Cai et al. (2003), Chavez & Messié (2009), Cloern & Jassby (2008), Frankignoulle et al. (1998; 1996), Frankignoulle & Borges (2001), Abril et al. (2002), Friedrich et al. (2002; 2008), García-Muñoza et al. (2005), Goyet et al. (1998), Kulinski and Pempkowiak (2008), Okkonen et al. (2004) , Raimbault et al. (2007) , Shin & Tanaka (2004)

In river-influenced areas, sea surface salinity (SSS) data are usually required as an additional variable in the algorithms. SSS can be derived in some cases from climatological fields (Gledhill et al. 2008), from remotely sensed images relying on CDOM (Lohrenz and Cai 2006), or other optical properties (Salisbury et al. 2008) although this is not necessarily the case at all coastal sites (K. Ruddick, personal communication). The situation could be improved by the NASA Aquarius mission (e.g. Lagerloef et al. 2010), although the expected resolution of SSS data (~100 km) will be too coarse for systems influenced by medium and small rivers. The most realistic and reliable options probably lie in the use of SSS fields from regional physical models, or from remotely sensed images relying on regional SSS-CDOM algorithms.

Self-organizing neural network approaches using remotely sensed chlorophyll-a, SST, and other variables can also be used to classify coastal areas into biogeochemical regions or provinces (e.g., Oliver et al. 2004; Chen and Zhang 2009) and improve the development and application of algorithms to scale data and derive pCO_2 fields.

While regional studies can be carried out without international coordination, if such an approach is applied globally, coordination will be required to define areas to be covered and ensure that the approaches are methodologically similar enough to derive comparable results. Application of remotely sensing techniques must go hand-in-hand with the improvement of related products, in particular in the optically complex case-II waters.

2.3. Observational needs for measuring other carbon fluxes and related parameters

Measurements of air-sea CO_2 fluxes provide only a small component of the carbon cycling and exchange that is occurring in coastal zones. It is necessary to provide a full carbon balance that incorporates both organic and inorganic pools measured with similar spatial and temporal resolution to constrain carbon budgets in these dynamic regions. Though the magnitude of the inorganic carbon pool is much greater than the organic carbon pool, gradients of both pools are the same order of magnitude (Vlahos et al. 2002) and readily comparable. Currently there are no *in situ* methods for the accurate detection of total and dissolved organic carbon pools. The development of such techniques needs to be a priority. Optical properties of DOM may provide useful proxies in areas with relatively consistent sources. These however fall apart in transition zones where there are shifts in the nature of the organic matter along the shelf. Thus, at this time, it is still very important to continue global scale measurements of coupled organic and inorganic carbon in coastal systems. Priorities include:

1. Regional differences based on hydrodynamics, frontal zone interactions and upwelling are very important in predicting shifts in the OC pool and carbon fluxes. A comprehensive study of continental shelves representative of latitudinal and hydrodynamic differences has begun (Liu et al. 2009) though much more is needed.
2. More information is needed on the diel changes that both organic and inorganic pools undergo in order to couple hydrodynamics to these varying concentrations.
3. Changing temperatures will lead to shifts in populations and net ecosystem production. Some of these changes may be predicted by comparing the known trophic status and carbon dynamics of continental shelf regions that may resemble the predicted conditions for another shelf region. Efforts to consolidate carbon data sets will augment this predictive ability.
4. Also, decreases in sea ice cover will increase the contribution of the organic carbon pool as primary productivity increases. Understanding the magnitude of these changes is imperative for carbon cycling and climate prediction.

Carbon flux through the air-sea interface is strongly modulated by net community production and particulate organic carbon (POC) export in the surface ocean (Chavez et al., 2007). Our understanding and skill in prediction of the air-sea CO_2 flux in coastal regions will be greatly improved with observations of net community production (NCP) and POC export on spatial and temporal scales similar to those of air-sea flux. NCP and POC export are often not possible to measure with the same resolution that pCO_2 can be observed using underway mapping systems and there are too few ship-based time-series stations to provide the required temporal or spatial resolution. Satellite ocean color observations are the only large-scale proxy that is available, and these observations are often difficult to interpret in coastal regions. However, it is now possible to use chemical sensors for carbon, oxygen or nitrate that are deployed on moorings (Johnson et al., 2006; Kortzinger et al., 2008; Martz et al., 2009) or profiling floats (Riser and Johnson, 2008; Martz et al., 2008) to estimate NCP with daily resolution. Autonomous observations with chemical sensors in the coastal environments can be used to assess NCP over multiple years (Johnson et al., 2006; Johnson 2009). This capability allows the impacts of changing biogeochemical processes on air-sea CO_2 fluxes to be quantified rigorously.

2.4. Developing an ocean acidification observational network for coastal oceans

A detailed description of an ocean acidification observational network for open and coastal oceans is given by Feely et al. (2009). In brief, the principal scientific objectives for a sustained ocean acidification observational network are: 1) determining the large-scale ocean physical, chemical and biological water property changes; and 2) improving existing technology and developing new methodology for elucidating the variability of seawater chemistry and for evaluating the responses of organisms to the changes that take place. The main approaches are: 1) repeat surveys of chemical and biological properties; and 2) time-series measurements at fixed stations and on floats and gliders. The relevant variables are: pCO_2, pH, DIC or total alkalinity, oxygen, PIC (particulate inorganic carbon), POC (particulate organic carbon), bio-optical properties.

2.5. Modeling needs for the coastal carbon cycle and ocean acidification impacts

Coupled physical and biogeochemical models with the required resolution to adequately simulate DIC dynamics in coastal environments are limited and of local to regional scale, and should be expanded to global scale. Global climatologies and future scenarios of forcing variables for the models are needed or can be improved (rivers inputs of organic and inorganic carbon and nutrients …). Inclusion of predictive power in such models is urgently needed, in the context of evaluation of the response to global changes and related impacts on C cycling (CO_2 fluxes and carbon export and sequestration), fisheries … Major potential drivers of global changes on C cycling in the coastal oceans are:

- Changes in circulation and stratification (change of upwelling intensity, expansion of OMZ, sea-ice retreat …)
- Changes in land-ocean fluxes of suspended sediments, DIC, DOC, POC and nutrients
- Changes in atmospheric deposition
- Ocean acidification

(Refer to Sect. 1.2 for details)

Coupled hydrodynamic ecosystem models represent a unique tool for investigating biogeochemical cycles through their ability to provide a complete, synoptic description of fluxes and budgets. They can also make mechanistic predictions. Their reliability is, however, substantially limited by the availability of observations of key components of the carbon cycle at appropriate spatial and temporal resolution. These are required for model calibration (parameter estimation) and validation both of the mean state and the important cycles (seasonal, inter-annual and eventually multi-decadal). It is only by demonstrating a model's ability to reproduce response to climate variability that we can gain confidence in its ability to predict the response to future climate change.

Since coastal/shelf seas form an important component of the Earth System, the goal is to include an adequate representation of these regions in fully coupled Earth System Models that link atmosphere, ocean and terrestrial systems. However, issues of resolution substantially restrict our efforts in this direction. For example, the wavelength and adjustment length (Rossby Radii) of long barotropic and baroclinic waves both tend to scale by h0.5 so decreases by an order of magnitude as the water depth reduces from 4000 m to 40 m. Hence, the barotropic Rossby radius at mid-latitudes is ~200 km and the baroclinic Rossby radius is typically 2-20 km. The dynamic scales in turn determine the scales of the distribution of material transported from the land-sea interface, such as in river plumes/coastal currents (1-300 km globally; Warrick and Fong, 2004), and exchange processes at fronts. From the scale of the ocean models used in the IPCC 4th assessment report, it is immediately apparent that the current generation of coupled climate models is a long way from being able to represent shelf-sea processes. These models have typical resolution of 1-2° often with some enhancement at the equator. Only the MIRICO3.2 (hi-res) model at 0.2812° longitude by 0.1875° latitude can start to resolve the barotropic Rossby radius in mid-latitude coastal seas. Ocean general circulation models (OGCMs) coupled to ecosystem models tend to be at the coarse end of this range. Peta-scale computing provides the computational resources to address these issues, and variable resolution models (unstructured grid, e.g. Pain et al. 2005) provide the technology to do this highly efficiently. Recently multi-scale, unstructured grid models such as this are being run coupled to simple ecosystem models (Ji et al. 2008). While this example only considers a regional simulation, expansion to ocean basin and eventually global scales and incorporation into Earth Systems Models will come in due course.

While there is a general consensus for the development pathway of the hydrodynamic model, this is not the case for the representation of the ecosystem. Contentious areas include appropriate complexity, parameter assignment and relation to observations. These are reviewed by Allen et al.(2010). Issues that specifically relate to the carbon cycle are de-coupling nutrient and carbon cycles (Patsch and Kuhn 2008), ocean-shelf exchange (Holt et al. (2009)), and terrestrial inputs. On the latter, the need to know the total alkalinity (for partitioning the DIC) is a particular issue, since while the relationships with salinity are accurate, they are generally regionally specific and mostly developed for open ocean conditions to date (e.g. Lee et al. 2006).

3. STRATEGY FOR A COASTAL CARBON OBSERVATIONAL NETWORK

3.1. Underway observations of carbon parameters on ships of opportunity

There is a need for the deployment of additional autonomous pCO_2 instrumentation on research and commercial Voluntary Observing Ships (VOS) to improve the spatial coverage of pCO_2 and other carbon and ancillary parameters in surface waters. The map in Figure 5 shows known underway carbon observation lines on commercial and research ships for oceanic carbon observations. For CO_2, the bulk of the effort has focused on the open ocean but some of these lines have covered parts of the coastal ocean. Recently underway observational systems have been installed on research and commercial vessels serving predominantly coastal regions. However, increased use of the VOS approach in continental shelf seas must be encouraged.

It is particularly recommended that in coming years research or commercial ships are instrumented to cover under-sampled regions such as the coastlines of the Russian Arctic, western South America, eastern Africa, large sections of western Africa, and most of Antarctica. It is also recommended that pCO_2 and other carbon data obtained in coastal waters by "open ocean" dedicated VOS lines (e.g., Monteiro et al. 2010) should be processed and banked and not discarded.

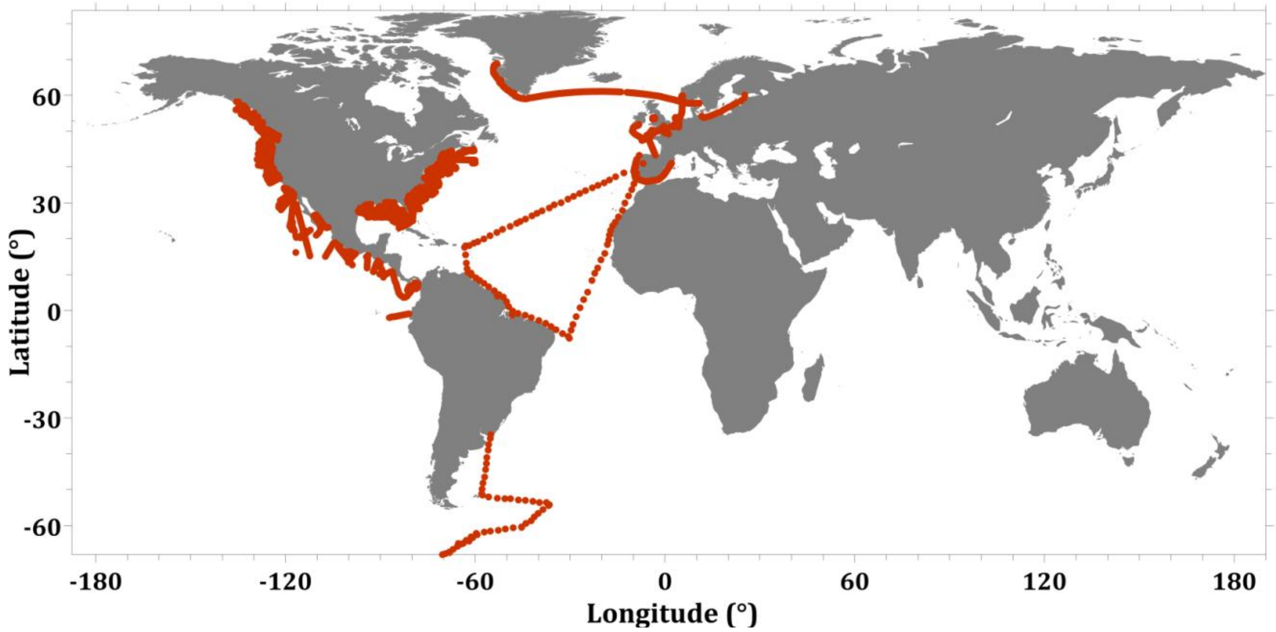

Figure 5 Carbon underway map: on-going and planned track lines (details in Tab 3)

3.2. Time-series measurements at fixed stations, on floats, gliders and autonomous surface vessels

Moorings can provide useful high-resolution observations at key sites where specific processes need to be studied with high temporal resolution and cannot be sampled by other means. As existing VOS lines have at best a weekly frequency, the VOS observatory needs to be complemented by moorings to provide information on temporal variability of pCO_2 at higher frequency (daily or sub-daily scale) and capture short-term extreme events (phytoplankton blooms, storms, high run-off, etc.) that are missed by VOS lines or even avoided (e.g. storms, hurricanes).

Moorings, floats, gliders and autonomous surface vessels should be equipped with a variety of automated sensors (pCO_2, pH, SSS, SST, O_2, chlorophyll-a, turbidity, inorganic nutrients, etc., as detailed in Sect. 2.4.) depending on the scientific issues addressed, such as C metabolism, ocean acidification (Feely et al. 2009), eutrophication, and so on. For instance, moorings in the open ocean equipped with O_2 sensors have provided high temporal resolution estimates of C production and export (Karl et al. 2003; Emerson et al. 2008) and can be also be deployed in coastal environments (e.g., Fig. 6).

Moorings require that equipment is designed to be robust to biological fouling. Modern methods of power generation mean that the power consumption of instruments is less of a constraint than it has been.

Drifting instrument packages have been used successfully in the open oceans and could be adapted

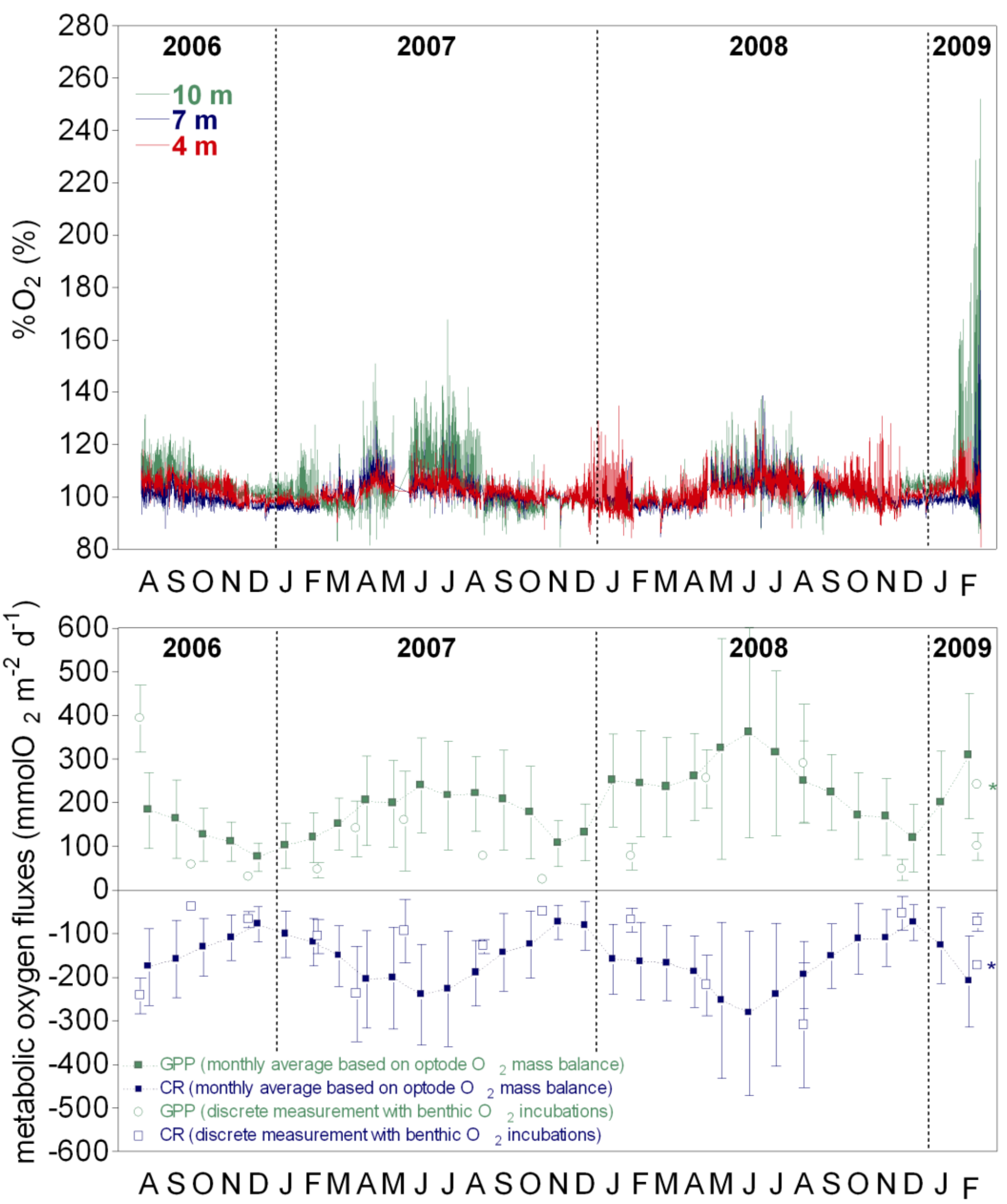

Figure 6 Time-series of oxygen saturation level on a shallow mooring (10m depth) over a Posidonia oceanica *seagrass meadow in the Mediterranean Sea and gross primary production and community respiration derived from diel cycles of %O_2 measured on the mooring (monthly averages) and measured discretely with benthic chambers (A.V. Borges, unpublished).*

for use in shelf seas. Currently gliders have the capacity to conduct cross-shelf depth profile transects of salinity, temperature, oxygen, chlorophyll-a, chromophoric dissolved organic matter, and turbidity. Sufficiently compact instruments to measure pH from a glider platform are under development, but there is a need for other inorganic carbon sensors to be developed for deployment on gliders.

The map in Fig. 7 shows known moorings and repeat stations for oceanic carbon observations. Such observations are lacking in most coastal waters with the exception of the U.S. east and west coasts, some sites in Europe, and some in India. It is recommended that in the coming years, mooring or repeat stations are developed to cover other areas of the coastal ocean.

While large-scale surveys can only be made with relatively low frequency, selected repeat stations similar to open ocean stations (HOT, BATS (Bermuda Atlantic Time-series Station), ESTOC (European Station for Time Series in the Ocean, etc…) should be developed in coastal environments to provide important information

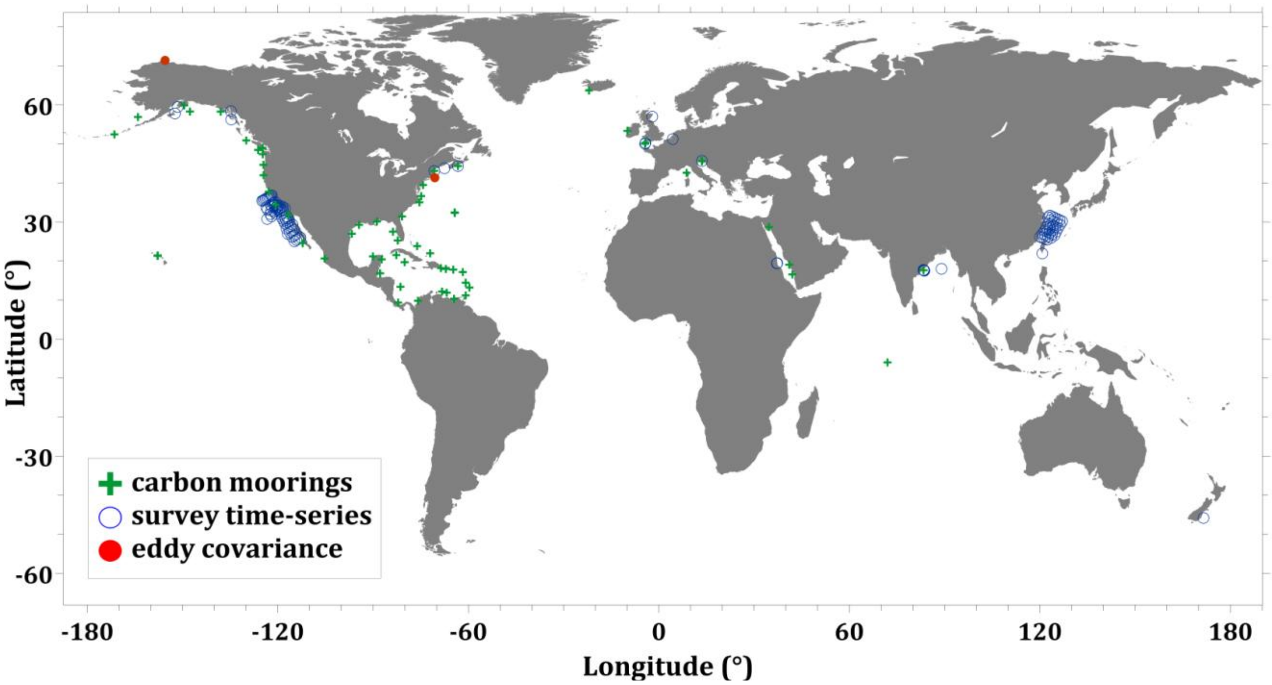

Figure 7 Coastal CO_2 moorings (green crosses), time-series (open blue circles), and eddy covariance (solid red circles) stations (details in Tabs. 1 and 2).

about short timescale variability (diurnal to seasonal). The choice of the sites may have to be a compromise between scientific relevance and accessibility from research institutes. In open ocean studies such repeat station long-term data-sets have been extremely valuable (e.g. Wong et al. 1999; Brix et al. 2004; Wakita et al. 2005; Santana-Casiano et al. 2007; Bates 2007). The presently extremely limited number of coastal areas (e.g., Californian Current, Fig. 2) must be increased. A number of long-standing coastal oceanography sampling programs (e.g. California Cooperative Oceanic Fisheries Investigations [CalCOFI], 1949–present; Investigaciones Mexicanas de la Corriente de California [IMECOCAL], 1997–present) are presently undertaking to add regular carbon measurements to their repertoire.

3.3. Large-scale repeat surveys of chemical and biological properties

The autonomous-automated approaches still need to be complemented by research cruises covering the largest possible area to investigate the vertical and basin-wide distributions of DIC variables and relevant biogeochemical processes (primary production, community respiration, calcification, organic carbon export, …) (e.g. Thomas et al., 2004, Bozec et al., 2006). Such cruises should be carried out to allow the coverage of the “present day” seasonality and spatial patterns and to place smaller scale studies into broader regional and process-oriented context. These surveys should be repeated in the future to investigate the impact of climate oscillations (NAO (North Atlantic Oscillation), ENSO (El Niño/Southern Oscillation), SAM (Southern Annular Mode), PDO, …) and/or climate change (changes in circulation, eutrophication, expanding oxygen minimum zones, ocean acidification, …) on DIC dynamics and overall carbon flows (e.g. Thomas et al., 2007).

3.4. Ancillary variables to pCO_2 and instrumentation improvement and development

Inclusion of ancillary variables on these automated pCO_2 measuring platforms (VOS, moorings, drifters, and autonomous surface vessels) is highly recommended if the data are to be fully interpreted. These ancillary variables are needed to interpret the processes controlling observed pCO_2 variations, classify the pCO_2 data regionally, and scale pCO_2 data. Robust technology is available for variables such as salinity, O_2, chlorophyll-a fluorescence, and turbidity, but is still emerging for inorganic nutrients (e.g. Adornato et al. 2010).

Work on pCO_2 systems (VOS, moorings, drifters, and autonomous surface vessels) is still needed to make them more robust and to lower the labor overhead. Technology to autonomously and reliably measure inorganic carbon variables other than pCO_2 is emerging. Developments of pH measurements are making good progress (Seidel et al. 2008), but for DIC and total alkalinity (TA), work is at an early stage and needs to be encouraged (e.g. Byrne et al. 2010).

It is recommended that inter-calibration exercises and technical workshops are carried out to help the development of these technologies.

3.5. Standard operating procedures (SOP) and quality control (QC) protocols for coastal measurements

While standard operation procedures (SOP) and quality control (QC) protocols are well established for open ocean CO_2 measurements, it is recommended that these SOP and QC protocols be adapted to account for the specific needs of coastal waters from a technical point of view e.g. bio-fouling, turbidity, and the need for fast-response instruments. From an analytical point of view, new standards for the calibration of pCO_2, DIC and TA measurements are needed, because typical measurement ranges are beyond those of open oceanic environments, e.g. in estuaries pCO_2 values up to 8000 ppm or TA/DIC values up to 4500 µmol kg^{-1} have been observed (e.g., Frankignoulle et al. 1996; 1998). In addition, research is needed into suitable constants for computations, in particular for brackish waters (carbonic acid dissociation constants, etc.). This will require laboratory work, technical workshops, and inter-calibration exercises.

Table 1. *Existing, planned, or proposed coastal carbon moorings or eddy covariance towers.*

Name	Years of operation	Region	Variables	PI	Institution	Country
Akumal	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Centro Ecological Akumal	
Alawai	2008–present	Pacific (Hawaii)	T, S, O_2, pCO_2	E. Di Carlo, C. Sabine	UH - Coral Reef Instrumented Monitoring Platform	USA
Amukta Pass 1 (Aleutians, Alaska)	2011	Gulf of Alaska	pCO_2, O_2, SSS, SST, OA†	P. Stabeno, C. Sabine, S. Alin	PMEL	USA
Archipelago Los Roques	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Fundation Los Roques	
Arrecife Alacranes	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	UNAM	
Bahia Magdalena	2008–present	Pacific (Mexico)	T, S, O_2, pCO_2	J.M. Hernandez-Ayon	UABC, CICESE, CICIMAR	MX
Barkley Canyon‡	2009	Pacific (N. America)	T, S, O_2, pCO_2	D. Ianson, V. Tunnicliffe	Neptune, UBC, IOS	Canada
Barrow Point§	2009–present	Alaska sea-ice	CO_2 fluxes	B. Delille, A.V. Borges	ULG	BE
Biloxi	2009–present (OA in 2010)	Gulf of Mexico	pCO_2, O_2, SSS, SST, OA	S. Lohrenz, C. Sabine	USM, NOAA/PMEL	USA
Bloody Bay Marine Park	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Little Cayman Research Center	
Bocos del Toro	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Smithsonian	
Bonaire NMP	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Bonaire National Marine Park	
Buccoo Marine Park	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	USGS	
Calvi	2006–present	Mediterrenean Sea	pCO_2, O_2, SSS, SST	A.V. Borges	ULG	BE
Cape Elizabeth (Aberdeen, Washington)	2006–present (OA in 2010)	Pacific	pCO_2, O_2, SSS, SST, OA	C. Sabine	NOAA/PMEL	USA
Cape Hatteras	2013	Atlantic	pCO_2, O_2, SSS, SST, OA	C. Sabine	NOAA/PMEL	USA
Chesapeake Bay	2013	Atlantic	pCO_2, O_2, SSS, SST, OA	C. Sabine	NOAA/PMEL	USA
Coastal Ocean Biogeochemistry Observatory (COBO)	2009	Bay of Bengal	T,S, O_2, chl, DIC, TA, pCO_2	V.V.S.S. Sarma	NIO	India
Corpus Christi, Texas	2012	Gulf of Mexico	pCO_2, O_2, SSS, SST, OA	C. Sabine	NOAA/PMEL	USA
Crescent Reef	2010	Atlantic (Bermuda)	T, S, O_2, pCO_2	Andersson, N. Bates, C. Sabine	BIOS, NOAA/PMEL	Bermuda
CRIMP	2005–present	Pacific (Hawaii)	T, S, O_2, pCO_2	E. Di Carlo, C. Sabine	UH - Coral Reef Instrumented Monitoring Platform	USA
Del Este; Punta Cana	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	NCORE	
Devils Hole	2009–present	Atlantic (Bermuda)	T, S, O_2	Andersson, N. Bates, Aucan	BIOS	Bermuda
E1	200X–present	English Channel	T, S, O_2	N. Hardman Mountford (DEFRApH)	Plymouth Marine Laboratory	UK
Enrique	2009–present	Caribbean	T, S, O_2, pCO_2	J. Hendee	UPR	
Ensenada	2008–present	Pacific (Mexico)	T, S, O_2, pCO_2	J.M. Hernandez-Ayon	UABC, CICESE	MX
Everglades National Park, Florida	2011	Gulf of Mexico	pCO_2, O_2, SSS, SST, OA	C. Sabine	NOAA/PMEL	USA
Farasan Islands MPA	proposed	Red Sea	pCO_2, O_2, SSS, SST, OA	J. Hendee	NOAA	USA
FATE-1 (near Kodiak Island, Alaska)	2014	Gulf of Alaska	pCO_2, O_2, SSS, SST, OA	P. Stabeno, C. Sabine, S. Alin	NOAA/PMEL	USA
Folkstone Marine Reserve	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	UWI	
Galveston, Texas	2013	Gulf of Mexico	pCO_2, O_2, SSS, SST, OA	C. Sabine	NOAA/PMEL	USA
Glovers Reef	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Wildlife Conservation Society	
Gray's Reef	2006–present (OA in 2011)	Atlantic	pCO_2, O_2, SSS, SST, OA	W.J. Cai, C. Sabine	UGA, NOAA/PMEL	USA
Great Chagos Bank	proposed	Indian	T, S, O_2, pCO_2, pH	J. Hendee, R. Salm	NOAA/TNC	
Gulf of Alaska 1	2010	Gulf of Alaska	T, S, O_2, pCO_2, pH	Mathis, Sabine	NOAA/PMEL, UAF	
Gulf of Aqaba	proposed	Red Sea	T, S, O_2, pCO_2, pH	J. Hendee	NOAA	

3.6. Achieving global coverage by international coordination and cooperative projects

While some areas are under-sampled due to the remoteness or harshness of climate (high latitudes), other areas are under-sampled due to lack of regional research capacity, or lack of funding and expertise from existing research institutes, particularly in emerging economy countries. Regarding the latter, it is recommended that cooperative projects are developed to build capacity for local research institutes to deploy, service, and process data from automated pCO_2 instrumentation (moorings, drifters). With forecasted changes in ice cover at high latitudes, large changes in

Table 1. Existing, planned, or proposed coastal carbon moorings or eddy covariance towers (Continued).

Name	Years of operation	Region	Variables	PI	Institution	Country
Gulf of Maine	2006–present (OA in 2010)	Atlantic	pCO_2, O_2, SSS, SST, OA	J. Salisbury, D. Vandemark, C. Sabine	UNH, NOAA/PMEL	USA
Hog Reef	2010	Atlantic (Bermuda)	T, S, O_2, pCO_2	Andersson, Bates & Sabine	BIOS, NOAA/PMEL	
Iceland shelf	2010	Iceland shelf	pCO2, SSS, SST, O2	J. Ólafsson	HAFRO	IS
Isle of Pines	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Inst. Invest.Ocean.	
Kilo Nalu	2008–present	Pacific (Hawaii)	T, S, O_2, pCO_2	E. Di Carlo, C. Sabine	UH - Coral Reef Instrumented Monitoring Platform	USA
L4	2009	English Channel	T, S, O2	N. Hardman Mountford (DEFRApH)	Plymouth Marine Laboratory	UK
Lee Stocking Island	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Perry Institute for Marine Science	
LEO-15	2012	Atlantic	pCO_2, O_2, SSS, SST, OA	C. Sabine	NOAA/PMEL	USA
M2	2014	Bering Sea	pCO_2, O_2, SSS, SST, OA	P. Stabeno, C. Sabine, S. Alin	NOAA/PMEL	USA
Mace Head	2008–present	Atlantic (NW Europe)	T, S, O_2, pCO_2	Ward, O'Dowd, Cave	CCAPS/ECI, NUI	Ireland
Martha's Vineyard Coastal Observatory§	2002–present	U.S. East Coast	CO_2 fluxes	W. McGillis	LDEO, WHOI	USA
Mochima	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Univ. Oriente	
NANOOS (LaPush, Washington)	2010	Pacific (N. America)	T, S, O_2, CO_2, ADCP, fluorescence, turbidity, NO_3	Newton, Sabine, Devol, Alford	UW, NANOOS, NOAA/PMEL	USA
North Sound	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	UM, TAMU	
off San Francisco Bay	2013	Pacific	pCO_2, O_2, SSS, SST, OA	C. Sabine, S. Alin	NOAA/PMEL	USA
PALOMA	planned	North Adriatic - Mediterranean (Europe)	T, S, O_2, pCO_2, pH	A. Luchetta	CNR (National Council of Research) -ISMAR (Marine Sciences Institute)	IT
Point Conception, California	2012	Pacific	pCO_2, O_2, SSS, SST, OA	V. Fabry, C. Sabine	CSUSM, NOAA/PMEL	USA
Poseidon E1-M3A	2000–present (pCO_2 in 2009)	Cretan sea	pCO_2, T, S, chl, turbidity, NO_3, PAR, O_2, currents	G. Petihakis, E. Krasakopoulou	HCMR	GR
Puerto Vallarta	2010	Pacific (Mexico)	T, S, O_2, pCO_2	J.M. Hernandez-Ayon	UABC, CICESE, UAG	MX
Salt River Canyon (NPS)	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	UVI	
San Bernardo	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Invesmart	
Scotian Shelf	2006–present	Scotian Shelf	pCO_2, SSS, SST, wind, air T, chl	H. Thomas	DAL	CA
Seaflower Biosphere Reserve	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Coralina (NGO)	
South Island area	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	IFREMER/IRD	
Stonewall Banks (Newport, Oregon)	2014	Pacific	pCO_2, O_2, SSS, SST, OA	B. Hales, C. Sabine, S. Alin	OSU, NOAA/PMEL	USA
Tampa-St. Petersburg, Florida	2012	Gulf of Mexico	pCO_2, O_2, SSS, SST, OA	C. Sabine	NOAA/PMEL	USA
Three Mary Cays	proposed	Caribbean	T, S, O_2, pCO_2, pH	J. Hendee	Turks and Caicos School for Field Studies	
Trinidad Head	2010 (OA in 2011)	Pacific	pCO_2, O_2, SSS, SST, OA	V. Fabry, C. Sabine	CSUSM, NOAA/PMEL	USA
Umm al-Qamari Islands MPA	proposed	Red Sea	pCO_2, O_2, SSS, SST, OA	J. J. Hendee	NOAA	USA
Vancouver-Queen Charlotte Islands	2012	Pacific	pCO_2, O_2, SSS, SST, OA	B. Hales, S. Alin, C. Sabine	OSU, NOAA/PMEL	USA
VIDA	2002–present (pCO_2 in 2007, O_2 + chl in 2008)	Gulf of Trieste	SST, SSS, wind, air temp, humidity, pCO_2, O_2, chl, currents, waves, bottom T	V. Malacic, D.Turk	NIB	SL
Yakutat-Juneau, Alaska	2013	Gulf of Alaska	pCO_2, O_2, SSS, SST, OA	B. Hales, S. Alin, C. Sabine	OSU, NOAA/PMEL	USA

† OA here refers to a second carbon parameter (i.e. pH, DIC, or TA) that will make the sensor package capable of reflecting ocean acidification conditions.
‡ This carbon observational system will be part of a cabled observatory node.
§ This station is an air-sea eddy covariance tower.

ocean uptake of atmospheric CO_2 are predicted, which makes instrumentation to record changes in coastal ocean uptake of atmospheric CO_2 are predicted, which makes instrumentation to record changes in coastal carbon fluxes at high latitudes especially desirable.

Furthermore, it would be useful to have an international organization that could help coordinate this coastal carbon observational system. Major issues that could be facilitated by this body include obtaining appropriate permissions from various countries to facilitate coastal carbon research within their exclusive economic zones (EEZ) and the facilitation of data sharing. Some countries legally restrict the rights of scientists to openly share data collected within their EEZs for security reasons. Data sharing and permitting issues stand to interfere with important coastal carbon research initiatives at a critical time when national and international research communities should be planning for active monitoring and data sharing efforts related to coastal CO_2 synthesis, ocean acidification early warning networks, and so on.

Table 2. *Coastal carbon time-series sampling stations.*

Name	Years of operation	Region	Variables	PI	Institution
Baranof Island†	2010	Gulf of Alaska	T, S, DIC, TA, nutrients	Carls, Sigler	NOAA/AFSC
Bay of Bengal Ocean Timeseries Station (BOTS)	2010	Bay of Bengal	T,S, O_2, chl, DIC, TA, pCO_2	V.V.S.S. Sarma	NIO
CalCOFI	1949–present (hydrography, fisheries), 2008–present (carbon)	Central and southern California	T, S, O_2, CO_2, TA, DIC, chl	A. Dickson (for inorganic carbon)	CalCOFI
Coastal time-series observations	2007–present (carbon 2008–present)	Coastal Bay of Bengal	T,S, nutrients, TA, pH, DIC, chl	V.V.S.S. Sarma	NIO
E1	2008–2010	English Channel	T, S, O_2, CO_2, pH, TA, DIC	N. Hardman Mountford (DEFRApH)	Plymouth Marine Laboratory
GNATS	1998–present	Gulf of Maine	T, S, nutrients, carbon fixation, phytoplankton biomass, POC, PIC, chl, biogenic silica, inherent and apparent optical properties	W. Balch	Bigelow Laboratory for Ocean Sciences
IMECOCAL	1997–present (hydrography), 2006–present (carbon)	Baja California coast	T, S, O_2, chl, nutrients, ^{14}C production, zooplankton	M. Hernandez-Ayon (for inorganic carbon)	IMECOCAL
Kasitsna Bay†	2010	Gulf of Alaska	T, S, DIC, TA, nutrients	Holdereid, Sigler	NOAA/AFSC
Kodiak†	2010	Gulf of Alaska	T, S, DIC, TA, nutrients	Foy, Sigler	NOAA/AFSC
L4	2008–2010	English Channel	T, S, O_2, CO_2, pH, TA, DIC	N. Hardman Mountford (DEFRApH)	Plymouth Marine Laboratory
Lena Point†	2010	Gulf of Alaska	T, S, DIC, TA, nutrients	Carls, Sigler	NOAA/AFSC
LORECS	2003–present	East China Sea	pCO_2, TA, DIC, O_2, nutrients, chl, PP, SST, SSS	G.C. Gong, C.M. Tseng, W.C. Chou	NTOU/NTU
Monterey Bay transect	2003–present	Monterey Bay, California	T, S, O_2, CO_2, TA, DIC	F. Chavez	MBARI
Munida time series	1998–present	south east coast of New Zealand	pCO_2, TA, nutrients, chl, SST, SSS	K. Currie	NIWA
Nanwan Bay	1986–present (4 times/yr)	South China Sea	pH, S, T, O_2, nutrients, chl	C.T.A. Chen	NSYSU
PALOMA	2008–present	North Adriatic - Mediterranean (Europe)	T, S, O_2, pH, TA, nutrients	A. Luchetta	CNR (National Council of Research) -ISMAR (Marine Sciences Institute)
Port Sudan	2009–2012	Red Sea	T, S, O_2, DIC, TA	I. Skjelvan, A. Omar, A. Elhag	UiB, Red Sea University
Prince Madog	2008–2010	Irish Sea	SSS, SST, F, O_2, TA, DIC, NO_3	J. Howarth (DEFRApH)	POL
Scotian Shelf	2006–present	Scotian Shelf	DIC, TA, pCO_2	H. Thomas	DAL
Ste Anna	2003–present	Upper Scheldt estuary	pCO_2, SSS, SST	A.V. Borges	ULG
Stonehaven	2008–2010	North Sea	SSS, SST, NO_3, TA, DIC	S. Hay (DEFRApH)	FRS
UNH Coastal Marine Lab	2006, 2008, resume 7/2009	Gulf of Maine, Piscataquis River	pCO_2, SSS, SST	J. Salisbury, D. Vandemark	UNH

† Sampling at these stations will be from seawater supplies piped into NOAA research labs from the adjacent coastal water bodies.

Contemporaneous efforts to implement the coastal GOOS (Global Ocean Observing System) module could be very synergistic with coastal carbon observational efforts, as the sharing of resources and observational capacity among communities should be mutually beneficial. The coastal GOOS community also seems to be further along with developing the types of international research facilitation strategies that will be needed for successful international coastal carbon syntheses and OA observational networks (e.g. Malone et al. 2010).

Table 3. Underway carbon observing systems deployed or planned for deployment in coastal waters globally.

Ship or Transect Name	Type of platform	Years of operation	Region	Variables	PI
Belgica	VOS line	2002–present	North Sea, English Channel, Celtic Sea	pCO_2, SST, SSS	A.V. Borges
Bergen-Amsterdam	VOS line	2005–present	North Sea	pCO_2, SST, SSS	A. Omar, T. Johannessen
Explorer of the Seas	Cruise ship	2002–2007	U.S. East Coast, Caribbean	pCO_2, SST, SSS, chl	R. Castle, B. Huss, R.Wanninkhof
Finnmaid	VOS line	2003–present	Baltic Sea	pCO_2, O_2, SSS, SST	B. Schneider
James Clark Ross	Research ship	2006–present	Southern Ocean and Patagonian shelves	pCO_2, O_2, SSS, SST, fluorescence, PAR	N. Hardman-Mountford
Las Cuevas	Tanker	2009	Gulf of Mexico	pCO_2, SST, SSS	D. Pierrot, K. Sullivan, R. Wanninkhof
LORECS	Research ship	2003–present	East China Sea	pCO_2, TA, DIC, O_2, nutrients, chl, PP, SST, SSS	
Luctor	VOS line	2008–present	whole Scheldt estuary	pCO_2, SST, SSS	A.V. Borges
NOAA ship *David Starr Jordan*	Research ship	2006–2008	U.S. West Coast, Central America	pCO_2, O_2, SSS, SST	S. Alin, R. Feely
NOAA ship *Gordon Gunther*	Research ship	2007–present	Northern Gulf of Mexico	pCO_2, SST, SSS	D. Pierrot, R. Wanninkhof
NOAA ship *McArthur II*	Research ship	2006–present	U.S. West Coast, Central America	pCO_2, O_2, SSS, SST	S. Alin, R. Feely
NOAA ship *Miller Freeman*	Research ship	2009–present	U.S. West Coast, Gulf of Alaska	pCO_2, O_2, SSS, SST	S. Alin, R. Feely
NOAA ship *Oscar Dyson*	Research ship	2010	U.S. West Coast, Gulf of Alaska, Bering Sea	pCO_2, O_2, SSS, SST	S. Alin, R. Feely
NOAA ship *Ronald H. Brown*	Research ship	since 1998	U.S. Gulf of Mexico, East, West coasts	pCO_2, SST, SSS, chl	R. Castle, K. Sullivan, R.Wanninkhof
Nuka Arctica	VOS line	2005–present	North Sea, Iceland Basin, Irminger Sea, West Greenland	pCO_2, SST, SSS	A. Olsen, T. Johannessen, G. Reverdin (SSS)
Oleander	VOS line	2006, 2009–present	New Jersey Coast, Bermuda Platform	pCO_2, SST	N.R. Bates, R. Wanninkhof
Plymouth Quest	Research ship	2005–present	Western English Channel	pCO_2, O_2, SSS, SST, fluorescence, transmissometer	N. Hardman-Mountford
Pride of Bilbao	VOS line	2005–present	English Channel, Celtic Sea, Bay of Biscay	SSS, SST, F, O_2, TA, DIC	D.J. Hydes (since 2008 DEFRApH)
Prince Madog	Research ship	2006–present	Irish Sea	pCO_2, O_2, SSS, SST	N. Hardman-Mountford
Rickers	Research ship	2008–present	Gulf of Alaska, North American West Coast	pCO_2, SSS, SST	B. Hales, W. Evans
Simon Stevin	VOS line	2011	Belgian coast	pCO_2, SST, SSS	A.V. Borges
TRANCOS	VOS line	2009–present	Iberian coast	pCO_2, O_2, SSS, SST	A. F. Ríos & C. Pelejero
VIBRA	VOS line	2010	Northeastern coast of South America	pCO_2, O_2, SSS, SST	A. F. Ríos
VOS-Ocean Biogeochemistry Observatory (VOBO)	Research ship	2010 (proposed)	Northern Indian Ocean	SST,SSS,O_2,chl, pCO_2	VVSS Sarma
Walton Smith	Research ship	2008–present	U.S. East Coast, Caribbean	pCO_2, SST, SSS	F. Millero

4. DATA MANAGEMENT, SYNTHESIS, AND PRODUCT DEVELOPMENT

4.1. Data Management and Products

Data banking in international, public, quality checked (Carbon Dioxide Information Analysis Center - CDIAC) and uniform format (Surface Ocean CO_2 Atlas - SOCAT) databases on coastal carbon need to be further developed, with funding allocated for their long-term maintenance and updating. Over the long-term, the related data synthesis will facilitate more robust air-sea CO_2 flux estimates in coastal environments, improve our knowledge of spatial and temporal (daily, seasonal, inter-annual, decadal) variations in air-sea CO_2 exchange, and equip the international research and monitoring communities with critical tools for anticipating and adapting to anthropogenic carbon cycle perturbations (warming, hypoxia, ocean acidification, eutrophication...).

4.2. Joint Synthesis Activities

Community data synthesis needs to be carried out at local, regional and global scales. The first coastal ocean CO_2 climatology for North America recently concluded that North American continental margins to a distance of ~1° offshore are a net source of 19±22 Mt C yr^{-1} in CO_2, based on a database of half a million data points (Chavez et al. 2007). Through this effort, substantial sampling gaps were identified in regions interpreted to be large sources or sinks (Gulf of Mexico and Gulf of Alaska, respectively). It is recommended that procedures to achieve a global climatology of coastal air-sea CO_2 fluxes be discussed within the scientific community, and a first version of such climatology be achieved in near future, as initiated in the framework of SOCAT. The first global coastal CO_2 climatology is likely to identify significant sampling gaps that will help target future observational efforts, as they have in North American waters. Efforts toward model-data comparisons of coastal carbon fluxes for North American coastal oceans have been initiated by the North American Carbon Program and are encouraged in other regions as well. Synthesis of data should be carried out with a variety of approaches such as remote sensing and biogeochemical modeling.

4.3. Forecast tools

Further work is needed in developing methods using historical CO_2 and related chemical data to generate seasonal CO_2 flux maps and proxy indicators for ocean acidification conditions that will allow researchers to generate forecasting tools useful for fisheries and resource management professionals.

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