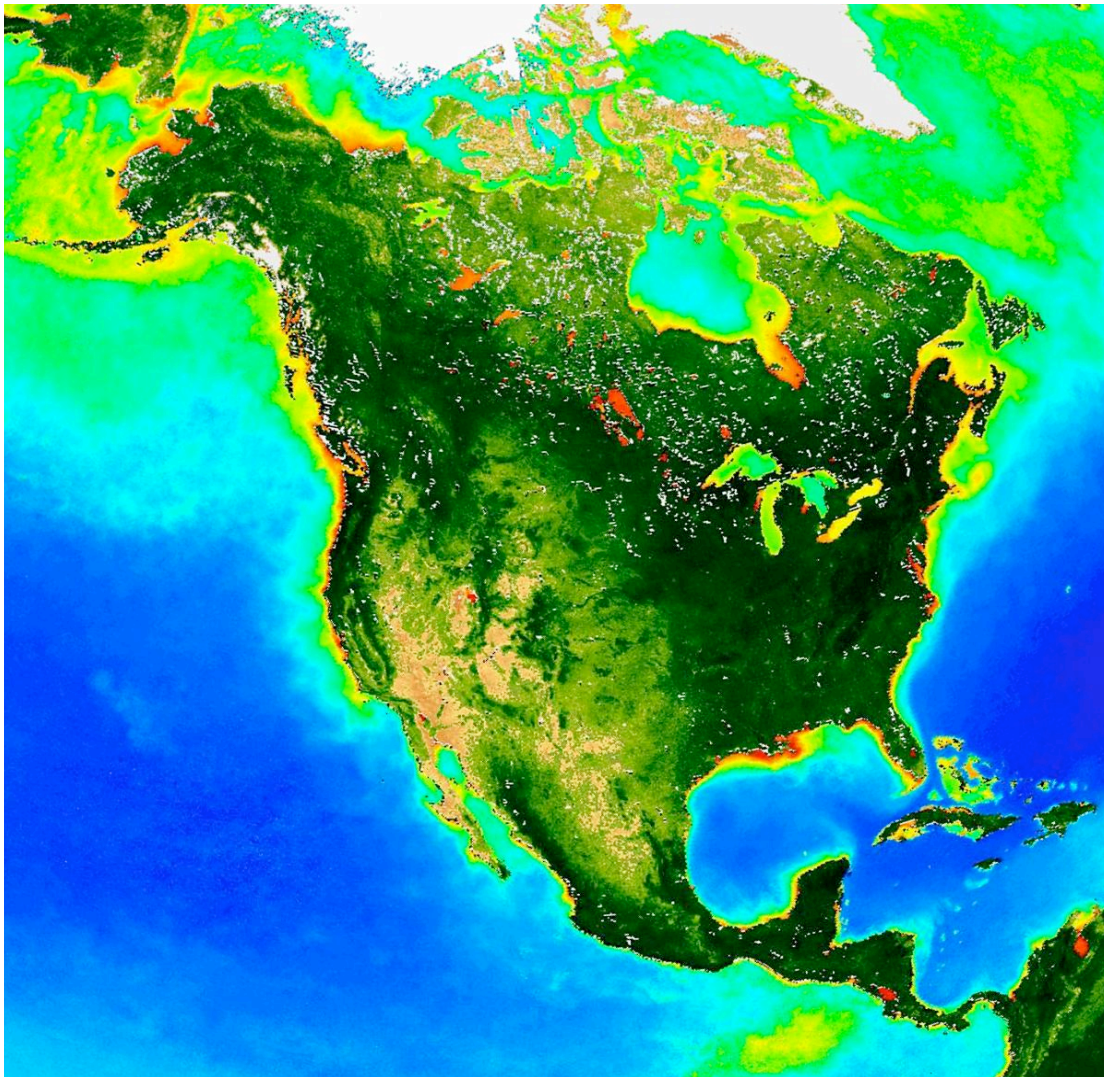
A Science Plan For Carbon Cycle Research In North American Coastal Waters



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Executive Summary

Relative to their surface area, continental margins represent some of the largest carbon fluxes in the global ocean, but sparse and sporadic sampling in space and time makes these systems difficult to characterize and quantify. Recognizing the importance of continental margins to the overall North American carbon budget, terrestrial and marine carbon cycle scientists have been collaborating on a series of synthesis, carbon budgeting, and modeling exercises for coastal regions of North America, which include the Gulf of Mexico, the Laurentian Great Lakes (LGL), and the coastal waters of the Atlantic, Pacific, and Arctic Oceans. The Coastal CARbon Synthesis (CCARS) workshops and research activities have been conducted over the past several years as a partner activity between the Ocean Carbon and Biogeochemistry (OCB) Program and the North American Carbon Program (NACP) to synthesize existing data and improve quantitative assessments of the North American carbon budget.

CCARS activities in all five regions resulted in data compilations that improved estimates of key carbon fluxes, particularly air-sea fluxes and primary productivity, for which the most observations exist. Updated carbon budgets have been published for the Gulf of Mexico (Coble et al., 2010; Benway and Coble, 2014), Atlantic coast (Najjar et al., 2012), Pacific coast (Alin et al., 2012), Arctic coast (Cross et al., 2014a, b; Evans et al., 2015), and the LGL (McKinley et al., 2011). Air-sea CO_2 flux syntheses have been published for coastal systems of the Arctic (Cross et al., 2014a; Evans et al., 2015), Atlantic (Signorini et al., 2013), and the northern Gulf of Mexico (Huang et al., 2015), and more are underway. For the California Current System (CCS), a convergence of model- and observation-based air-sea fluxes reflects both the increasing sophistication of the models and the increase in surface seawater and atmospheric pCO_2 observations. A summary of published carbon flux estimates suggests that Lakes Superior, Michigan, and Huron are slight CO_2 sources and Lakes Erie and Ontario are slight CO_2 sinks (McKinley et al., 2011). CCARS activities fostered collaborative synthesis and intercomparison across 3-4 different models that provide published estimates of carbon delivery to coastal regions, which yielded updated estimates of riverine carbon fluxes for most regions. Despite sparse data sets, CCARS participants also produced some of the first regional estimates of carbon fluxes from respiration, burial, and submarine groundwater discharge. Cross-shelf carbon fluxes, which are extremely difficult to constrain with the limited number of data sets, were calculated using a combination of models and data from tracer studies. Finally, using a statistical modeling approach, the first estuarine organic carbon budget for the Atlantic coast was developed based on studies in 12 representative estuarine systems (Herrmann et al., 2015).

Key recommendations of the CCARS data synthesis activities include:

- A **comparable synthesis of data from Mexican (Gulf of Mexico and Pacific coasts) and Canadian (Atlantic coast) waters**
- **A sustained observing program in all five Laurentian Great Lakes**, minimally including carbon and biogeochemical rate measurements across all seasons
- **Improved observational coverage (in space and time) of the Gulf of Alaska and other sea ice-bearing portions of the Arctic**

- **Further development of event-scale observing capacity (e.g., novel autonomous platforms)** in all continental margin systems to better quantify impacts of episodic events on coastal carbon budgets
- **Increased use of satellite products and development of algorithms for key carbon flux estimates** (e.g., primary productivity and surface-water pCO_2) are needed, especially observations from high spatial and high temporal resolution satellite sensors
- **Coordination of an all-inclusive carbon flux measurement campaign with universally established protocols across a small set of representative estuarine and tidal wetland systems** (using a typology approach) across all regions, including carbon flux measurements in **degraded or drowned coastal ecosystems** to better understand policy implications of coastal ecosystem change
- **Further development of three-dimensional biogeochemical models with interactions among tidal wetlands, estuaries, sediments, and shelf waters** to scale up limited observations and integrate across the land-ocean continuum
- Improved process understanding of how energy and land use by humans modify carbon stocks and fluxes in coastal waters to facilitate **anthropogenic attribution**
- I**ntegration of social scientists and policy specialists** into the planning process for developing integrated observational and modeling efforts as well as data harmonization strategies across the land-ocean continuum.

Introduction

Despite their relatively small surface area, continental margins are regions of intense carbon and nutrient processing, export and exchange, and thus have a significant impact on global biogeochemical cycles and, therefore, the Earth's climate. An understanding of carbon cycling in coastal waters is also prerequisite knowledge for a host of ecologically and societally relevant issues including coastal dead zones (hypoxia), nutrient over-enrichment (eutrophication), harmful algal blooms, acidification, the sustainability of fisheries, tidal wetland loss due to sea-level rise and development, and the economic value of tidal wetlands and other coastal systems (e.g., seagrasses, kelp, mangroves, coral reefs, etc.) as large sinks and reservoirs of carbon ("blue" carbon).

To characterize and quantify margin systems requires a level of spatiotemporal sampling that is difficult to achieve and sustain, and modeling margin systems presents significant scaling challenges. While a great deal of carbon cycle research is being conducted in margin systems, the associated research communities and scientific outcomes tend to be grouped by scientific discipline or flux boundary (terrestrial-river vs. river-estuary vs. estuary-open ocean), creating a need for coordinated scientific activities that cut across these boundaries.

In the late 1990s, the Carbon Cycle Interagency Working Group (CCIWG) requested that a science plan for carbon cycle research be developed. In 1999, such a plan was published (Sarmiento and Wofsy, 1999) and led to the formation of the North American Carbon Program (NACP) (www.nacarbon.org) and the Ocean Carbon and

Biogeochemistry (OCB) Program (www.us-ocb.org), sister organizations with overlapping domains in the coastal zone of North America. Both programs recognized the importance of the coastal zone in the global carbon cycle and the relative lack of coordinated research in this area. Two key reports (Denning, 2005; Doney et al., 2004) called for improved estimates of carbon fluxes across land-ocean, air-sea, and coastal-open ocean interfaces (diagnosis) along with improved understanding of factors controlling biogeochemical transformation processes (attribution) for the purpose of closing the carbon budget over North America. A workshop was subsequently proposed to the CCIWG to discuss the state of knowledge of carbon cycling in the North American Continental Margins (NACM). The workshop, funded by NASA, NOAA, and NSF, was held in 2005 and several recommendations emerged, including data synthesis in North American continental margin systems and carbon budget estimation based on a control volume concept (Hales et al., 2008). As a result, OCB and NACP began collaborating in 2008 on a series of Coastal CARbon Synthesis (CCARS) activities to synthesize individual, small-scale observational and modeling studies from different regions of the North American continental margin across broader spatial and temporal scales to improve quantitative assessments of the North American carbon budget. The CCARS activities were also preceded, and in part informed by a global-scale synthesis conducted in the early 2000s by the Joint Global Ocean Flux Study (JGOFS) and Land-Ocean Interactions in the Coastal Zone (LOICZ) projects through the Continental Margins Task Team (CMTT), which summarized the state of knowledge on the physical, biogeochemical and ecosystems processes in continental margin systems around the world (Liu et al., 2010).

The CCARS activities were divided geographically into five regions: Atlantic Coast, Pacific Coast, Gulf of Mexico, Arctic Ocean, and Laurentian Great Lakes. CCARS workshops and collaborative research activities have resulted in the development of regional coastal carbon budgets based on recent literature- and model-based estimates of major carbon fluxes for each region with estimated uncertainties. In addition, multiple peer-reviewed papers, presentations and other publications by involved researchers have highlighted these findings and provided more in-depth analyses of key processes underlying major carbon fluxes in continental margin systems. This synthesis work has yielded many beneficial outcomes to move the field forward, including:

- Coastal carbon cycling models that are sophisticated enough to start directly comparing with observations
- Convergence of air-sea flux estimates from models and observations
- Increased density of observations enabling the analysis of seasonal and inter-annual variability of some fluxes
- New and improved retrievals of biogeochemical variables from satellite observations

CCARS has contributed to the first two steps in the NACP Plan, *diagnosis* and *attribution*, although there are still improvements that can be realized via additional data collection and model development that would reduce uncertainties in estimates of fluxes and transformation rates. For example, one of the biggest remaining unknowns, due in

large part to a lack of data and a lack of models that can work across a range of temporal and spatial scales, is the role of tidal wetlands and estuaries in modifying exchanges among land, ocean, and atmosphere, including drowned and degraded systems that have been lost to sea level rise or land use changes. The next phase of research should focus on developing the last two elements of the NACP Plan: 1) Quantify the extent to which sources could increase or disappear (*prediction*); and 2) Design and develop resources for decision makers (*decision support*).

As a culminating outcome of these synthesis efforts, this comprehensive science plan highlights key knowledge gaps identified during this synthesis and provides explicit guidance on future research and observing priorities in continental margin systems to help inform future agency investments in continental margins research. After presenting the overarching science questions guided by the NACP Plan, this report identifies research needs in each of the five North American coastal regions as well as by key coastal carbon cycle fluxes and processes (terrestrial inputs, biological transformations, sedimentary processes, atmospheric exchanges, and lateral transport). The report closes with overarching priorities and recommendations.

Overarching Science Questions

1. How does the coastal zone contribute to the net carbon balance of North America? *[Diagnosis]*
2. What are the dominant mechanisms of seasonal to interannual variability in North American coastal zone carbon fluxes? How do these vary regionally? *[Process Attribution]*
3. How will climate change and management impact the North American coastal zone carbon fluxes and associated ecosystem services? *[Prediction / Decision Support]*

North American Coastal Regions

The study area encompasses the coastlines of Canada, the United States, and Mexico. The landward boundary is well defined by the head of tide. The seaward boundary should include all waters that are influenced by coastal processes, such as riverine input, coastal upwelling, and boundary currents. As such, the offshore boundaries used across the North American coastal regions reflect the dominant physical processes influencing coastal carbon cycling within each region.

Gulf of Mexico

Regional Setting

The Gulf of Mexico is a large, semi-enclosed water body geopolitically shared almost equally by the United States (US) and Mexican governments. Large river plumes,

particularly the Mississippi River, represent an important component of the Gulf carbon budget. The Gulf of Mexico drainage basin extends over roughly 40% of each nation and comprises 33 major river systems. Thus, large-scale changes in land use practices and water management in both countries, as well as changes in temperature and rainfall due to climate change, will profoundly affect Gulf carbon sources and sinks.

The Gulf of Mexico was subdivided into five different regions based on differing inputs, distinctive physical forcings and ensuing biogeochemical characteristics and processes:

- West Florida Shelf (WFS) - influenced by upwelling, river discharge, and groundwater influx
- Louisiana Shelf (LA) - river-dominated, receiving major discharge from the Mississippi-Atchafalaya River system
- Texas Shelf (TX) - dominated by upwelling and by eddies shed from the Loop Current
- Mexican Shelf (MX) - influenced by upwelling and by groundwater and river (Usumacinta-Grijalva) discharge
- Open Gulf - deep, semi-enclosed oligotrophic basin with an energetic circulation strongly connected to the Caribbean Sea and Atlantic Ocean

Synthesis Findings and Remaining Gaps

The state of knowledge of the Gulf of Mexico carbon budget can be found in a recent workshop report (Benway and Coble, 2014). Major advances have been made in refining estimates of air-sea flux (with over 400,000 pCO_2 measurements made since 1996) and primary productivity (with estimates based on direct measurements, satellite algorithms, and numerical ecosystem models), as well as improvements in estimates of respiration and terrestrial fluxes. A newly funded NASA project *Air-Sea CO_2 Flux and Carbon Budget Synthesis and Modeling in the Entire Gulf of Mexico* (PIs: L. Robbins et al.) will involve the compilation of a comprehensive set of surface ocean carbon measurements available in the region. Gulf of Mexico investigators will use these data to produce a monthly air-sea CO_2 flux climatology in the open ocean, northern, and WFS portions of the Gulf.

The top priorities for the Gulf of Mexico region are divided into those that require no new data and those that do require new data.

Incorporate existing data – non-funded projects

- Relevant data for the entire Mexican coastline have not been incorporated into the existing Gulf of Mexico carbon budget. Anecdotal reports indicate that much of these data exist and additional data collection is in progress, but despite past efforts, full collaboration with Mexican scientists has not been achieved. Such collaboration might be facilitated with the help of the Commission for Environmental Cooperation (CEC) and/or CarboNA, an international

collaboration between Canada, Mexico, and the United States for carbon cycle research throughout North America and adjacent ocean regions

- Satellite data have been underused for estimates of carbon cycle parameters in this region. Existing data should be used to develop new and improved remote-sensing algorithms for primary productivity and surface-water pCO_2, which will enable us to assess influence of spatial and temporal variability (including episodic events) on flux estimates and uncertainties.
- Carbonate production in this region is thought to be very important but is largely unknown. Shellfish can consume measurable amounts of river alkalinity, which is very high for the Mississippi River. Calculations of carbonate production should be made with available data, particularly for the Mississippi River plume.

Priorities requiring new data

- Improve quality and coverage of submerged aquatic vegetation (SAV) maps in the Gulf of Mexico and collect more observations to improve estimates of seagrass productivity and the factors that drive it
- Collect more pelagic and benthic respiration measurements in all sub-regions of the Gulf, including measurements on seasonal-annual scales; recent cruises following the BP oil spill represent a potential new data source
- Devise a carbon flux measurement campaign using established protocols (e.g., Howard et al., 2014) in different types of tidal wetland and estuarine systems around the Gulf of Mexico, as well as comparative studies across different systems
- Apply combined observational/modeling approaches to improve understanding of mechanisms of transformation among carbon pools
- Increase the number of flux towers for better constraints on mean and variance of fluxes, as well as the NASA Orbiting Carbon Observatory (OCO-2) ground-truthing
- Collect additional data on natural benthic seeps to quantify contribution to the Gulf carbon budget
- Obtain values for atmospheric deposition (wet and dry) of fixed pools of carbon, POC, DOC
- Make more measurements of terrestrial submarine groundwater discharge (SGD) for all parts of the Gulf (most are currently concentrated in Florida and Louisiana Shelf regions), as well as radionuclide tracer studies for estimating recirculated marine SGD
- Investigate the reported increase in Sargasso weed and macroalgae as a function of environmental degradation
- Conduct process-oriented studies focused on events such as eddy-shelf interactions, tropical storms, etc. (on scales of 10s of km and days to weeks) that combine observations and modeling

Atlantic Coast

Regional Setting

The Atlantic Coast domain is typically divided into three main subregions: the Gulf of Maine (GoM), the Mid-Atlantic Bight (MAB), and the South Atlantic Bight (SAB). A reasonable seaward boundary is the 500-m isobath. Source waters for the Atlantic Coast are dominated by the Labrador Sea and Scotian Shelf Water to the north and the Gulf Stream to the south, which form a dynamic boundary where they flow adjacent to each other between the Scotian Shelf and Cape Hatteras, near the SAB/MAB border. The subregions differ dramatically from each other in terms of their biogeochemistry, due in part to this circulation, but also due to differences in bathymetry, latitude, and land use and cover along the coast and its watershed (Tian et al., 2015; Yang et al., 2015). The GoM is semi-enclosed with several deep sub-basins and a strong spring bloom. It also has strong winter mixing that creates conditions for the potential of returning CO_2 to the atmosphere. The MAB is strongly influenced by riverine inputs of terrestrial carbon and nutrients that are processed by large estuaries having long residence times, such as Chesapeake Bay, Delaware Bay, and the Hudson River Estuary. Tidal freshwater and brackish marsh systems also have been shown to export large amounts of dissolved organic carbon and nitrogen to these estuaries, affecting estuarine optics and biogeochemistry (Tzortziou et al. 2011). The SAB has a landward boundary containing extensive tidal marshes and, at its seaward boundary, is strongly influenced by Gulf Stream intrusions and filaments that generate blooms every few weeks. A more in-depth comparison of the three subregions can be found in Jahnke et al. (2008).

Synthesis Findings and Remaining Gaps

A workshop in 2012 on the carbon biogeochemistry of the Atlantic Coast domain led to the construction of a preliminary budget and identification of areas of greatest uncertainty (Najjar et al., 2012). Primary production, most of which occurs in shelf waters, was identified as the best-known and likely largest term at 140 Tg C yr^{-1}. Riverine input was found to be between 4 and 11 Tg C yr^{-1} (mostly dissolved inorganic and organic fractions, DIC + DOC) and the net uptake of atmospheric CO_2 by shelf waters was estimated to be 0-8 Tg C yr^{-1}. Many other budget terms were examined during the workshop and were found to have very large uncertainties. Research since the workshop (e.g., Signorini et al., 2013; Herrmann et al., 2015) has reduced uncertainties in some of these terms. The comparatively few studies of respiration that have been conducted in the SAB differ by an order of magnitude in some regions, particularly the outer shelf, but agree in characterizing the continental shelf as a net heterotrophic system (Griffith and Pomeroy, 1995; Jiang et al., 2010).

Substantial progress in recent years has been made in the riverine input term. Stets and Striegl (2012) calculated the riverine flux of inorganic and organic carbon from the conterminous US to the ocean by applying USGS's LOADEST method to measurements of streamflow and water quality. Tian et al. (2015) used a process-based model to simulate riverine dissolved organic carbon (DOC), particulate organic carbon (POC), and

dissolved inorganic carbon (DIC) fluxes to the East Coast domain (as defined here) from 1901 to 2008. Long-term trends were found in these fluxes, particularly at the scale of individual subregions, in response to changing land cover, atmospheric nitrogen deposition, fertilizer input, and atmospheric CO_2. Simulated mean annual fluxes (±1 standard deviation) of DOC, POC, and DIC during 1980-2008 were estimated at 2.37 ± 0.60, 1.06 ± 0.20, and 3.57 ± 0.72 Tg C yr^{-1}, respectively. Many of the differences in riverine fluxes among the studies by Stets and Striegl (2012), Tian et al. (2015), and prior work (e.g., Shih et al., 2010) were reconciled by Tian et al. (2015) based on drainage area and stream flow estimates. The total riverine carbon flux for the Atlantic Coast domain can now be estimated with some confidence to be ~7 Tg C yr^{-1}, split evenly between inorganic and organic forms.

Considerable progress was made recently on the Atlantic Coast's estuarine organic carbon budget. Herrmann et al. (2015) applied statistical models to constrain the overall organic carbon budget of a set of US Atlantic Coast estuaries (Fig. 1a) that collectively represent the broad range of estuarine settings observed in the Atlantic coast domain. Organic carbon inputs from fluvial and tidal-wetland sources for the region were estimated at 3.5 and 1.9 Tg C yr^{-1}, respectively. To our knowledge, this was the first regional-scale estimate of the contribution of the flux of organic carbon from tidal wetlands to estuaries; it was based on an average of 12 studies in the Atlantic Coast domain. In the aggregate, US Atlantic Coast estuaries were found to be net heterotrophic, with net ecosystem production (NEP) equal to -1.5 Tg C yr^{-1}. The loss of estuarine organic carbon to burial was 0.5 Tg C yr^{-1} and export to the ocean, determined by difference, was the largest loss term at 3.4 Tg C yr^{-1}. The SAB was found to dominate all budget terms except burial, which occurred mainly in the MAB (Fig. 1b).

Kroeger et al. (2012) used information on tidal wetland surface area from the National Wetland Inventory and reported estimates of tidal carbon fluxes to estuaries along the Atlantic coast (e.g., Cai et al 2011; Tzortziou et al. 2008; Wang and Cai 2004) to calculate lateral export from tidal wetlands to estuaries and the ocean of 2 Tg C y^{-1} of DIC and 2–6 Tg C y^{-1} of DOC.

Estimation of air-water fluxes has also improved since the 2012 workshop. Signorini et al. (2013) developed a remote sensing approach for estimating air-sea exchange of CO_2 for the Atlantic Coast domain and found that shelf waters take up 4 Tg C yr^{-1} of CO_2 from the atmosphere. Laruelle et al. (2015) estimated that the estuaries from Cape Hatteras to Nova Scotia (which are dominated by the MAB) outgas 0.8 ± 0.5 Tg C yr^{-1} of CO_2. However, as the authors note, this estimate is very poorly constrained because it is based on estimates from only seven estuaries and does not include flux estimates from the largest two estuaries, Chesapeake and Delaware Bays.

Although the carbon budget for the Atlantic Coast is well developed compared to other regions, there are still very large gaps, particularly for the following fluxes:

- *Lateral advective exchanges.* The fluxes from tidal wetlands to estuaries, from estuaries to the coastal ocean, and from the coastal ocean to the open ocean (i.e., the cross-shelf flux) are all very poorly quantified. For the Atlantic Coast domain, the current estimate of the wetland-estuary flux is based on an arithmetic average of a limited number of field estimates. Furthermore, only the organic carbon portion of this flux term has been estimated in the peer-reviewed literature. The carbon flux from tidal wetlands to estuaries is of extreme importance because it quantifies potential losses and fates of tidal wetland carbon in a changing environment, which has policy implications as scientists are called upon to quantify the sequestration capacity of tidal wetlands (i.e., blue carbon). The estuary-ocean organic carbon flux for the whole Atlantic Coast domain was estimated as a residual term in the estuarine organic carbon budget (Herrmann et al., 2015). Direct estimates of this flux and its inorganic counterpart are needed. Finally, the cross-shelf flux term is potentially large, of order 10 Tg C yr^{-1}, but is very poorly constrained. There are only a few published estimates based on tracer distributions. Numerical models coupled with observations (e.g., from cruises, satellites, and the Ocean Observatories Initiative) provide a potential pathway for estimating this difficult-to-constrain flux. Reoccupation of sections surveyed during the Ocean Margins Program could provide additional insights. Constraining the water and salt budgets in collaboration with physical oceanographers is likely to be an essential first step in determining the cross-shelf carbon flux.

- *Respiration*. There are very few respiration data and hence this flux term needs to be better constrained, particularly in continental shelf waters, where the integrated respiration is very large (likely comparable to primary production, which is of order 100 Tg C yr^{-1}). Additional respiration measurements are urgently needed; such measurements should be made in concert with primary production in order to determine NEP. The relative contributions of benthic and water-column processes to respiration also need to be determined.

- *Estuarine exchange with the atmosphere*. It is likely that tidal wetlands remove CO_2 from the atmosphere and estuaries outgas CO_2, but the fluxes are essentially unknown due to limited direct observations. There are only two wetland sites (flux towers) in the Atlantic Coast domain (one mangrove and one salt marsh) that have reported CO_2 fluxes (using the eddy covariance method) in the published literature. There are a few other flux towers collecting data. Methods need to be developed to extrapolate the limited measurements to the whole Atlantic Coast domain. Similarly, the surface-water pCO_2 data needed to determine estuarine outgassing of CO_2 are very limited.

- *Benthic primary production*. Submerged grasses and benthic algae contribute to the carbon balance of coastal waters by removing CO_2 from water, but the overall importance of this budget term is not known, except in selected regions. As in the Gulf of Mexico, submerged grass beds are poorly mapped, except in selected

areas. Partnerships with state natural resource agencies may present opportunities for improved mapping coverage.

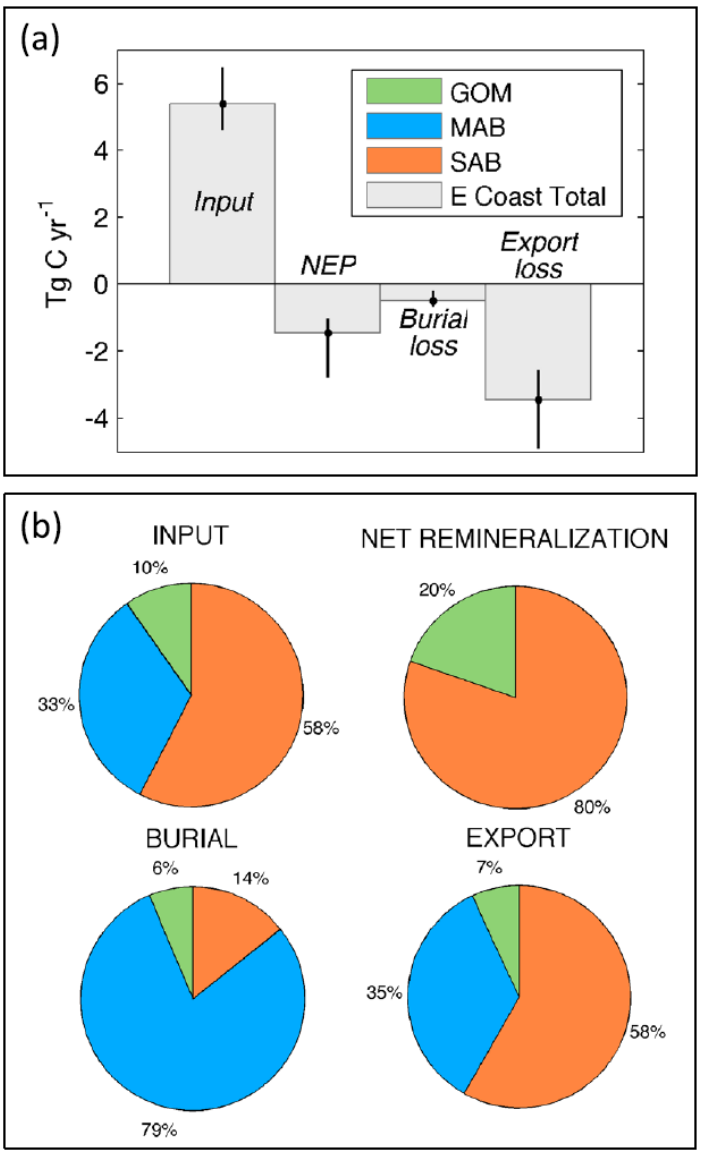

Figure 1 (a) Area-integrated organic carbon budget for estuaries of the US Atlantic Coast. Organic carbon fluxes are shown as the best estimate (bars) and the 95% confidence intervals (whiskers). The burial and export terms are shown as negative numbers to emphasize that these fluxes represent loss of organic carbon from the estuaries. **(b)** Relative contribution of the subregions to the total area-integrated US Atlantic Coast fluxes; note that the MAB does not contribute to net remineralization because the best estimate for the NEP flux is positive (net autotrophic). Reproduced from Herrmann et al. (2015).

- *Tidal wetlands and estuaries*. The dominance of tidal wetlands and estuaries in the Atlantic Coast region presents a challenge because of the large number and great diversity of these wetland-estuary systems. It will simply be too expensive and time consuming to measure all of the relevant carbon fluxes in each of these systems. One strategy for addressing this challenge would be to choose a small number (~5-10) of these systems that cover the relevant parameter space (wetland area, seagrass area, tidal range, stratification, geomorphology, temperature, etc.). System selection could also be dictated by existing infrastructure and knowledge base or by measures of rapid change (e.g., losses of wetland carbon to sea-level rise and development). In each of these systems, teams of investigators would quantify all of the relevant fluxes, including their variability. For robust comparisons among systems, it will be important to establish measurement protocols, calibration procedures, data formats, etc., similar to other successful large marine biogeochemical field programs (e.g., JGOFS and GEOTRACES). A hierarchy of models, evaluated and calibrated with the rich data sets collected, would then be developed to describe these systems. The models would range from statistical to fully mechanistic and could be applied to a much larger group of estuaries than the initial set and thereby be used to constrain processes and budgets for large coastal regions.

In addition to gaps in processes and fluxes, there is a regional gap in the North American coastal carbon synthesis: Eastern Canada. From an oceanographic perspective, it makes sense for the Atlantic Coast domain to extend further north, at least to Newfoundland, so as to include Scotian Shelf, the Gulf of St. Lawrence, and the tidal portion of the St. Lawrence River. Collaborations with Canadian scientists to extend coastal carbon synthesis efforts to this region would be a welcome advance.

Pacific Coast

Regional Setting

The Pacific Coast is the longest coastline on the North American continental margin, extending from Panama to the Aleutian archipelago. As such, the coastline ranges from tropical to subarctic ocean climate zones (~7–60°N) and spans nearly 12,000 km and roughly 87° of longitude (or the equivalent of seven time zones). Not surprisingly, carbon cycle drivers vary substantially along this continental margin. The western continental shelf of North America can be divided into sub-regions on the basis of the dominant oceanographic, climatic, and geomorphic drivers of coastal biogeochemical dynamics for the purpose of synthesizing carbon cycle science knowledge and needs (Fig. 2, Table 1).

The southernmost of the Pacific coast sub-regions is the Central American Isthmus (CAI), which ranges from Panama to the southern tip of Baja California. The Pacific coast of the CAI experiences intense, persistent wind events, large eddies, and high waves, which combine to produce upwelling and strong near-shore mixing. In addition to alongshore winds, passes in the Central American cordillera allow the formation of

strong seasonal wind jets that create upwelling hotspots and drive production during boreal winter months in the Gulfs of Tehuantepec, Papagayo, and Panama (Chelton et al., 2000). The major surface current in this sub-region is the North Equatorial Counter Current, which transports surface water from the West Pacific warm pool to the cooler eastern Pacific and is stronger during El Niño events. The least is known about coastal carbon cycling in the CAI relative to other sub-regions, and we are not aware of any high-resolution coastal biogeochemical models that cover this sub-region.

The California Current System (CCS) extends from the southern end of Baja California to the northern end of Vancouver Island, in British Columbia. Many strong physical gradients exist along the CCS, and the major carbon cycle fluxes are expected to vary accordingly. As the most is known about carbon cycling in the central part of the Pacific North American coastline, we were able to subdivide the region further (Table 1). The southern California Current System (SCCS) extends from southern Baja California north to Point Conception, the central California Current System (CCCS) spans the California coastline from Point Conception to Cape Mendocino, and the northern California Current System (NCCS) runs from Cape Mendocino north to the end of Vancouver Island.

Table 1. Physical factors controlling carbon cycle fluxes within each of the sub-regions of the North American Pacific coast. The number of diamonds in each process or pattern box scales with the relative strength or consistency of this driver within that sub-region. Up arrows indicate upwelling dominated systems, and down arrows indicate downwelling-dominated systems. *Red symbols indicate that this factor is not particularly well known.*

		Oceanographic factors			*Geomorphic factors*			*Climatic factors*	
Region	Latitude range (°N)	Major current	Vertical circulation	Eddies	Shelf width	Shoreline complexity	Tidal mixing	Freshwater inputs	Winter storms
Central American Isthmus	7–22.8	North Equatorial Counter Current	↑	◆◆◆	◆	◆	?	◆	?
Southern California Current System	22.8–34.4	California Current	↑	◆◆◆	◆	◆◆	◆	◆	?
Central California Current System	34.4–40.3	California Current	↑↑	◆◆	◆	◆	◆	◆◆	◆◆
Northern California Current System	40.3–50.8	California Current	↑	◆	◆◆	◆◆	◆◆	◆◆◆	◆◆
Gulf of Alaska	50.8–60.3	Alaska Current	↓	◆◆◆	◆◆◆	◆◆◆	◆◆◆	◆◆◆◆	◆◆◆

In the SCCS, the continental shelf is so narrow that upwelling filaments often spill over onto the water column seaward of the shelf break, such that coastal processes influence carbon cycling well past the shelf region and over continental slope and bathyal habitats. Upwelling persists year round due to continually favorable wind forcing. Riverine input of freshwater, carbon, and nutrients is minimal and highly episodic. Eddy formation during summer months in the Southern California Bight can serve as an important pathway by which nutrient- and CO_2-rich and O_2-poor waters are brought toward the surface. Islands and deep basins throughout the Southern California Bight make for complex circulation throughout this northern part of the SCCS.

The CCCS has the strongest and most consistent wind-driven upwelling during the upwelling season (May−October). The continental shelf widens to the north within the CCCS, but remains narrow relative to more northerly margins. Freshwater input follows a similar pattern, with a few moderately sized rivers draining into the central part of the CCCS watershed (Salinas, San Joaquin, and Sacramento rivers) and a few small

mountainous rivers (SMRs) with episodic discharge throughout the rest of the domain associated with winter rain events. The biogeochemical importance of eddy formation is

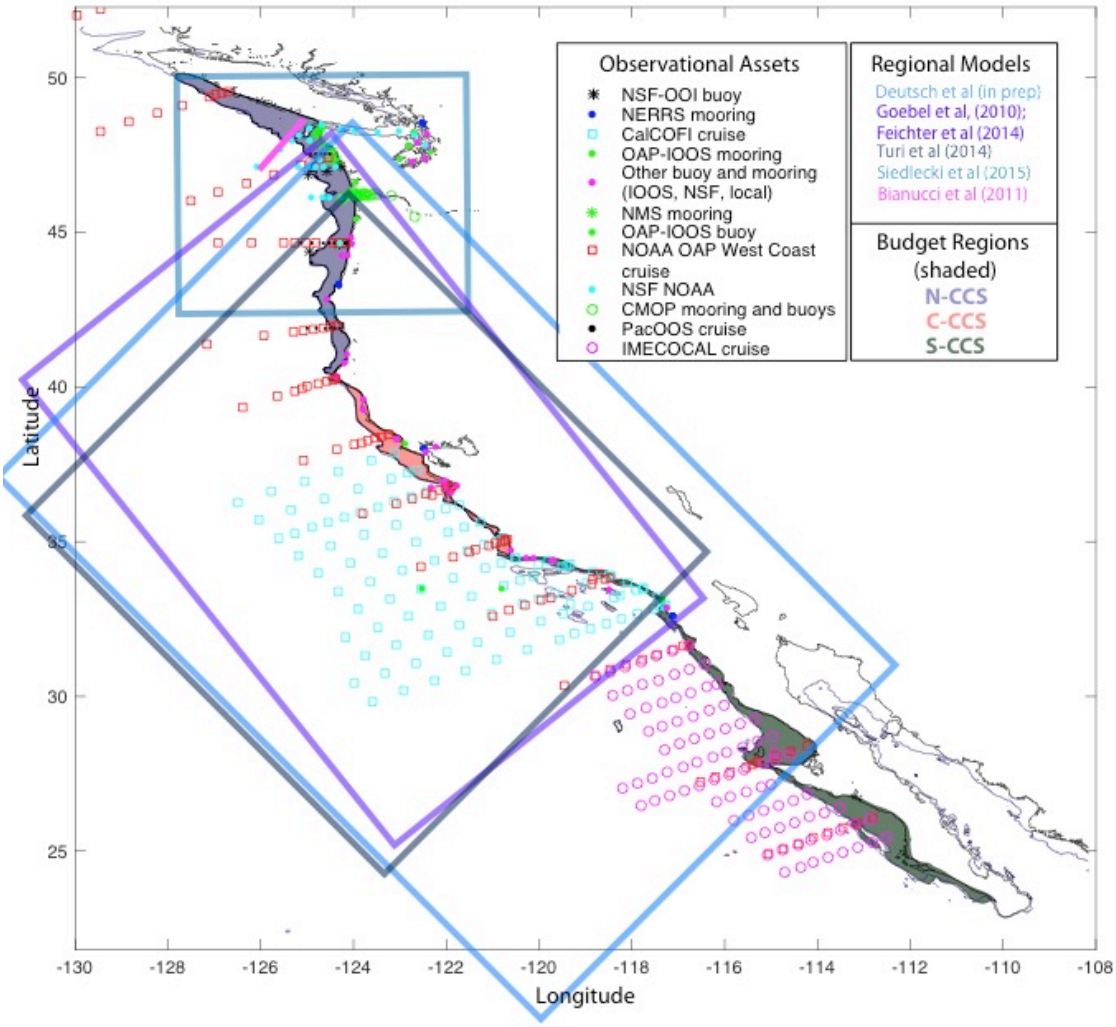

Figure 2. The California Current System (CCS) was divided into three budget regions defined on the basis of several environmental drivers described within the text: The Northern CCS (NCCS, purple shading), the Central CCS (CCCS, pink shading), and the Southern CCS (SCCS, green shading). The 200 m isobath outlines each region showcasing the variability in shelf size along the coast. In addition to the sub-regions, the observational assets and regional models are identified for the CCS. Note the regional model domains may extend further offshore in some cases than could be represented here.

lower in the CCCS than the SCCS, but filaments can be an important pathway for the offshore transport of coastal carbon and nutrients.

The NCCS has the broadest shelves, the lowest influence of eddies, and the highest input of freshwater within the CCS. Upwelling also occurs from late spring through early fall in the NCCS but is more episodic than in the CCCS, and downwelling conditions can

occur in winter during poleward winds. Freshwater inputs are numerous, ranging from the Columbia and Fraser rivers to the combined rivers of Puget Sound. In addition to the influence of upwelling, the freshwater input from these large-volume sources can affect the magnitude and variability of carbon cycle fluxes across a wide area, both directly via freshwater inputs of carbon and nutrients and indirectly via freshwater influence on stratification and coastal circulation. The small mountainous rivers lining the NCCS coastline are less important for stratification due to freshwater input or dissolved carbon and nutrients but provide a sizeable sediment delivery, with as much as half of the particulate organic carbon on the West Coast being delivered to the coastal ocean by SMRs, largely in association with storm events. The wide continental shelves also play an important role in coastal carbon cycling in that sinking organic matter gets trapped on the shelf and respires *in situ*, contributing to the on-shelf production of dissolved CO_2 and recycled nutrients, but also drawing down shelf oxygen supply, which can affect the biota, as well as biogeochemical reactions at low O_2 concentrations.

Finally, the Gulf of Alaska (GAK) encompasses the coastline from the northern end of Vancouver Island to the Aleutian Archipelago. The GAK contains the widest shelves on the coastline, is a downwelling-dominated coastal region, and is characterized by strong seasonality typical of high latitudes. Rivers, snowpack and glacier melt combine with strong seasonal precipitation and insolation changes to alter the stratification and circulation of the region, and provide significant inputs of sediment and terrestrial carbon and nutrients. Tidal transport and large eddy features dominate the exchange with the open ocean in this region.

Synthesis Findings and Remaining Gaps

The Pacific coast of North America is a global hotspot for ocean carbon cycle change and its impacts on marine ecosystems (e.g., ocean acidification and hypoxia), making it a natural laboratory for studying these processes.

Since the North American Continental Margins report (Hales et al., 2008), several key advancements in our understanding of the CCS coastal carbon cycle have emerged. For example, air-sea flux estimates from models and observations are converging (Hales et al., 2012; Fiechter et al., 2014; Turi et al., 2014). This accomplishment highlights that coastal carbon cycle models are becoming sufficiently sophisticated to directly evaluate with observations. This accomplishment also reflects the major increase in observations of surface seawater and atmospheric pCO_2 at sufficient temporal and spatial resolution to generate improved empirical air-sea flux estimates to compare to model results. For other coastal carbon fluxes, we are starting to have enough carbon observations along the CCS for initial syntheses of spatial and seasonal to interannual variability. Key examples include California Cooperative Oceanic Fisheries Investigations (CalCOFI) (since the mid-2000s when the suite of carbon cycle-relevant measurements expanded), Investigaciones Mexicanas de la Corriente de California (IMECOCAL), Oregon coastal work since 2001, moored pCO_2 time-series, and NOAA coastal carbon cruises.

However, uncertainties in a few key fluxes result in significant gaps in our understanding. Those fluxes include:

- **Primary Production**. Based on satellite observations, the NCCS is more productive than the SCCS. However, the lack of consensus amongst the various methods employed to measure net primary production (NPP) (^{14}C, satellite algorithms, ^{15}N) generates uncertainty in the magnitude of this important flux. In addition, some sub-regions (SCCS) have more observations than others. All Pacific Coast sub-regions would benefit from greater seasonal and spatial coverage of primary production measurements. Net community production estimates based on geochemical budgets could be generated without measurements of NPP and prove useful for carbon budgets. Few such estimates exist because they require extensive physical observations to constrain the geochemical budgets (Hales et al., 2006; Messié et al., 2009; Munro et al., 2013).
- **Respiration**. Respiration estimates from observations are rare, except in the NCCS. These could be used in combination with NPP measurements to calculate NCP or compare with observations of NCP. In addition, differentiating the relative contributions of water column, benthic, and within-sediment respiration is important for understanding the fate of organic carbon produced on and delivered to these productive margins, as well as for understanding the development and severity of hypoxia and ocean acidification.
- **Estuarine exchange**. Rivers transport a substantial amount of POC, DOC, and DIC to the coastal ocean, but the fate of terrestrial material within estuaries that govern that boundary is largely unconstrained and interannual variability in these fluxes can be large. Most large rivers have been monitored for decades, but small mountainous rivers can provide large fluxes in short, ephemeral events (Goñi et al., 2013).

The uncertainty surrounding those fluxes provide the basis for following future research priorities:

- **Carbon flux measurements from Gulf of Alaska and Central American Isthmus sub-regions**. There is both a dearth of observations and a lower level of development of coupled physical-biogeochemical models of sufficient resolution to provide robust regional estimates of most coastal carbon fluxes and their variability in space and time in both the Gulf of Alaska and the Central American Isthmus sub-regions.
- **Across the full Pacific coast, better constraint on water column metabolism is needed**. Solid observation-based estimates for how much production and respiration occur in Pacific coastal systems and where the net community production ends up do not exist for most areas; where estimates do exist, they may be in sufficiently different form as to make intercomparison difficult. These gaps hamper our ability to compare observed and model-based estimates of metabolism in the present day, as well as our ability to project the likely impacts of changing environmental drivers such as upwelling and river inputs on carbon cycle fluxes. This is critical for understanding the processes driving the development of hypoxic, corrosive, and toxic (e.g., harmful algal

blooms) conditions along this coastline.

- **Winter measurements**. In the CCS, winter storm events play a critical role in priming the system for growing-season production, respiration, and the development of physiologically stressful ecosystem conditions through the upwelling season.
- **Lateral fluxes**. Both estuary-to-coast and coast-to-open ocean fluxes are critical to understanding the above processes and impacts. While models provide a means to help constrain these fluxes and should be applied to this end, there is also a need for better observational constraints.

We offer below a few specific considerations on ways to improve our understanding of coastal carbon cycling and likely trajectories of change under future scenarios.

- **Further mining and synthesis of existing/ongoing long-term data sets**. Existing time-series programs such as CalCOFI and IMECOCAL provide excellent targets for further mining and synthesis work.
- **Improve linkages between offshore and nearshore observations**. These often fall under different research programs, but understanding linkages across the shelf is critical with respect to understanding and projecting major coastal carbon cycle impacts (ocean acidification, hypoxia, etc.).
- **Event-scale observations are important**. Substantial transport of carbon from land to coastal oceans occurs during storm events, but these events are poorly constrained by observations as conditions during storms make field observations particularly challenging. Leveraging existing and planned OOI and other autonomous infrastructure is critical for facilitating these observations.
- **Quantify accumulation or loss of carbon in estuaries, tidal marshes, and other 'blue carbon' systems**. The currently funded projects led by Najjar and Windham-Myers that are mentioned in the Gulf of Mexico section will also contribute new understanding and identify remaining gaps for Pacific Coast estuaries and tidal marshes.
- **Use models to give context to and integrate across datasets in space and time**. Models, when well validated with available observations, offer a platform with which to understand lateral transport, the interactions between biogeochemistry and circulation, and the impacts of extreme events.

Arctic

Regional Setting

As a result of increases in atmospheric carbon dioxide and other greenhouse gases, the Arctic Basin (AB, Figure 3) is predicted to be sea ice free during summer as early as 2020 and as late as 2080, with the range depending on large-scale climate drivers that are not well understood. Arctic temperatures over the last decade have increased at least three times the rate of mid-latitudes relative to temperatures at the end of the 20th century. Multiple interacting feedbacks are a hypothesized cause for this Arctic amplification and much of the current uncertainty in projected change. Climate feedbacks involving ocean

circulation, sea ice dynamics, cloud processes, rising greenhouse gas levels, and atmospheric dynamics act on a regional basis and their non-linear interactions are not well captured in climate models. Accordingly, there is wide scatter in sea ice forecasts on multiple time scales leading to gaps in understanding of ocean warming and biogeochemical impacts, such as ocean acidification (OA).

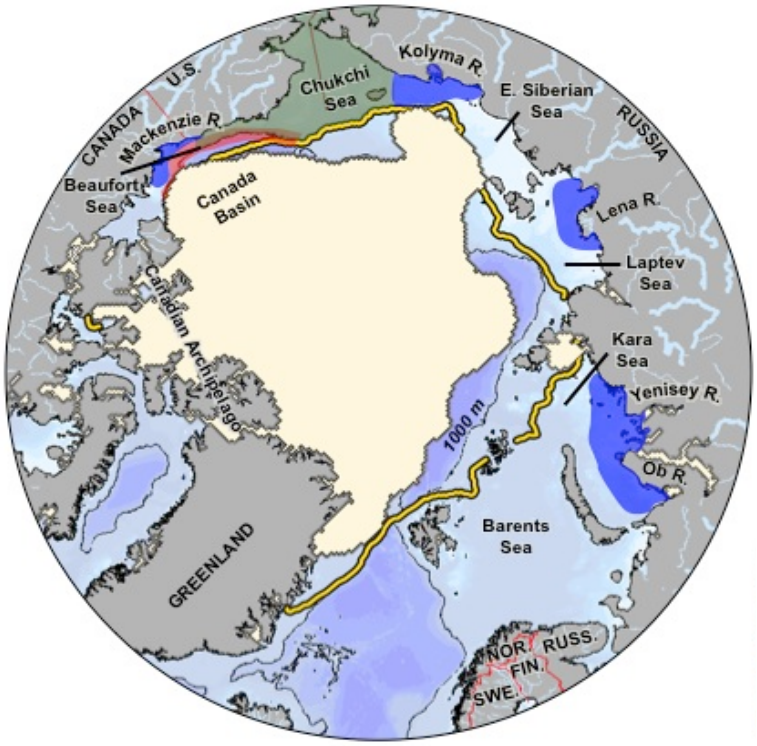

Figure 3. Map of the Arctic Basin (AB). September 2014 ice extent is shaded in light yellow and the mean September ice extent for 1976 to present is marked by a bold dark yellow line. Red, green, and blue shading indicate the influences of upwelling, primary production and respiration, and river discharge, respectively.

Although current seasonal sea-ice cover mitigates some of the potential atmosphere-ocean gas exchange in the Arctic Ocean, the AB still takes up CO_2 on the order of 10 to 200 Tg C yr^{-1} (10^{12} g C), contributing 5–14% to the global balance of CO_2 sinks (Evans et al., 2015). Because of this, the AB could have an important influence on the global carbon cycle. The AB marine carbon cycle and atmosphere-ocean CO_2 exchanges are sensitive to regional and global climate change feedbacks. In the near-term, feedbacks resulting in further sea-ice loss, warming, and increases in phytoplankton growth rates are expected to increase the uptake of CO_2 by AB surface waters. Thus, the capacity of the Arctic Ocean to absorb CO_2 is expected to be highly dynamic in the coming decades as transitions in climate conditions drive environmental changes. These changes are likely to continue to modify the physics, biogeochemistry, and ecology of the continental shelves of the Arctic Ocean and sub-arctic Bering Sea in ways that are not yet fully understood, particularly with respect to OA.

New insights from recent surveys, such as the Russian-American Long-term Census of the Arctic (*RUSALCA*), Impacts of Climate on the Eco-Systems and Chemistry of the Arctic Pacific Environment (*ICESCAPE*), and the Bering Sea Ecosystem Study (*BEST*)) throughout the AB and the Bering Sea have clearly shown that the intrusion of anthropogenic CO_2 is not the only driver of reductions of pH and carbonate mineral

saturation states (Ω) in the region. Several other processes, such as melting sea ice, terrestrial and marine organic matter respiration (Mathis et al., 2011), and upwelling (Mathis et al., 2012) are exacerbating the effects of OA, leading to rapid changes in the marine environment (Mathis et al., 2015). Furthermore, if CO_2 uptake from the atmosphere by the AB increases as predicted, OA will increase there as well. Recent observational data from the AB and Bering Sea were used to predict that the continental shelf seas in the region will become undersaturated with respect to aragonite at approximately 30-year intervals (Beaufort Sea, 2001; Chukchi Sea, 2033; Bering Sea, 2062), indicating that aragonite undersaturation gradually progresses upstream along the flow path of the waters as it moves north from the Pacific Ocean (Mathis et al., 2015).

Naturally high variability in the aragonite saturation state may indicate higher resilience of the Bering Sea ecosystem to ocean acidification conditions compared to the Chukchi and Beaufort Seas. Based on these initial results, the annual mean for aragonite saturation states will pass below the current range of natural variability in 2025 for the Beaufort Sea and 2027 for the Chukchi Sea. Because of the higher range of natural variability, the annual mean for aragonite saturation states for the Bering Sea does not pass out of the natural variability range until 2044. As aragonite saturation in these shelf seas slips below the present-day range of large seasonal variability by mid-century, it could put tremendous pressure on the diverse ecosystems that support some of the largest commercial and subsistence fisheries in the world (Mathis et al., 2015).

Synthesis Findings and Remaining Gaps

Recently, over 600,000 surface seawater CO_2 partial pressure (pCO_2) measurements spanning from 2003 to 2014 were compiled and analyzed, providing the best estimate to date of CO_2 fluxes in the western Arctic Ocean (Evans et al., 2015). Using space-time co-located, reconstructed atmospheric pCO_2 values coupled with the seawater pCO_2 dataset, monthly climatologies of sea-air pCO_2 differences (ΔpCO_2) were created on a 0.2° latitude x 0.5° longitude grid. Sea-air CO_2 fluxes were computed using the ΔpCO_2 grid and gas transfer rates calculated from a climatology of wind speed second moments. Fluxes were calculated with and without the presence of sea ice, treating sea ice as an imperfect barrier to gas exchange. This allowed for carbon uptake by the western Arctic coastal ocean to be assessed under existing and reduced sea ice cover conditions, in which carbon uptake increased 30% over the current 10.9 Tg C yr^{-1} of sea ice-adjusted exchange in the region.

Recent studies of CO_2 fluxes in the Bering Sea (Cross et al., 2014a,b) showed that although the region is a moderate to strong atmospheric CO_2 sink, autumn and winter CO_2 effluxes balanced 65% of spring and summer CO_2 uptake. Ice cover reduced sea-air CO_2 fluxes in December, April, and May. Our estimate for ice cover-corrected fluxes suggests that mechanical inhibition of CO_2 flux by sea ice cover has only a small impact on the annual flux (<2%). An important data gap still exists for January to March, the period of peak ice cover and the highest expected retardation of the fluxes. By interpolating between December and April using assumptions of the described autumn

and winter conditions, it was estimated that the Bering Sea shelf area is an annual CO_2 sink of ~6.8 Tg C yr^{-1}.

Although considerable progress has been made in the past few years to constrain both CO_2 fluxes and ocean acidification, most of the measurements that these studies are based on are both temporally and spatially biased. There are virtually no wintertime observations, and biogeochemical conditions when sea ice cover is in place are largely unknown. The lack of wintertime observations in the Arctic and Bering Sea represents the largest data gap. There is also a severe lack of high-resolution spatial data. Both of these gaps can be overcome through the use of autonomous platforms. Moorings that can track CO_2 fluxes and ocean acidification parameters should be deployed year-round in the Arctic. In open-water months, new remotely piloted vehicles that can cover significantly more area than research vessels should become the backbone of Arctic and Bering Sea observing networks.

Laurentian Great Lakes

Regional Setting

The Laurentian Great Lakes (LGL) is the largest freshwater system on Earth, containing 18% of the global liquid surficial freshwater and 84% of North America's. This freshwater "Third Coast" is a vital resource for the region's 34 million residents, supporting tourism, shipping, fishing and other industries that create 1.5 million jobs and $62 billion in annual wages (Vaccaro and Read, 2011). Varying size and depth leads to water residence times from 2.6 to 174 years (Table 2). Biogeochemical differences among the lakes are large. For example, Table 2 shows that mean alkalinity varies by more than a factor of two among the lakes, which is largely a reflection of different geologic settings (Chapra et al., 2012). Consistent with their huge economic impact, the LGL have a long history of anthropogenic impacts followed by remediation and degrees of recovery. At present, the Lakes are all subject to an array of ecological and physical stressors, including invasive species, eutrophication, and climate change (Lehman, 2002; Allan et al., 2013).

At the lake-wide scale, there is a dearth of knowledge with respect to carbon cycling and associated biogeochemistry (McKinley et al., 2011; Sterner, 2010; Allan et al., 2013). Biogeochemical studies in the LGL have left many gaps in knowledge about basic parameters. This situation is particularly acute from the standpoint of dissolved inorganic carbon (DIC), pCO_2, and pH. Observations of DIC are sparse (Zigah et al., 2011), and high-quality pH measurements from the most accurate, state-of-the-art sensors are lacking. Gridded datasets for DIC, alkalinity, nutrients, and physical properties do not exist. Since 2008, pCO_2 data have been collected on a vessel of opportunity, the Lake Michigan ferry (*Lake Express*, Bootsma et al., in prep.), which represents the only multi-year effort to record this parameter in the LGL. Ice cover is prevalent in winter and thus wintertime data are essentially non-existent. Satellite algorithms for biogeochemistry have only recently been developed (Mouw et al., 2013). The overall lack of understanding of the carbon cycle and related biogeochemical processes is of particular

concern in light of the desire to better manage the lakes so that they can continue to sustainably support ecosystems and economies in the face of the many anthropogenic stressors (Great Lakes Restoration Initiative 2010, http://greatlakesrestoration.us/pdfs/glri_actionplan.pdf), including ocean acidification (NOAA, 2010, Phillips et al., 2015).

Despite the lack of observations, modeling, and synthesis on the carbon cycle in the LGL, it is quite certain that large changes in carbon cycling and related biogeochemistry have occurred in all of the LGL over the past few decades. Successful management of phosphorus inputs has decreased primary production (PP) in the open waters of all of the lakes (e.g., Chapra et al., 2012; Mida et al., 2010; Bunnell et al., 2014). Nitrate has risen in response to atmospheric deposition, as well as in-lake cycling (e.g., Sterner et al. 2007; Chapra et al., 2012). Reductions in phosphorus inputs have also been linked to increases in nitrate (Finlay et al., 2013). The invasive *Dreissenid* mussels have caused measurable drops in calcium and alkalinity due to shell burial in Lakes Erie and Michigan (Barbiero et al., 2012). A complex interplay of climate change, agricultural practices, and invasive species is thought to be responsible for the re-eutrophication of Lake Erie and associated increases in the extent of hypoxia (e.g., Kane et al., 2014; Zhou et al., 2013). Large shifts in food webs have occurred concomitantly, including increasing occurrences of harmful algal blooms (Michalak et al., 2013), large changes in zooplankton abundance and composition (Barbiero et al., 2009), and major changes in the relative abundance of commercially important fish species (e.g., Bunnell et al., 2009; Pothoven et al., 2001; Claramunt et al., 2007). Since the mid-2000s, there has been a dramatic increase in the concentration of energy and biomass in the nearshore, primarily in the form of *Dreissenid* mussels (Nalepa et al. 2009) and the filamentous green alga, *Cladophora* sp. (Bootsma et al., 2005; Auer et al., 2010), both of which are benthic.

Synthesis Findings and Remaining Gaps

Of the five Great Lakes, the carbon cycle for Lake Superior is the best understood. Compilation of sparse observations and numerical modeling supports the conclusion that lake-average pCO_2 is only slightly elevated above atmospheric pCO_2 due to riverine carbon inputs (Atilla et al., 2011; Bennington et al., 2012). Besides the respiration of these allochthonous inputs in the nearshore zone, the long-term pCO_2 of Lake Superior is dominantly set by equilibration with the atmosphere. A summary of the few published estimates of autochthonous and allochthonous carbon fluxes also suggests that Lake Superior, as well as Lakes Michigan and Huron, are slight CO_2 sources and that Lakes Erie and Ontario are slight CO_2 sinks (McKinley et al., 2011). Lakes Erie and Ontario are likely to be sinks due to their higher productivity and lesser depths, which lead to a larger fraction of primary production being buried (Eadie and Robertson, 1976). Quantitative uncertainty with respect to the magnitude of the fluxes is high, and the net source/sink status of the LGL system is unknown (McKinley et al., 2011). Comparative studies across lakes globally indicate a strong size-dependence in the CO_2 coupling of atmosphere and lakes (Kelly et al., 2001; Kortelainen et al., 2006). In general, larger

lakes have surface waters closer to atmospheric equilibrium due to the lesser importance of allochthonous organic matter to integrated carbon budgets (Kankaala et al., 2013).

Multiple groups have developed numerical models for the LGL. These models range from historical water quality management models without physical dynamics (Chapra, 1977) to advanced three-dimensional physical models (Bai et al., 2013). Many three-dimensional models are only presently set up for physical simulations, while others include biogeochemistry (Chen et al., 2004; Pauer et al., 2011) and carbon cycling (Bennington et al., 2012, Pilcher et al., 2015). Given the vast differences among the LGL, it is common that models are set up independently for each lake. A partial inventory of models is available at http://glos.us/data-tools/great-lakes-model-inventory. Given the size and physical complexity of the lakes, integration of three-dimensional physical-biogeochemical-carbon cycle models with observational efforts is a promising path forward. The existing three-dimensional physical models for each LGL are likely the appropriate starting points for development of fully coupled biogeochemical-carbon modeling systems. The observational priorities identified below have been selected, in part, because they will be valuable for the parameterization and evaluation of numerical models.

To move forward on constraining the carbon cycle of the Laurentian Great Lakes, priorities are to

- Constrain inorganic carbon budgets
- Constrain organic carbon budgets
- Understand winter processes
- Constrain key biogeochemical rates
- Use these data to constrain models and refine satellite algorithms

Specific observational priorities for each of the five lakes include:

- Inorganic carbon
    - Underway (R/V, VOS) and moored pCO_2 and pH
    - High-quality DIC and alkalinity
    - Air-lake CO_2 flux
    - Reassessment of freshwater carbonate chemistry constants. The community uses Millero (1979). Seawater constants have been fit and refit multiple times to improve.
- Organic carbon: DOC and POC
- Key biogeochemical rates
    - PP spatio-temporal distribution
    - Respiratory quotients
    - Growth efficiencies
- Winter observations
- Data to support satellite algorithm development (CDOM, Chl, PP, optics)

With respect to existing infrastructure or observational programs in 2015 that may provide opportunities for augmentation to increase carbon cycle understanding:

- For air-lake CO_2 flux
    - Augment the existing towers of the Great Lakes Evaporation Network (GLEN)
    - Co-locate in-water pCO_2 observations
- NOAA National Buoy Data Center (NBDC) moorings for meteorology and surface lake physics could be augmented with pCO_2 and pH sensors
- Gliders in Lake Superior (LLO) and Lake Michigan (GLOS) – O_2 observations could help to constrain PP and respiration, including in winter
- Bi-annual EPA monitoring to all 5 LGL; sampling and analysis methods could be enhanced
- Data mining
    - Municipal drinking water intakes

Table 2. Physical and carbon biogeochemistry characteristics of the Laurentian Great Lakes

Lake	Surface Area (m^2 x 10^{10})[a]	Water Residence (yr)[a]	Mean [max] depth (m)[a]	Temp. (°C)[a]	Spring/ summer alkalinity (µmol/kg)[b]	Spring/ summer Ca^{2+} (µmol/kg) 2009[c]	$[CO_3^{=}]$ (µmol/kg) 2009[d]	Ω_{Arag} 2009[d]
Superior	8.21	174	149[406]	5.4±4.8	840	340	2.73	0.15
Michigan	5.78	104	85 [282]	7.1±6.7	2181	897	20.0	2.92
Huron	5.96	21	59 [229]	6.7±6.7	1561	659	10.1	1.08
Erie	2.57	2.6	19 [64]	11.3±9.0	1817	801	14.2	1.93
Ontario	1.90	7.3	86 [244]	7.8±7.2	1836	836	15.1	2.07

a. NOAA Ocean and Great Lakes Acidification Research Plan (2010) Tables 7.1, 7.2
b. US EPA GLENDA database
c. Chapra et al. 2012
d. Assumes $pCO_2^{lake} = pCO_2^{atmosphere}$ and an A2 concentration pathway as shown for pH in Figure 2
e. Calculation assumes Ca^{2+} unchanged from 2009

Fluxes and Processes

Terrestrial Inputs

Rivers

The major flux of carbon from land to ocean is carried by river networks. Stream monitoring data are available for some rivers from the United States Geological Survey (USGS) National Water-Quality Assessment Program (NAWQA) and National Stream Quality Accounting Network (NASQAN). Records are far from providing a complete picture of carbon inputs to coastal water, but much progress has been made using multiple modeling approaches to scale monitoring data over space and time.

There are currently four models providing published estimates of carbon delivered to river networks and to coastal regions. The *LOADEST* (Load Estimator) model is designed to quantify riverine loads of various water quality constituents, and has been used to estimate loadings of forms of carbon observed at USGS gauging stations where data on

streamflow and carbon concentrations are measured routinely. One challenge with this approach is that many of the USGS monitoring stations are located inland from the coasts, often with the closest gauges situated above the fall line where rivers are not tidally influenced. To scale from monitoring stations to unmonitored locations and to coastal waters, three models have been applied over large portions of North America. The *Global NEWS* (Nutrient Export from Watersheds) tool is a statistical model designed to forecast coastal eutrophication in various large marine ecosystems around the world. The *SPARROW* (Spatially Referenced Regression on Watershed Attributes) water quality model is a hybrid empirical and mechanistic model that integrates monitoring data and describes the location of nutrient sources and the watershed factors that affect delivery of carbon to streams and coastal waters (e.g., land use, permeability, climatic variability), proving estimates of annual carbon loads for river networks. The *DLEM* (Dynamic Land Ecosystem Model) model is a process-based terrestrial ecosystem model, which includes driving factors (climate, atmospheric composition, land use and disturbances), as well as controlling factors (soil, geomorphology, river network properties, land cover, land use), providing estimates of daily and annual loadings to river networks.

While some of the advances in estimating delivery of carbon to coastal waters is attributed to the CCARS activities, additional impetus was generated by the 2007 Energy Independence and Security Act, Section 712, which mandated that the Department of Interior conduct an assessment of carbon storage, carbon sequestration, and fluxes of major greenhouse gases in and out of ecosystems across the US. This effort has been led by the USGS, which initiated the LandCarbon Program for estimation of carbon flux and sequestration for all major terrestrial and aquatic ecosystems. The end result of agency and academic efforts in the past seven years is the development of the first estimates of lateral fluxes of carbon from the terrestrial landscape to coastal waters for the entire nation, with the exception of Alaska, which is under development and near completion, with contributions from some CCARS participants.

The fact that these models have been developed to represent varying time frames (e.g., long-term, decadal, or contemporary) and to represent varying spatial locations (e.g., entire regions or specific water bodies) makes a comparison of published model outputs challenging. Estimates for all forms of carbon are available for all regions, though not from all of the models. Work is underway to re-express the output from the models to common geographic watershed areas that are a better match for the five regions stipulated by CCARS. The fact that the models require a significant amount of information about the physical and chemical properties of the watershed to estimate fluxes means that dominant controlling processes such as land use and climate are also well understood at this time.

High priorities for future research

- Continued and/or new monitoring sites: Declines in funding for monitoring of streamflow and water quality constituents at USGS gauging stations are a large concern. For example, USGS monitoring sites that have adequate data for estimating loads of total organic carbon are continuing to decrease, with a

reduction from 1467 to 366 sites between 1990 and 2004. Sites located downstream of tidal influence are also needed for better estimates of the amount of streamflow and carbon actually entering the coastal zone.

- Improved flux estimates of all forms of carbon (e.g., organic and inorganic) and elements other than carbon (e.g., predictions for nitrogen and sediment export suggest both of these will increase in future years, leading to harmful algal blooms, hypoxia, coastal acidification, and potentially increased carbon sequestration in coastal areas)
- Improved understanding of the fluxes and dynamics of dissolved organic matter in coastal regions and the interplay of microbial and photochemical processes that transform organic matter during transport from land to ocean
- Improved understanding of sources, quality, and seasonal variability of riverine carbon loadings
- Better representation in lateral flux models of the influence of tidal and upland wetlands on river carbon fluxes
- Integration of transport, biogeochemical, multi-element, multi-scale models based on improved understanding of controlling mechanisms
- Better integration of remotely sensed data, in part using existing data, which requires new algorithms in both catchment and coastal regions, but also development of new modeling frameworks that are capable of direct assimilation of remote sensing data into models

Groundwater

Submarine groundwater discharge (SGD) is a potentially important source of carbon to coastal waters, particularly in continental margin settings of the east and Gulf of Mexico coasts, but remains poorly quantified. SGD is defined as all fluid discharged from benthic sediments into coastal water bodies and describes submarine inflows of carbon via fresh and marine waters. Terrestrial SGD delivers freshwater, carbon, and nutrients laterally to the coastal zone and can be estimated using: 1) the measured discharge from a coastal aquifer, and 2) the measured average carbon (organic and inorganic) concentrations of the terrestrial groundwater source. Globally, terrestrial SGD represents a significant flux to the coastal zone, with estimates in the range of 5-10% of river discharge (Burnett et al., 2003). Marine SGD consists of seawater recirculated into and out of the seabed and typically requires the use of radionuclide tracers to constrain fluxes.

Key controls on SGD carbon fluxes include climate; hydrogeology (aquifer composition, hydraulic gradients, etc.); redox gradients and microbial communities; and mixing, tidal pumping, waves, and sea level differences. Only in the last decade have reliable measurement techniques become available to help quantify flows of and associated material fluxes from SGD and also to fingerprint and quantify relative contributions of marine vs. terrestrial SGD to coastal waters. However, SGD data are sparse and carbon fluxes tend to be highly variable across coastal aquifers in different geologic settings, making it difficult to scale site-specific studies to regional scales. For example, in a literature-based synthesis for the Gulf of Mexico (Smith and Cherrier, 2014), SGD estimates were limited to only the Florida and Louisiana shelf regions, and associated

organic (inorganic) carbon flux estimates, further limited to the Florida shelf, ranged over 3-4 (1-2) orders of magnitude.

High priorities for future research

- More routine SGD measurements (volume, carbon forms and concentrations, etc.) in coastal aquifers along most strongly influenced regions of the North American coast (Gulf of Mexico, East Coast) in contrasting geologic settings and ecosystems
- Development of more cost effective, less invasive SGD measurement techniques
- Development of regional SGD databases to assist prediction efforts
- Process studies focused on mixing of SGD with seawater (e.g., tidal mixing) and associated transformations of carbon species
- Further development of coastal aquifer typologies along different coastlines and across different geologic settings and other key characteristics (e.g., carbonate vs. siliciclastic terrains, organic-rich muds vs. organic-poor sands, etc.)
- Models that more effectively integrate biogeochemical and hydrological processes on spatial and temporal scales that constrain estimates of SGD and associated carbon fluxes

Biological Transformations

Depending on how boundaries are defined, coastal margins represent only ~5-10% of the global surface area, yet they are estimated to contribute as much as 10-30% of global primary production (Ryther, 1969; Walsh, 1981; Longhurst et al., 1995; Antoine et al., 1996; Muller-Karger et al., 2005; Dunne et al., 2007), and with as much as half of the globally integrated new production occurring over the continental shelves and slopes (Walsh, 1991; Doney and Hood, 2002; Jahnke 2010). Dunne et al. (2007) estimated that those portions of the continental shelves less than 50 m in depth account for 2% of the surface area of the global ocean, but as much as 48% of the total organic carbon flux to the seafloor.

In addition to the high productivity, ~900 Tg (i.e., 900 x 10^{12} g) total carbon is delivered annually by rivers to continental margins, of which about 500 Tg is organic carbon (del Giorgio and Duarte, 2002; McKee, 2003; McKee et al., 2004). The fate of this carbon remains unclear, although most of it appears to be recycled (Hedges et al., 1997; Gattuso et al., 1998; Seitzinger et al., 2005; Bianchi, 2011).

Here, we summarize the major biological transformations relevant to coastal carbon cycling and attempt to identify high priorities for future research. Major biological transformations include the following:

1) Primary Production or
2) Respiration (Autotrophic, Heterotrophic, Ecosystem)

3) Net Ecosystem Production, Net Ecosystem Metabolism, or Net Community Production (NEP, NEM, NCP)
4) Vertical Fluxes, Export Production, and New Production
5) Other Transformations:
    a. Secondary Production (grazing, microbial production, DOM production)
    b. DOM utilization, remineralization, degradation, photodegradation
    c. Nutrient transformations (regeneration, nitrification, denitrification, annamox, uptake, new vs. regenerated) (Devol, 2015)

Primary Production

Primary production measurements are some of the most common biological rate measurements made in coastal systems and encompass a wide variety of methods. Primary production measurements are useful for comparisons among different systems as well as in characterizing spatial and temporal patterns within systems. Primary production remains a critically important quantity in characterizing ecosystem function and its relationship to environmental variability, elemental cycling, and community structure. In referring to primary production, it is important to understand how it is defined. A brief summary based on Chapin et al. (2006), Chavez et al. (2011), and Staehr et al. (2012) is given as follows:

- Gross Primary Production (GPP) – total autotrophic conversion of inorganic carbon to organic carbon
- Ecosystem Respiration (R or ER) – total oxidation of organic carbon to inorganic carbon; ER = Autotrophic Respiration (AR) + Heterotrophic Respiration (HR)
- Net Ecosystem Production (NEP) = GPP – ER; NEP is also referred to as Net Community Production and Net Ecosystem Metabolism
- Net Primary Production (NPP) = GPP – AR
- Net Ecosystem Carbon Balance (NECB) – Net accumulation of carbon in a system (negative if carbon is lost)

Estimates of NPP are the most prevalent given that the consensus is that the widely used ^{14}C bottle incubation method (Steeman-Nielsen, 1952) provides an estimate of NPP (Marra, 2002, 2009). Other incubation techniques include the oxygen light-dark bottle method and isotopic approaches (^{18}O, ^{13}C). See Staehr et al. (2012), Chavez et al. (2011), and Peterson (1980) for more information. While discrete estimates exist for many coastal ocean regions, temporal and spatial resolution is generally lacking with the exception of a few sites. An alternative to discrete bottle measurements are open-water or *in situ* methods (Munro et al., 2013; Staehr et al., 2012; Needoba et al., 2012; Quay et al., 2010; Emerson et al., 2008), some of which can provide regional-scale or system-wide estimates and are not subject to the artifacts of containment in an enclosure. However, these methods have other limitations and cannot be applied routinely across systems, particularly in coastal regions.

Discrete estimates can be extrapolated on the basis of bio-optical characterizations of biomass, light absorption, and photosynthesis-irradiance relationships. Such bio-optical approaches have been applied in a variety of studies (e.g., Bidigare et al., 1987, 1992; Morel, 1991; Uitz et al., 2008). Bio-optical approaches can benefit from the use of technology such as optical profilers, autonomous underwater vehicles, and profiling optical floats.

Satellite ocean color estimates of primary production provide a means of extrapolation over larger spatial scales and can provide temporal information (Platt et al., 1991; Behrenfeld and Falkowski, 1997; Carr et al., 2006; Westberry et al., 2008; Friedrichs et al. 2009; Saba et al., 2011; numerous others). Satellite-based approaches rely on bio-optical and empirical relationships of ocean color-derived products to known properties and parameters of primary production. Systematic efforts have been made to evaluate the performance of different ocean color algorithms relative to ^{14}C-based NPP (Campbell et al., 2002; Carr et al., 2006; Friedrichs et al., 2003, 2009). Satellite observations provide a tremendous advantage in extending measurements to regions and times for which other measurements do not exist or are inaccessible. However, there are large uncertainties in such estimates and differences among methods and models (Friedrichs et al., 2009; Saba et al., 2011).

Satellite observations are also valuable in guiding sampling of features that may not be easily detectable or adequately characterized by ship-based operations alone, such as spatially localized or transient phenomena. For example, satellite observations can be used to constrain the influence of river outflows. Satellite observations are also useful in identifying different water mass types with differing optical properties and community composition. Recent efforts have refined satellite bio-optical primary production algorithms by accounting for phytoplankton composition (Claustre et al., 2005; Uitz et al., 2008, 2010).

Despite their advantages, the utility of satellite observations has limitations, particularly in coastal regions, due to cloud and ice cover and land adjacency effects. In addition, algorithms may not perform well in optically complex coastal waters and where the bottom contributes to the measured above-water reflectance. To some extent, these limitations can be addressed through the use of regionally tuned algorithms and use of multiple sensors with differing spatial resolution and temporal coverage (e.g., Werdell et al., 2009; Le et al., 2013; Aurin et al., 2013; Mouw et al. 2013). Continuity of ocean color observations is another concern for the continued future applications of satellite algorithms (NRC, 2011), and such continuity is critical for the ability to detect trends in NPP in relation to other factors such as climate and anthropogenic impacts (e.g., Beaulieu et al., 2012).

The wide variety of coastal ecotypes represents another challenge for comprehensive estimation of regional primary production and other aspects of carbon cycling. For example, salt marshes, estuaries, and inland waters can exhibit high and variable rates of productivity. The estimated contribution to carbon burial by salt marshes, seagrasses, and

mangroves exceeds that in the pelagic ocean (Cloern et al., 2013; Duarte et al., 2005). Factors such as sea level, salinity, nutrient inputs, and tidal forcing can be important environmental drivers (Morris et al., 2013). In particular, salinity and inundation have been shown to have important influences on the productivity of mangroves (Barr et al., 2010; 2013) and salt marshes (Yan et al., 2008; Kathilankal et al., 2008; 2011). Such systems have also been identified as potentially important sites for carbon sequestration – so called "blue carbon" (McLeod et al., 2011; Hopkinson et al., 2012; Bianchi et al., 2013; CEC, 2016). As noted above, there are challenges in applying satellite approaches to such complex and heterogeneous coastal regions. For example, existing remote sensing productivity algorithms perform very poorly in mangrove ecosystems (Barr et al., 2013). However, it has been shown that remote sensing algorithms can be improved in salt marshes by calibration with tower-based measurements of net ecosystem exchange and inclusion of appropriate environmental parameters, such as sea level (Yan et al., 2010). It is likely that an array of different sensors and platforms may be needed to further develop satellite primary production estimates of different coastal ecotypes.

Contributions of the benthic community to overall net primary production may also be significant in shelf waters (e.g., Jahnke, 2010; Lehrter et al., 2014) and should be included in comprehensive carbon cycle budgets. Regional estimates of benthic production have been made based on estimates of light availability (Jahnke et al., 2008). Alternatively, estimates must rely on direct observations as well as empirical and mechanistic approaches for extrapolation.

High priorities for future research

- Develop and refine regional satellite NPP algorithms for diverse environments found in coastal margins (marshes, mangroves, estuaries, and shelf waters) and use to characterize spatial and temporal variability and trends
- Understand long-term (climate, eutrophication, ocean acidification) and event-scale changes in community structure and implications for NPP
- Incorporate new information regarding seagrass distributions (e.g., CEC, 2016) and expand observations of seagrass habitat and benthic algal contributions to NPP to better understand their role in coastal carbon budgets
- Document changes due to invasive species (e.g., mussels, HABs)
- Examine long-term changes in coastal NPP in relationship to climate and anthropogenic drivers
- Conduct more extensive cross-system analysis – comparisons and identification of dominant processes, standardization of approaches
- Explore utility of primary production in integrated ecosystem management approaches – improved management of living marine resources
- Evaluate food web length in relationship to production of higher trophic levels
- Identify regime shifts - e.g., shifts between benthic vs. water column related to eutrophication
- Assess linkages between phytoplankton community structure and PP

- Determine consequences of ocean acidification for PP and community structure relationships
- Evaluate relationships between nutrient availability and phytoplankton size and community composition
- Examine relative importance of inorganic vs. organic nutrient inputs
- Address issues of scaling – capturing smaller spatial scale patterns for inland waters, estuaries, wetlands and event scale transport phenomena (intrusions, upwelling, shelf exchange processes)

Respiration

Estimates of respiration in coastal ecosystems are more limited than for NPP, although there have been some regionally comprehensive studies (e.g., Murrell et al., 2013; Jiang et al., 2010). As noted by Marra (2009), "respiration is the biggest unknown factor in our understanding of the C budget of the ocean." A similar statement can be made for the Great Lakes (Bennington et al., 2012; McKinley et al., 2011; Urban et al., 2005). Contributions to respiration include autotrophic and heterotrophic components, which are not easily distinguishable. Some efforts have been made to separate the two (Marra, 2009), although generally respiration is measured as the combination of autotrophic and heterotrophic or ecosystem respiration as, for example, is determined by oxygen bottle incubations (Murrell et al., 2013) and other methods (e.g., McCarthy et al., 2013). The benthic component of respiration can often be a large fraction of the total coastal ecosystem respiration (Middleburg et al., 2005). As noted by Bauer et al. (2013), there is a lack of consensus as to whether continental shelf waters are net autotrophic or heterotrophic. One train of thought is that continental shelves are shifting from being a net source to net a sink of CO_2 because of increasing anthropogenic nutrient input and increasing atmospheric levels of CO_2 (Cai, 2011, Bauer et al., 2013; Mackenzie et al. 2004). Clearly, more and sustained observations are needed to resolve this.

High priorities for future research

- Assess variations in respiratory quotient in different coastal systems
- Evaluate stoichiometry of decomposition and production as related to the composition of organic substrate (nutrient content, elemental stoichiometry, DOM lability)
- Constrain estimates of growth/transfer efficiencies – important for modeling
- Improve understanding of the role of different trophic groups in contributing to respiration (plankton, bacteria, macrophytes)
- Consider challenges of scaling (system-wide vs. discrete, methodological differences, temporal coverage)

Net Ecosystem Production

From a carbon balance point of view, the most biologically relevant rate is net ecosystem production (Hales et al., 2008). At steady state, the integrated NEP over a given control volume must equal the organic carbon leaving and inorganic carbon entering that volume

via advection and diffusion. Furthermore, NEP estimates provide insights on the factors controlling hypoxia and food web structure in coastal ecosystems (Kemp and Testa, 2011).

Recent review articles by Kemp and Testa (2011) and Staehr et al. (2012) describe the wide variety of methods that have been developed to estimate NEP in various aquatic environments. Kemp and Testa (2011) focus on estuarine environments and illustrate the important role that riverine input plays in determining the sign and magnitude of NEP. Specifically, synthesis of numerous studies suggests that NEP increases as the riverine loading ratio of dissolved inorganic nitrogen to total organic carbon increases. This loading ratio is reasonably well known for numerous estuaries and was recently exploited to show that US Atlantic Coast estuaries are net heterotrophic in the aggregate (Herrmann et al., 2015).

In marshes and mangroves, NEP is closely related to net ecosystem exchange (NEE), which can be measured directly using the eddy covariance technique. At steady state, NEP is equal to –NEE minus the lateral advective export of DIC. Unfortunately, estimates of NEE and lateral export are rare in tidal marshes and mangroves. We are aware of only a few systems in which NEE estimates in the US have been reported in the literature (Barr et al., 2012; Kathilankal et al., 2011; Heinsch et al., 2004; Moffett et al. 2010; Schedlbauer et al., 2010).

Vertical Fluxes, Export Production, and New Production

Estimates of vertical export of organic matter in coastal ecosystems are also very limited in comparison to other rate measurements. Sediment traps are still a prominent method in estimating fluxes, but with limitations particularly in coastal regions. Challenges in the interpretation of sediment trap-derived fluxes in coastal systems include the potential for inclusion of resuspended material in traps, hydrodynamic effects on trapping efficiencies (Gust et al., 1996), and the variable and heterogeneous nature of coastal systems. Alternatives to sediment traps include isotopic methods (^{234}Th, van der Loeff et al., 2006) and optical techniques. Sedimentary processes in coastal regions can be highly dynamic as noted by McKee et al. (2004), which ultimately has implications for the fate of carbon in coastal sediments. Bauer et al. (2013) noted that organic carbon burial in wetland and estuarine sediments is poorly constrained, but accounts for the vast majority of global carbon burial in oceanic systems. Using a satellite-based algorithm relating primary production to sinking particle flux, Dunne et al. (2007) determined that 21% of the particle flux, 71% of the flux to sediments, 85% of the total burial flux, and 48% of dissolved organic matter release occur on the continental shelves (cf., Muller-Karger et al., 2004).

Estimates of new production provide an indirect assessment of the fraction of NPP that contributes to export production. The concept of new production as defined by Dugdale and Goering (1967) is less easily applied to coastal regions. New or allocthonous sources of nutrients include that introduced from terrestrial organic and inorganic sources,

nitrogen fixation, and atmospheric deposition, as well as contributions from upwelling from offshore waters (Messié et al., 2009). The various contributions from these sources are difficult to constrain. Moreover, the types of nitrogen entering coastal ecosystems can have an impact on community structure and carbon cycling (e.g., Bronk et al., 2007).

High priorities for future research

- Develop new methods for rigorously estimating the error in scaling up individual measurements for the determination of NEP at large scales
- Increase the number of CO_2 eddy covariance measurements in tidal marshes and mangroves
- Improve estimates of vertical and lateral fluxes of carbon in coastal waters through direct observations and modeling
- Relate long-term patterns and trends in fluxes to changes in climate and ocean conditions and the structure of the planktonic food web
- Improve understanding of climate and land use impacts on terrestrial carbon and nitrogen exports and the impacts of these changes on coastal primary production, respiration, and net ecosystem production

Other Transformations

Various other transformations have important implications for coastal carbon cycling. These include secondary production (grazing, microbial production), processes involving dissolved organic matter (production, utilization, remineralization, degradation, photodegradation), and nutrient transformations (regeneration, nitrification, denitrification, annamox, uptake, new vs. regenerated). While information is available for specific locations and time periods, the magnitude and variation in these processes remain highly uncertain for many coastal ecosystems.

High priorities for future research

- Improve estimates of grazing and bacterial secondary production in relationship to other carbon cycling processes
- Improve understanding of the fluxes and dynamics of dissolved organic matter in coastal regions
- Improve understanding of nutrient transformations and their implications for long-term changes in carbon cycling
- Evaluate competition for organic and inorganic nutrients between bacteria and phytoplankton
- Evaluate importance of variations in stoichiometry among taxonomic groups (nutrient uptake, remineralization, relationship to organic matter composition)

Sedimentary Processes

As key sites of temporary storage, transformation, exchange with the overlying water column, and long-term sequestration of both organic and inorganic carbon, continental

margin sediments play important roles in the fluxes and processing of carbon and associated elements (Liu et al., 2010). In order to fully develop carbon budgets for continental margins, the magnitude and nature of these processes must be quantified and constrained through a combination of models and observations at a variety of temporal (e.g., event-driven, seasonal, annual, and decadal) and spatial (e.g., local/regional depocenters and margin-wide estimates) scales. Key processes and associated observing priorities are highlighted throughout this chapter. However, better representation of these sedimentary processes in biogeochemical models will also be essential to scale up limited observations and integrate across spatial and temporal scales.

Particle Export and Deposition

The delivery of particulate material to the coastal margin sediment-water interface is a highly dynamic process that occurs over much broader range of time-scales than in the open-ocean. Seasonal and short-term events such as plankton blooms, storms and floods, wind-driven upwelling-downwelling, and mesoscale eddy and meander activity, substantially impact the magnitude of the particle flux, deposition, resuspension/re-deposition, and lateral export off the margin. In turn, particle carbon content and lability will also be driven by the frequency and rates of these processes, which vary significantly among margin settings. Over longer, interannual to decadal time-scales, climate modes (e.g., the El Niño-Southern Oscillation, North Atlantic Oscillation, and Pacific Decadal Oscillation) exert considerable control over organic matter delivery and burial on the margin. Due to the multiple factors influencing the carbon particle flux on the margin (e.g., autochthonous production, allochthonous inputs from atmosphere and land, subsurface resuspension and lateral exchange), it is of the utmost importance to quantify the magnitude and time-scale of such processes in different regions to provide accurate and comparable carbon export and deposition budgets (Jahnke et al., 1990).

High priorities for future research

High-resolution measurements of particulate flux and composition across the sediment-water interface at distinct temporal and spatial scales are needed, which will require *in situ* instrumentation to measure fluxes and collect samples for analysis. This includes the use of sediment traps (moored/free drifting), benthic lander/moorings equipped with optical and acoustic sensors, and ship-based efforts to collect samples across the sediment-water interface. The use of radionuclides with contrasting half-lives (e.g., ^{7}Be and ^{210}Pb) is needed to evaluate sediment deposition rates at different time scales (seasonal, inter-annual, and decadal) that can be compared directly to other carbon flux measurements.

Temporary Storage and Biogeochemical Transformations

Benthic boundary layer and sedimentary processes are also critical to coastal carbon budgets because they represent sites of temporary storage and transformation of carbon-relevant species. Particle residence time and biogeochemical dynamics occurring in the benthic nepheloid layer, a common feature on many margins, are important processes

impacting the fluxes of key constituents (e.g., oxygen, macro- and micro-nutrients) across the sediment-water interface (Townsend et al., 1992; Hwang et al., 2013; Pilskaln et al., 2014). Biologically mediated reactions in surface sediments (Burdige, 2007) are responsible for the degradation and alteration of organic matter, affecting the distributions, cycling and benthic fluxes of redox-sensitive species. Contrasts in the temporal and spatial distribution of these sedimentary processes relative to other important fluxes (e.g., productivity, carbon export, and gas exchange) across key interfaces (i.e., land-ocean, shelf-open ocean, and ocean-atmosphere) increases complexity in our attempts to draw budgets at specific temporal and spatial scales (e.g., seasonal and margin-wide).

High priorities for future research

Accurate measurements of sedimentary processes and fluxes of carbon-relevant species across the sediment-water interface over appropriate time and space scales to provide closure and context to other flux measurements, including new technologies and remote platforms that provide continuous measurements of key constituents (e.g., oxygen, CDOM, CO_2) combined with sampling campaigns designed to capture the temporal and spatial heterogeneity typical of continental margin systems; other specific measurement priorities identified throughout the regional CCARS activities include:

- Measurements of benthic primary production in different margin settings
- Measurements in and around benthic seeps that examine contribution of chemoautotrophy to sedimentary carbon budgets

Long-term Sequestration and Burial

Burial in margin sediments has long been recognized as one of the key long-term carbon sinks over geological time scales. However, sequestration in margin sediments over shorter periods of time (i.e., decades) is also an important flux term that is often poorly constrained in regional carbon budgets (Bauer et al., 2013; Alin et al., 2012). New studies highlighting the importance of natural carbon sequestration along continental margins (e.g., Howard et al., 2014; Smith et al., 2015) have provided insight into how to accurately measure this potentially important term. As with other sedimentary fluxes described above, long-term sequestration depends to a large extent on sediment accumulation rates, which display large spatial and temporal variability in continental margin settings. Estimates of long-term accumulation rates integrate periods of low, zero, or negative (i.e., erosion) accumulation and are thus inherently lower than those calculated over shorter periods of time. Because burial rates estimated using ^{210}Pb-based sediment accumulation rates represent net sequestration over decades, these carbon fluxes need to be compared to other fluxes across key interfaces (e.g., land-sea, ocean-atmosphere, shelf-slope) at similar time-scales. Sedimentary carbon budget exercises should be completed for high-accumulation rate regions where seasonal to decadal data are available, such as the Gulf of Maine (Keigwin and Pilskaln, 2015) and the Pacific Northwest margin (Wheatcroft et al., 2013), and considered alongside the long-term sequestration budgets.

High priorities for future research

- Higher-resolution (temporal and spatial) studies of sediment accumulation rates and carbon distributions in different coastal regimes are needed to gain a more comprehensive understanding of burial rates along North America's margins (e.g., Hastings et al., 2012). Land-use changes, hydrology, climate, sea level rise, and episodic events (e.g., floods and storms) have the potential to affect the magnitude and location of inorganic sediment supply delivered and deposited on coastal margins. Studies attempting to determine carbon sequestration over these time scales must account for such variability and consider these processes when interpreting down-core composition to evaluate burial rates.
- Higher spatial resolution studies along and across margins are needed to identify sediment depocenters, as well as regions of off-shelf, near-bottom transport of particle-bound carbon and evaluate their importance in overall long-term carbon budgets.

Overall Fate of Carbon and Carbon-relevant Constituents in Sediments

The post-depositional fate of carbon (i.e., sequestration vs. regeneration) depends on several factors, including the degree of exposure to effective oxidants, protection against decay by association with mineral (or organic) matrices, and the presence (or formation) of inherently resistant organic and organo-mineral structures. Multiple processes acting at variable time-scales impact these factors, contributing to a highly dynamic and heterogeneous pattern of carbon sequestration along continental margins.

Elevated rates of sediment supply and net accumulation in depositional settings generally result in lower rates of exposure to effective oxidants such as oxygen and subsequently more efficient burial than in regions with lower net accumulation rates. While the concept of oxygen exposure time (OET) is an attractive concept that integrates complex processes that affect organic matter turnover (e.g., resuspension, transport and re-deposition, bioturbation, and burial), quantifying its overall magnitude in the highly dynamic and non-steady state continental margin settings has proven challenging (e.g., Goñi et al., 2013).

Other more intrinsic factors, such as the inherent recalcitrance of organic compounds and their association with protective (mineral/organic) matrices also affect carbon sequestration rates. Moreover, the input of reactive organic matter can lead to a 'priming effect' of otherwise recalcitrant carbon pools and result in elevated degradation rates. Thus, the structure and mineral associations of organic matter in sediments influence its susceptibility to remineralization under different oxidant exposure scenarios, resulting in variable relationships between preservation efficiency and oxidant exposure for depositional systems with contrasting organic matter compositions.

High priorities for future research

- To better understand the controls and feedbacks of post-depositional processes on the exposure of organic matter to effective oxidants and oxidant concentrations (e.g., dissolved oxygen concentrations, and re-oxidation of metal oxides) across the range of depositional and erosional environments that characterize continental margins
- To improve our mechanistic understanding of carbon fluxes (e.g., the role of recalcitrance/reactivity, mineral associations) in different depositional settings in order to scale up observations of carbon transformation and preservation

Atmospheric Exchanges

Coastal oceans are an important interface in the journey of carbon transport from terrestrial ecosystems to the ocean, where rates of carbon transformation and biogenic gas fluxes are high. The coastal ocean comprises several subsystems, including estuaries, their upstream tidal rivers and surrounding tidal wetlands (marshes and mangroves), and the continental shelves. All of these subsystems are connected to the atmosphere. Thus, CO_2 fluxes between the atmosphere and coastal subsystems reflect (and are driven by) both the NEP of an individual subsystem and lateral transport of organic and inorganic carbon between subsystems. It is generally believed that DOC and POC exports from rivers and wetlands support the very high net ecosystem respiration rate (NEP<0) and CO_2 degassing fluxes observed in most estuarine waters (Borges and Abril, 2011; Cai, 2011). However, we know very little about regional CO_2 degassing fluxes in North American estuaries, as existing data are insufficient (in space and time) for robust synthesis and extrapolation. In contrast, due to efforts of the past decade, some directly as a result of CCARS, we know CO_2 uptake fluxes over North American shelves with relatively high confidence.

Exchanges with Estuaries

Frankignoulle et al. (1998) were among the first to recognize that CO_2 emissions from estuaries (based on data from Europe) represented a significant component of regional CO_2 budgets. Subsequent studies yielded estimates of global estuarine CO_2 effluxes on the order of 200-400 Tg C y^{-1} (Borges and Abril, 2011; Borges et al., 2005; Cai, 2011; Laruelle et al., 2010). While estuaries make up a very small portion of the global ocean area (0.3%), their CO_2 degassing fluxes are disproportionately large and of the opposite sign compared to CO_2 exchanges between the open ocean and atmosphere, an uptake of ~1.5 Pg C y^{-1} (Takahashi et al., 2009). However, the uncertainty in any regional or global estuarine CO_2 degassing flux is high due to very limited spatial and temporal observational coverage, large physical and biogeochemical variability, and insufficient use of generalized hydrodynamic-biogeochemical models in estuaries (Bauer et al., 2013; Cai, 2011; Laruelle et al., 2013). While on a global scale, estuarine CO_2 degassing flux has been estimated with some confidence, we have little information on regional CO_2 degassing rates in most parts of the world, particularly for North American estuaries. The only regional estuarine CO_2 degassing flux estimate was provided by a recent modeling study based on a spatiotemporally sparse network of estuarine data sets: Laruelle et al.

(2015) estimated that the estuaries from Cape Hatteras to Nova Scotia (i.e., MAB and Gulf of Maine) outgas 0.8 ± 0.5 Tg C yr^{-1} of CO_2. However, there have only been three estuarine CO_2 studies along the Mid-Atlantic coast: Crosswell et al. (2012) in the Neuse River, NC; Raymond et al. (1997) in the Hudson River, NY; and Raymond et al. (2000) in the York River, VA; and a few in the Gulf of Maine (Hunt et al., 2014; Hunt et al., 2011). Data are missing from most of the large, more characteristic Atlantic coast estuaries (e.g., the Chesapeake and Delaware Bays). Clearly, any regional flux estimate based on data from small heterotrophic estuaries without information from large, possibly autotrophic estuaries is likely unreliable.

While we know general patterns of estuarine CO_2 distribution and variation, we are unable to effectively synthesize and extrapolate CO_2 fluxes from a few sites into a regional flux with good confidence. There are multiple reasons why our knowledge of the estuarine CO_2 degassing flux is still rudimentary. First, estuarine systems that have been studied represent only a small fraction of existing systems. Among them, most are focused on smaller rivers/systems rather than larger, more quantitatively important North American estuaries, and thus do not adequately represent the full range of air-sea exchange regimes. Second, of those studied, spatial and temporal coverage are generally inadequate, particularly in older studies. For example, CO_2 degassing flux was estimated from two estuaries in the southeastern US based on a single field study, despite the presence of a very strong spatial pCO_2 gradient between the narrow upper estuary and the wide lower stream (Cai and Wang, 1998). Third, open-ocean gas exchange parameterizations have often been applied to estuarine systems, which are typically less windy but more turbulent relative to the open ocean if under the same wind conditions, creating the potential for large errors in estuarine degassing fluxes (e.g., Jiang et al., 2008a). However, some parameterizations exist and others could be developed that take into account the changing contributions of both wind and water current velocities to gas exchange along the land-ocean continuum and may yield estuarine air-sea exchange estimates with reduced uncertainties (Borges et al., 2004a,b; Alin et al., 2011). Fourth, a shortage of sustained, high-resolution estuarine time-series precludes our capacity to capture event-scale variability in estuarine systems that can yield radical changes in a matter of hours or days (e.g., Crosswell et al., 2012). Fifth, and finally, the boundaries between estuarine waters and surrounding marshes are often blurred, possibly leading to double counting (e.g., Cai, 2011). While these issues have thus far hindered our ability to reliably estimate regional estuarine CO_2 fluxes, scientists have attempted to address many of these problems with more sophisticated and systematic studies in recent years (Hunt et al., 2014; Joesoef et al., 2015).

Exchanges with Tidal Wetlands

While direct measurements are very limited, wetlands are most likely a CO_2 sink due to apparent plant production, burial, and organic carbon export (Bauer et al., 2013; Bouillon et al., 2008; Hopkinson, 1988; Woodwell et al., 1973). Human-driven land-use changes that have resulted in a loss of tidal wetland systems (mangroves, salt marshes, seagrasses, etc.) have caused a rapid decline in the tidal wetland CO_2 sink in recent decades (Duarte

et al., 2005; Hopkinson et al., 2012). Furthermore, many small creeks inside marshes and mangroves are actually areas of strong CO_2 degassing (CO_2 source) (Bouillon et al., 2008; Cai, 2011; Morris and Whiting, 1986; Neubauer and Anderson, 2003). Regional and global estimates of wetland CO_2 exchanges with the atmosphere are hampered by a scarcity of reliable wetland surface area estimates and a lack of studies of net CO_2 flux that include both uptake (by plant production) and release (by heterotrophic waters) over reasonable temporal and spatial scales. For example, there are only a few wetland sites with flux towers that have reported net CO_2 fluxes based on the eddy covariance method (e.g., Barr et al., 2010; Kathilankal et al., 2008).

Exchanges with Shelf Waters

It has long been recognized that continental shelves represent an important CO_2 sink for the ocean (Tsunogai et al., 1999). Most recent global-scale syntheses are based on upscaling methods, whereby different shelf systems are classified by dividing them into a few provinces (Cai et al., 2006) or typologies (Laruelle et al., 2010; Laruelle et al., 2014). These estimates suggest a lower, but still significant net atmospheric CO_2 uptake flux, ~0.25 PgC/yr, when comparing to the open ocean (Bauer et al., 2013; Cai, 2011; Dai et al., 2013). In the context of the CCARS synthesis and coastal carbon budgeting activities, we have much better constraints on the shelf air-sea CO_2 fluxes relative to tidal wetland and estuarine subsystems. CCARS data synthesis and modeling activities, as detailed in the earlier sections of this report, have resulted in much improved estimates of regional atmospheric CO_2 fluxes in North American continental margins (e.g., Signorini et al., 2013; Robbins et al., 2014; Evans et al., 2015; Huang et al., 2015). In general, regions close to land tend to be sources of CO_2, mostly due to their high rates of respiration of terrestrial and estuarine organic carbon and lateral transport of high-CO_2 waters from adjacent inshore systems. In contrast, mid- to outer shelf waters are a sink of CO_2. This general pattern results from decreased terrestrial organic carbon supply, increased primary production as light conditions improve offshore, and increased accessibility to nutrients supplied by upwelling and mixing across the shelf break (Jiang et al., 2008b; Walsh, 1991). This pattern of a nearshore CO_2 source transitioning to mid-/outer shelf CO_2 sink varies regionally, particularly in river- (Huang et al., 2015) or upwelling-dominated (Hales et al., 2005) systems, and depends to a large extent on wind stress, river discharge, and other physical conditions.

High priorities for future research

In summary, North American tidal wetlands remove CO_2 from the atmosphere and estuaries outgas CO_2, but the fluxes are poorly quantified due to a lack of sustained observations from these subsystems. Shelves are the best-known subsystems in the coastal ocean, and North American shelves are clearly a CO_2 sink. Recommendations for better constraining atmospheric CO_2 fluxes in tidal wetlands, estuaries, and shelves include the following:

- Increase the number of sustained high-resolution measurements of pCO_2 in both space (e.g., wave gliders) and time (e.g., moored sensors and other time-series), particularly in estuarine and tidal wetland systems where data are sparse
- Improve estimates of North American tidal wetland surface area
- Conduct more process studies, particularly in characteristic North American tidal wetland and estuarine systems, that focus on net CO_2 flux
- Improve coastal carbon satellite algorithm development to support new gas exchange parameterizations for estuarine, tidal wetland, and shelf systems; and improve integration of satellite measurements into flux synthesis and model development
- Develop/improve mechanistic coastal models using ocean pCO_2 and other biogeochemical data
- Develop an enhanced observing system in the Laurentian Great Lakes to improve our mechanistic and predictive understanding of atmospheric CO_2 fluxes in freshwater systems

Coastal Methane Fluxes

Despite its low atmospheric concentration (~2 parts per million), methane (CH_4) plays an important role in climate and atmospheric chemistry. CH_4 is a potent greenhouse gas, second only to carbon dioxide in its contribution (17%) to the current anthropogenic global warming rate (Myhre et al., 2013). CH_4 also degrades the ability of the atmosphere to cleanse itself of pollutants by reacting with an important oxidant, the hydroxyl radical. Atmospheric CH_4 concentrations have increased by 150% since pre-industrial times, largely as a result of agricultural practices and fossil fuel burning, though significant uncertainties remain in the current budget and large uncertainties loom in the future (Conrad, 2009).

Bakker et al. (2014) provide an excellent overview of the flux of methane from the ocean (including mangroves and estuaries) to the atmosphere and conclude that it is poorly constrained at the global scale. Current estimates of the marine source are 10–48 Tg C yr^{-1}, relatively small compared to the total source, 377–458 Tg C yr^{-1} (2–13%), though possibly as high as nearly half of the natural source, 109–195 Tg C yr^{-1}. Remarkably, the open ocean contributes only ~0.3 Tg C yr^{-1} to the atmosphere, making the coastal zone the dominant component of the marine source. Each component of the coastal source (upwelling systems, continental shelf waters, estuaries, mangroves, and continental margin seeps) has an uncertainty range of about an order of magnitude.

There are few estimates of methane emissions from North American coastal waters. Bridgham et al. (2006) estimated that North American tidal marshes, mangroves, and mudflats emit a total of 0.059 Tg C yr^{-1} of methane, with a large uncertainty (there was 95% confidence that the estimate for marshes and mangroves was within 50% and for mudflats was within 100%). We know of no large-scale methane emission estimates in upwelling systems, continental shelf waters, estuaries, and continental margin seeps of North America or any of its major coastlines. There have been a number of studies of

methane in North American coastal waters (e.g., Angelis and Scranton, 1993; Brothers et al., 2013; Lapham et al., 2008; Martens and Val Klump, 1980; Neubauer, 2013; Newman et al., 2008; Pfeiffer-Herbert et al., 2015; Skarke et al., 2014; Wilson et al., 2015), but no effort has been made to synthesize them.

Much research is also needed to better understand the processes regulating methane cycling in coastal waters. As noted by Bakker et al. (2014), particularly vexing is the direct emission of methane-filled bubbles from sediments to the atmosphere (ebullition). Methane is unique among gases in that, at least locally, its primary delivery to the atmosphere may be via ebullition, a process that is highly variable in space and time and difficult to predict from first principles. The emission and fate of methane from continental margin seeps is another poorly constrained and understood process. For example, tectonically inactive areas have recently and unexpectedly been shown to be substantial methane sources (e.g., off the seafloor off of the eastern U.S., Skarke et al., 2014). As such regions are fairly common throughout the world's oceans, the current estimates of methane seepage from the seafloor and subsequent flux to the atmosphere may be too low. Furthermore, it is well known that there are massive methane reserves in the sediments of the coastal ocean and that their stability is dependent on the temperature of bottom waters. The release of this methane may be underway along the U.S. east and west coasts as a result of ocean warming (Hautala et al., 2014; Phrampus and Hornbach, 2012), and there is the potential for further substantial releases globally over the coming centuries, though the uncertainties are large (Archer et al., 2009). Finally, much work needs to be done to examine the net "blue carbon" benefits of tidal wetlands, which sequester CO_2 but emit CH_4 (Weston et al., 2014).

High priorities for future research

Despite the large gaps in our understanding of the exchange of CO_2 between coastal waters of North America and the atmosphere, the gaps for methane are much larger. In order to move forward, efforts are needed to:

- Synthesize current CH_4 data and research in North American coastal waters; for example, the Surface Ocean CO_2 Atlas (SOCAT), which has been extremely helpful for constraining the atmosphere-ocean exchange of CO_2, should be expanded to include other greenhouse gases such as CH_4; similar data synthesis efforts for CH_4 fluxes in tidal wetlands should be coordinated with the synthesis of blue carbon stocks and CO_2 fluxes
- Collect observations of coastal water CH_4 concentrations and bubble plume distributions to provide an improved understanding of potential hotspots of CH_4 emissions
- Conduct process-oriented studies of CH_4 in continental margin settings to improve representation of key CH_4-related processes in models and build predictive capacity

Lateral Transport

In most North American continental margin systems, the lateral cross-shelf transport flux of carbon is one of the largest of the net source/sink terms in the coastal carbon budget. These transport fluxes are extremely difficult to measure directly, which leads to great uncertainty associated with estimates of their magnitude. Although concentrations of inorganic and organic carbon along the outer shelf may be estimated from *in situ* or satellite observations, to estimate lateral fluxes of carbon, the net transport of water across this boundary is also required. This transport is difficult to constrain from observations alone, due to the high temporal and spatial variability associated with these fluxes.

Whereas the majority of carbon flowing into the coastal ecosystem from land primarily does so at distinct locations along the coast (i.e. through rivers), the transport of carbon across the coastal/open ocean boundary occurs all along the outer shelf. The locations of strongest across-shelf transport also vary on daily to seasonal to interannual time scales, depending on tidal variability, mesoscale eddy activity, and interannual variability in general circulation patterns. On the contrary, the locations of strongest land-ocean transport (i.e. river locations) are essentially fixed on these time scales. This strong spatial and temporal variability in lateral cross-shelf carbon fluxes makes them difficult to monitor, particularly when compared to the relatively well-monitored inputs of carbon from riverine systems along the North American shelf.

Our current knowledge of lateral transport fluxes comes primarily from studies that estimate these terms either "by difference" using mass balance approaches (Vlahos et al., 2002, 2012), or that estimate them from model simulations (Hofmann et al., 2011). However these two different approaches are each associated with considerable uncertainties, and can generate estimates that disagree even in the direction of the net flux. New approaches that combine model simulations, *in situ* carbon measurements, and remotely-sensed satellite data with high spatial and temporal resolution hold much promise for the future (Mannino et al., 2014; Fishman et al. 2012).

Subregional fluxes between estuaries and the continental shelf are typically better constrained than cross-shelf fluxes, but much uncertainty surrounding these fluxes still exists. Such fluxes are again typically estimated "by difference" (Boynton et al., 1995; Kemp et al., 1997; Hermann et al., 2015). If the remaining carbon budget terms are quantified and summed, the residual is attributed to the lateral export of carbon out of the estuary. Although these types of estimates may provide information on the climatological average estuarine export to the shelf, they cannot yield insight into the temporal variability of such fluxes. Because of the high temporal variability of water flow through the mouths of estuaries and the resultant problems associated with tidal aliasing, generally it is not possible to estimate this flux directly from observations. Thus, numerical models are generally required to provide information on the temporal/spatial variability of carbon and nutrient export fluxes from estuaries (Feng et al., 2015; Mannino et al., 2014) and resolve relative contributions of the different processes affecting carbon quality and fluxes (Tzortziou et al 2007).

Highly productive tidal wetlands flank many estuaries and laterally export both DOC and POC to support respiration and CO_2 degassing in estuaries. The limited studies that are available suggest that wetlands act as a net source of carbon to estuaries that may be comparable to riverine carbon supply (Cai, 2011). However, most of the carbon supplied from wetlands is recycled in estuaries, with only a small amount buried in sediments or exported to continental shelves (Bauer et al., 2013; Bouillon et al., 2007). CCARS activities have catalyzed newly funded collaborative research projects to address fluxes and exchanges within and across tidal wetlands and estuaries:

- *Measurements, Modeling And Remote Sensing of excHanges to quantify wetland Carbon CYcling and Links to Estuaries (MARSHCYCLE)*: This project will integrate advanced remote sensing observations of wetlands and coastal ocean color with new mechanistic carbon cycling modeling (PIs: M. Tzortziou et al., http://www.carbonwetlands.com/index.html)
- *The Carbon Budget of Tidal Wetlands and Estuaries of the Contiguous United States: A Synthesis Approach (WETCARB = Wetland-Estuary Transports and CARbon Budgets)*: This project will develop a carbon budget for tidal wetlands and estuaries of the contiguous US (including Gulf of Mexico) using existing field observations, remote sensing products, and statistical models (PIs: R. Najjar et al., http://cce.nasa.gov/cgi-bin/cce/cce_profile.pl?project_group_id=3165)
- *Linking Satellite and Soil Data to Validate Coastal Wetland "Blue Carbon" Inventories: Upscaled Support for Developing MRV and REDD+ Protocols*: This project will estimate tidal marsh standing stocks at six sentinel sites across the US (PIs: L. Windham-Myers et al., http://nspires.nasaprs.com/external/viewrepositorydocument/cmdocumentid=430111/solicitationId=%7B41E74515-E19D-72E5-3111-41FE7A816E29%7D/viewSolicitationDocument=1/CMS14 selections.pdf)

Furthermore, the Commission for Environmental Cooperation (CEC) has published the first set of comprehensive blue carbon (seagrasses, salt marshes, mangroves) maps for North America, which show 47,776 km^2 of blue carbon mapped to date, along with associated carbon stock estimates (CEC, 2016). Given the vulnerability of these blue carbon systems to environmental stressors and their subsequently high loss rates, further efforts like these are needed to characterize and quantify the role of these systems in the coastal carbon budget.

High priorities for future research

- Use all available resources, combining information from models, remotely sensed data, and *in situ* observations
- Implement nested models to simulate critical processes occurring at different temporal and spatial scales
- Perform synthesis and data mining of existing field and satellite data
- Target field observations to areas of high variability to constrain fluxes through focused studies

Overarching Priorities and Recommendations

In order to advance coastal carbon cycle science in North America, several overarching needs pertain across all regions. To best address these needs, strong integration across modeling and observational efforts is recommended, with a particular focus on developing models capable of integrating across the land-ocean continuum.

Considerable insights can be gained through continued synthesis and mining of carbon flux data (e.g., long-term time-series), which may be facilitated through creation of a centralized coastal carbon data repository. Improved understanding of mechanisms underlying coastal carbon fluxes and exchanges is needed to improve their representation in models. To that end, sites representing different coastal and estuarine typologies should be identified for additional targeted process-focused observations, as well as model development (e.g., Waquoit Bay National Estuarine Research Reserve field-validated models, http://wbnerrwetlandscarbon.net/). Ideally these representative sites can leverage existing nearshore and offshore infrastructure (e.g., flux towers, OOI observing assets, NOAA coastal CO_2/ocean acidification moorings) and may be identified through continued coastal carbon data synthesis efforts (e.g., WETCARB). To that end, we underscore the ongoing importance of sustained, long-term observations across the land-ocean continuum that will provide a framework for the recommended process studies and allow us to track the response of coastal carbon fluxes and ecosystems to progressive additions of anthropogenic carbon, nutrients, and heat (e.g., Alin et al. 2015). Continued synthesis should include comparisons of methodologically independent estimates of the same fluxes, model-data comparison, and multi-model intercomparisons. A key goal would be to yield broadly applicable observational methods and process models. Thus, community effort toward developing a blueprint for a comprehensive process study on coastal and estuarine carbon would be fruitful.

Community-level efforts to develop and carry out next-generation synthesis approaches are also needed. For instance, with many terrestrial and ocean satellite platforms approaching their mission end or start dates and new hyperspectral sensors being deployed, new and broader collaborations are needed for development of new satellite algorithms for use in continental margin ecosystems (for pCO_2, primary production, etc.) and to facilitate better use of relevant satellite products in all regions. Development of statistical/modeling techniques to utilize satellite-based and other high-resolution data sets will also facilitate scaling up of local carbon flux estimates.

Models can be used to calculate fluxes across different spatial scales (e.g., river-wetland, wetland-estuary, estuary-shelf, shelf-open ocean, benthic-pelagic) and to increase process understanding with respect to local physics, biogeochemistry, and biology. Models can also be extremely useful for interpreting complex datasets. For many systems, existing physical/hydrodynamic models could incorporate biogeochemical processes, whereas in others the underlying physical configurations do not yet exist. At a process level, modules describing benthic, submerged aquatic vegetation, and marsh carbon cycling are in particular need of model development.

Continued development and improvement of mechanistic numerical models is an ongoing need at the appropriate scale for studies of the coastal carbon cycle (i.e., tens of kilometers or less). Comprehensive, data-constrained fully coupled physical-biogeochemical-biological models with two-way nesting across river-wetland, wetland-estuary, estuary-shelf, shelf-open ocean, and benthic-pelagic scales will be needed in the long term to understand the evolving coastal carbon cycle. In the interim, much can be learned from models at a range of physical and process complexities that are well integrated with observational programs. With significant recent investment in new coastal observations and the increase in sophistication of coastal biogeochemical models over the last decade, models can be used to identify remaining observational gaps and inform the community how best to fill them - e.g., through the use of Observing System Simulation Experiments (Masutani et al., 2010; Phillips et al., 2015).

Finally, we note that coastal carbon cycle science will greatly benefit from and should play a leadership role in developing methods for data harmonization across the great many observing platforms in operation today and planned for the near future; no environment better represents the need for cross-cutting, interoperable data systems than those along the continental margin, which are concurrently influenced by atmospheric, terrestrial, marine, and human processes (Ciais et al., 2014; McKinley et al., 2015). Opportunities and challenges in this environmental domain loom large in the coming decades, both in terms of potential carbon cycle impacts and in making policy-relevant carbon cycle science available in a timely fashion; an increase in funding and coordination for data harmonization efforts will be essential. Because coastal resources with significant economic and ecological importance are inherently linked to coastal biogeochemical cycles, we recommend integrating social scientists and policy specialists into the planning process for developing integrated observational and modeling efforts as well as data harmonization strategies across the land-ocean continuum. Emphasis on improved process understanding of how energy and land use by humans modify carbon stocks and fluxes in coastal waters will facilitate anthropogenic attribution, which is essential to the formulation of effective policy and mitigation strategies (Michalak et al., 2011; McKinley et al., 2015). Broad participation of scientists and stakeholders will be necessary to ensure that the process will yield policy-relevant and accessible outcomes and information products from this next generation of coastal carbon cycle science (Alin et al., 2015).

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Appendix 1. CCARS Workshop Materials

North American Carbon Program

Coastal CARbon Synthesis (CCARS) Community Workshop

Woods Hole Oceanographic Institution, Clark 507

August 19-21, 2014

WORKSHOP AGENDA

Tuesday August 19, 2014

07:30 Continental Breakfast, hang posters (Clark 5)

08:30 Welcome and Introduction (Paula Coble, USF)

PLENARY 1. Carbon Fluxes in North American Coastal Systems: Key Processes

Chairs: *Marjy Friedrichs (VIMS), Simone Alin (NOAA/PMEL)*

Terrestrial fluxes (45 min. talk, 15 mins. for questions)

9:00 Lateral transfers of carbon from terrestrial watersheds to the oceans: Rivers and groundwater (Richard Alexander (USGS), Beth Boyer (PSU), Joe Needoba (OHSU), Ted Stets (USGS), Richard Smith (USGS))

10:00 Break

Tidal wetland fluxes (45 min. talk, 15 mins. for questions)

10:30 Tidal wetland fluxes overview (Chuck Hopkinson, Univ. Georgia) - primary production and CO_2 uptake, burial, lateral fluxes, etc.

Estuarine and shelf water fluxes (30 min. talk with 10 mins. for questions)

11:30 Lateral fluxes: Shelf-open ocean exchange (Marjy Friedrichs (VIMS), Penny Vlahos (UConn))

12:10 Lunch

13:30 Coastal primary production in North America (Steve Lohrenz, UMassD)

14:10 Coastal Net Ecosystem Production (NEP) in North America (Michael Kemp, UMCES)

14:50 Air-sea fluxes (Wei-Jun Cai, UDel)

15:30 Break

15:50 Burial and sediment-water exchange (Miguel Goñi, OSU)

16:30 Group Q&A and discussion

17:00-19:00 Poster session and welcome reception (Clark 5)

Wednesday August 20, 2014

07:30 Continental Breakfast, hang posters (Clark 5)

PLENARY II. Regional Coastal Carbon Budgets: Existing Gaps and Potential New Approaches

Chairs: *Ray Najjar (PSU), Paula Coble (USF)*
Structure: 15-minute talks to demonstrate synthesis work and updated budgets from each region, key accomplishments and remaining gaps/holes with 5 minutes for questions

08:30 East coast (Ray Najjar (PSU), Marjy Friedrichs (VIMS))

08:50 West coast (Simone Alin, NOAA/PMEL)

09:10 Gulf of Mexico (Paula Coble, USF)

09:30 Arctic (Jeremy Mathis (NOAA/PMEL), Jessica Cross (NOAA/PMEL))

09:50 Great Lakes (Galen McKinley, Univ. Wisconsin)

10:10 Break

10:30-12:30 BREAKOUT 1. Coastal Fluxes and Processes

Goal: *Based on current regional budgets and associated gaps in understanding, identify highest-priority process studies for advancing our understanding of the coastal carbon budget*

Groups (self-assigned)

- Air-sea exchange (Lead: J. Mathis)
- Terrestrial inputs (Lead: P. Coble)
- Estuarine and tidal wetland fluxes (Lead: M. Herrmann)
- Biological transformations (Lead: S. Lohrenz)
- Carbon loss terms: Burial and cross-shelf exchange (Leads: M. Friedrichs, S. Alin)

12:30 Lunch

14:00 Breakout 1 reports to plenary

15:00-17:00 BREAKOUT 2. Coastal Observations

Goal: *Based on current status of regional budgets, identify highest priority observations (by region) for coastal processes and fluxes discussed in Breakout 1*

Groups (self-assigned)

- East coast (Lead: R. Najjar)
- West coast (Lead: S. Alin)
- Gulf of Mexico (Lead: P. Coble)
- Arctic (Lead: J. Mathis)
- Great Lakes (Lead: G. McKinley)

15:45 15-minute break during Breakout 2

17:00 Poster session (Clark 5)

18:00 Workshop Dinner

Thursday August 21, 2014

07:30 Continental Breakfast (Clark 5)

08:30 Breakout 2 reports to plenary

09:30-11:30 BREAKOUT 3. Scaling Up: Integration of Observations and Models in Coastal Systems

(Same regional groups and leaders as Breakout 2)

Goal: *Recommend highest priorities for model development and integrated data and modeling approaches across different time and space scales*

Potential discussion points

- Working across terrestrial-coastal ocean interface
- Estuarine and tidal wetland processes
- Coastal ocean processes
- Working across coastal-open ocean interface

10:30 15-minute break during Breakout 3

11:30 Breakout 3 reports to plenary

12:15 Lunch

13:30 **GROUP DISCUSSION** - Science plan, strategize about near-term research and field priorities and existing funding opportunities

15:00 Workshop adjourn and steering group meets to discuss science plan and writing assignment

Coastal CARbon Synthesis (CCARS) Community Workshop

Woods Hole Oceanographic Institution, Clark 507

August 19-21, 2014

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