Carbon, Coast, and the Climate FREE

Katja Fennel, Dalhousie University, Tyler Cyronak, Nova Southeastern University, Michael DeGrandpre, University of Montana, David T. Ho, University of Hawai'i at Mānoa, Goulven G. Laruelle, Université Libre de Bruxelles, Damien Maher, Southern Cross University, and Julia Moriarty, University of Colorado Boulder

https://doi.org/10.1093/acrefore/9780190228620.013.824

Published online: 15 August 2022

Summary

The Earth's climate is strongly affected by the partitioning of carbon between its mobile reservoirs, primarily between the atmosphere and the ocean. The distribution between the reservoirs is being massively perturbed by human activities, primarily due to fossil fuel emissions, with a range of consequences, including ocean warming and acidification, sea-level rise and coastal erosion, and changes in ocean productivity. These changes directly impact valuable habitats in many coastal regions and threaten the important services the habitats provide to mankind. Among the most productive and diverse systems are coral reefs and vegetated habitats, including saltmarshes, seagrass meadows, and mangroves. Coral reefs are particularly vulnerable to ocean warming and acidification. Vegetated habitats are receiving heightened attention for their ability to sequester carbon, but they are being impacted by land-use change, sea-level rise, and climate change. Overall, coasts play an important, but poorly quantified, role in the global cycling of carbon. Carbon reservoirs on land and in the ocean are connected through the so-called land–ocean aquatic continuum, which includes rivers, estuaries, and the coastal ocean. Terrestrial carbon from soils and rocks enters this continuum via inland water networks and is subject to transformations and exchanges with the atmosphere and sediments during its journey along the aquatic continuum. The expansive permafrost regions, comprised of ground on land and in the seabed that has been frozen for many years, are of increasing concern because they store vast amounts of carbon that is being mobilized due to warming. Quantitative estimates of these transformations and exchanges are relatively uncertain, in large part because the systems are diverse and the fluxes are highly variable in space and time, making observation at the necessary spatial and temporal coverage challenging. But despite their uncertainty, existing estimates point to an important role of these systems in global carbon cycling.

Keywords: carbon cycling, sensors, rivers, estuaries, marshes, reefs, permafrost, continental shelves

Subjects: Hydrological Cycle, Climate Systems and Climate Dynamics, Climate Impact: Marine Ecosystems, Development and Sustainability, Climate and Coasts

Key Concepts in Carbon Cycling, Climate, and Coasts

The carbon cycle exerts a major control on Earth's climate because it determines the abundance of atmospheric carbon dioxide (CO_2) and methane (CH_4), both major greenhouse gases. Greenhouse gases warm the atmosphere because they are transparent to incoming energy from the sun, mostly in the form of visible and ultraviolet light, but absorb and re-emit heat (infrared light) that is emitted from Earth's surface. This process was first recognized about 200 years ago

by the French mathematician Joseph Fourier (Fourier, 1827), who termed it the greenhouse effect. Even relatively small changes in the carbon cycle can have massive impacts on global climate, as seen, for example, during glacial–interglacial periods.

Human activities have considerably increased atmospheric CO_2 and other greenhouse gases, mostly due to combustion of fossil fuels, but also deforestation, other land-use changes, and industrial activities, and they continue to do so. The average atmospheric CO_2 for 2018 was 407 parts per million (ppm; Friedlingstein et al., 2019), almost 50% higher than the preindustrial value of 280 ppm (Barnola et al., 1987). This rapid increase in atmospheric CO_2 has led to an imbalance between incoming and outgoing heat fluxes. With more heat being trapped on Earth, the ocean and atmosphere have warmed by 0.8°C and 1.1°C, respectively, and warming will continue for as long as the imbalance of heat fluxes persists.[1]

Carbon is unevenly distributed between different reservoirs on Earth and is constantly exchanged between them. By far the largest carbon inventory resides in rocks, but its mobilization through weathering is slow, occurring on timescales on the order of millennia. Thus, on timescales that are relevant for human civilization, only exchange between the so-called mobile carbon reservoirs in atmosphere, ocean, terrestrial biomass, soils, and fossil fuel reserves matter. In the atmosphere, carbon is present primarily in the inorganic gaseous forms CO_2 and CH_4. The atmospheric CO_2 reservoir currently amounts to 860 Gt C (Gt = gigaton = 10^9 ton = 10^{15} g; Friedlingstein et al., 2019). Mobile carbon on land is mostly in organic forms as living biomass and detrital organic matter in soils, estimated at 600 to 1,000 Gt C and 1,200 Gt C, respectively (Falkowski et al., 2000). These atmospheric and terrestrial reservoirs are dwarfed by the oceanic reservoir of 38,000 Gt C (Falkowski et al., 2000), which is dominated by dissolved inorganic carbon (DIC). DIC is comprised of dissolved CO_2, and its ionic dissociation products bicarbonate and carbonate. The organic carbon reservoir in the ocean is smaller and is dominated by dissolved organic carbon (DOC) estimated at 660 Gt C, while particulate organic carbon (POC) is a relatively small pool, at 1 to 2 Gt C (Hansell et al., 2009). The POC pool includes carbon contained in living biomass (from microscopic plankton to whales). The DOC pool includes carbon in free-floating organic molecules.

Among the mobile carbon reservoirs, DIC in the ocean is the largest by far (Figure 1). Thus, relatively small changes in the oceanic storage of DIC can have large effects on atmospheric CO_2. Two of the main mechanisms by which carbon can be redistributed between the atmosphere and the ocean on relatively short timescales are the so-called solubility and biological pumps (Volk & Hoffert, 1985). The solubility pump denotes the temperature-driven uptake of atmospheric CO_2 in subpolar regions, where cold, dense, carbon-rich water is formed and sinks to the deep ocean.

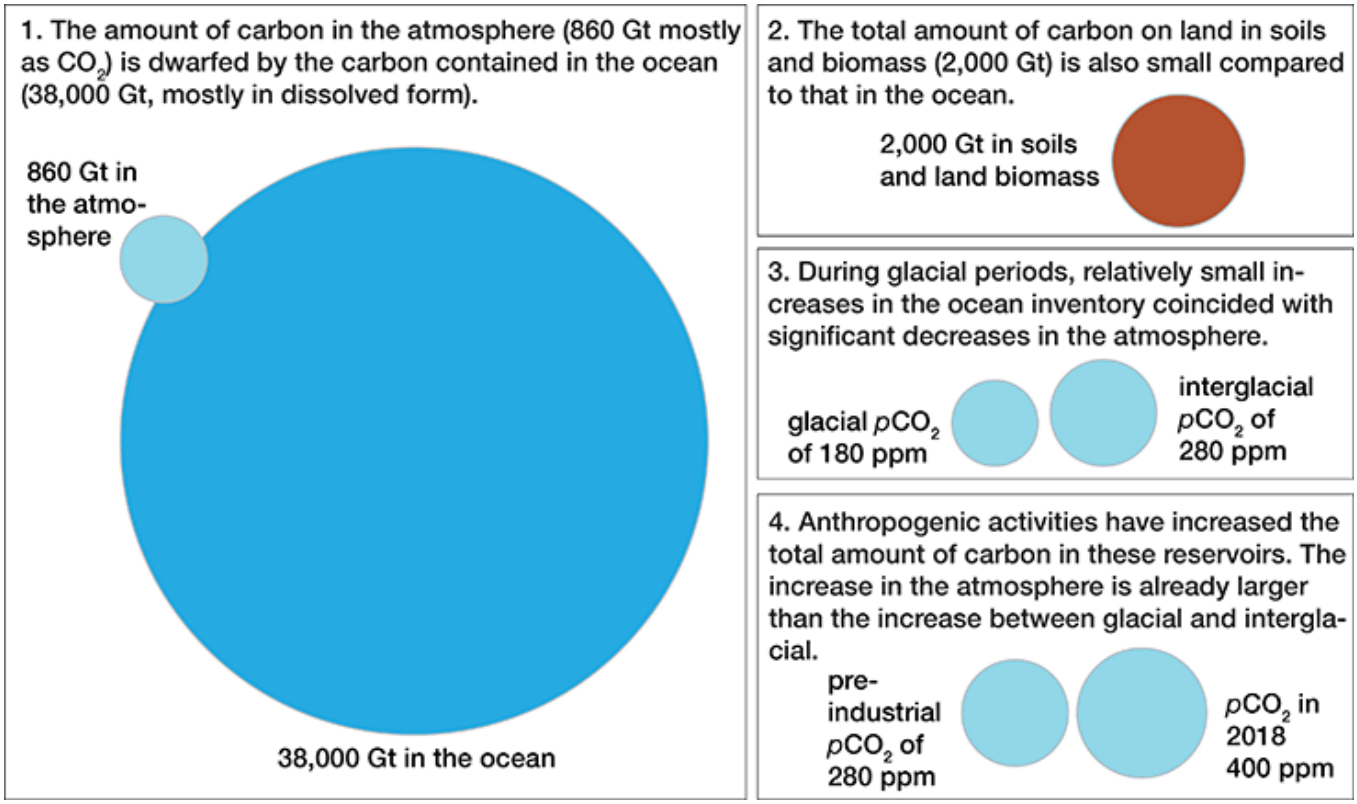

Figure 1. Sizes of the oceanic and atmospheric carbon reservoirs on Earth and changes in the atmospheric reservoir over time. The area of the circles scales with reservoir size.

The biological pump refers to the movement of carbon to the deep ocean that occurs because a fraction of photosynthetically produced organic matter sinks from the sunlit ocean surface to depth, where it is respired back into CO_2 and remains sequestered for centuries to millennia. Thus, even though the oceanic pool of POC is small, its photosynthetic production and subsequent sinking are a major regulator of atmospheric CO_2.

Over multiple glacial–interglacial cycles during the past 500,000 years, atmospheric CO_2 fluctuated periodically between 180 and 280 ppm (Siegenthaler et al., 2005), which corresponds to an addition/removal of roughly 200 Gt C to and from the atmosphere (i.e., less than 1% of the oceanic inventory; Figure 1). Periods of low atmospheric CO_2 coincided with the ice ages, which were marked by large-scale expansions of massive ice sheets over Europe and North America lasting for >10,000 years. Climate is also known to have changed on much shorter timescales of about 1,500 years during the so-called Dansgaard-Oeschger events and Heinrich events (Alley, 2000). Although the causes underlying these past changes have not been conclusively determined, it is widely accepted that a repartitioning of CO_2 between ocean and atmosphere played a major role (Broecker, 1982).

While the Earth's climate and carbon cycle have been relatively stable since the last ice age (the past 11,600 years), they are massively affected by the ongoing anthropogenic release of fossil fuel carbon and the subsequent repartitioning among the mobile carbon reservoirs (Falkowski et al., 2000). Cumulative emissions of CO_2 since the beginning of the Industrial Revolution were

estimated at 375 Gt C from fossil fuel burning and other industrial activities, and 180 Gt C from land-use changes (Ciais et al., 2013). Only roughly 40% of this so-called anthropogenic carbon has accumulated in the atmosphere (reflected in the increased atmospheric CO_2 of 407 ppm in 2018 compared to the preindustrial level of 280 ppm), while 30% of emitted CO_2 was absorbed by the ocean, and 30% by the terrestrial biosphere and soils (Ciais et al., 2013). The ocean's uptake of CO_2 is thus mitigating the global warming that would occur if all CO_2 from fossil fuel combustion had accumulated in the atmosphere. However, the subsequent increase of DIC in the ocean is responsible for ocean acidification, a decrease in the pH of seawater due to the formation of carbonic acid, which has far-reaching implications for ocean ecosystems, especially coral reefs.

The coastal oceans, operationally defined here as waters shallower than 200 m, have a unique role in the global carbon cycle as the interface between land and ocean, and because they are the only places where the carbon reservoirs of atmosphere, ocean, and the terrestrial biosphere intersect. Before the 1990s, coastal regions were largely neglected in studies of carbon exchange between ocean and atmosphere. However, while occupying only 8% of the ocean's surface area, coastal regions contribute approximately 20% to marine primary production (Gattuso et al., 1998), up to 80% of organic matter burial in marine sediments occurs on shelves (Muller-Karger et al., 2005), and shelf sediments hold about 16% of the total marine sedimentary carbon stock within their top meter (Atwood et al., 2020). An estimated 90% of global marine sedimentary remineralization occurs within shelf sediments (Gattuso et al., 1998).

Since the early 2000s, two major pathways of carbon flow mediated by the coastal ocean are especially receiving attention: the lateral input of terrestrial carbon through rivers, estuaries, wetlands, and groundwater, and the uptake of CO_2 from the atmosphere. Both carbon inputs are subject to dynamic processing in coastal waters (i.e., exchange between the organic and inorganic forms through primary production, respiration, and other transformations) and ultimately either export to the open ocean, burial in coastal sediments, or accumulation in coastal waters. Coastal oceans play an important role in the global carbon cycle (Bauer et al., 2013) and are recognized as an important component of the so-called land–ocean aquatic continuum (Regnier et al., 2013). However, since carbon fluxes in coastal oceans are highly variable, with large amplitude fluctuations, accurate observations and extrapolations are challenging. Many estuaries and some shelves act as sources of CO_2 to the atmosphere because they respire more organic matter than is produced by photosynthesis, while some coastal ecosystems, such as mangroves, seagrass meadows, and marshes, are efficient at taking up atmospheric CO_2 and support the blue carbon economy. Coral reefs can, in contrast, be net sources of CO_2 to the atmosphere due to their uptake of ocean alkalinity, even though their rates of photosynthesis exceed those of respiration.

The impacts of climate change are typically more severe in coastal regions than in the open ocean and are more directly relevant to human activities. Coastal regions host productive and diverse ecosystems but are increasingly threatened by the compounding stressors of ocean warming, acidification, and sea-level rise. Some coastal ecosystems, such as coral reefs, are especially prone to the devastating effects of rising CO_2 levels and warming, while others may play a disproportionate role in the future carbon cycle. For example, disappearing permafrost may lead to the release of vast reservoirs of organic carbon and CH_4 that would be unprecedented in timescales of human civilization.

History of Coastal Carbon Research

Early global models describing the role of the carbon cycle in climate (Maier-Reimer & Hasselmann, 1987; Sarmiento & Toggweiler, 1984; Siegenthaler & Wenk, 1984) focused on atmosphere–ocean exchange but ignored coastal oceans and the inputs of organic and inorganic matter from land. Nevertheless, the significance and potential importance of terrestrial inputs to the coastal oceans have been emphasized by some scientists since the late 1980s and early 1990s (Smith & Hollibaugh, 1993; Smith & Mackenzie, 1987). Smith and Mackenzie (1987) suggested that the ocean as a whole, and particularly the coastal oceans, are net heterotrophic (i.e., respiration exceeds photosynthetic production of organic matter). If exchanges between the mobile carbon reservoirs were in steady state, net heterotrophy would imply outgassing of CO_2 from the ocean to the atmosphere. This outgassing would have to be balanced by uptake from the atmosphere on land. In this scenario, land ecosystems would be net autotrophic (i.e., photosynthesis would exceed respiration). Smith and Hollibaugh (1993) estimated that 30% of the oceanic net respiration flux is contributed by the coastal oceans (0.084 Gt C/year of a total of 0.28 Gt C/year), which at steady state would escape to the atmosphere. In the current non-steady-state situation, where the atmosphere holds a large and increasing excess of CO_2 relative to equilibrium with the ocean, even a net heterotrophic system can act as a sink for atmospheric CO_2, although at a smaller rate than an autotrophic system would. Taken together, this early work on the global carbon cycle implied that coastal oceans either do not matter or outgas CO_2 to, rather than uptake CO_2 from, the atmosphere.

In contrast, in the late 1990s to early 2000s, a sequence of studies proposed a disproportionately large contribution of coastal oceans to the uptake of anthropogenic CO_2 from the atmosphere and subsequent export to the deep ocean (Thomas et al., 2004; Tsunogai et al., 1999; Yool & Fasham, 2001). Tsunogai et al. (1999) estimated the annual mean partial pressure of CO_2 (pCO_2) in surface waters of the East China Sea to be below that of the atmosphere, thus driving uptake by the coastal ocean. By extrapolating their estimate to the global continental shelf area, they arrived at an estimated global uptake of 1 Gt C/year in shelf regions and coined the term *continental shelf pump* (CSP). A subsequent global modeling study by Yool and Fasham (2001), where the CSP was crudely parameterized, estimated a global uptake of 0.6 Gt C/year. Thomas et al. (2004) estimated the annual mean pCO_2 in the North Sea to be below the atmospheric pCO_2 and, by extrapolating to the global shelf area, estimated an uptake of 0.4 Gt C/year. These studies elevated coastal oceans to the global carbon-cycling discussion. Although it is generally accepted that the coastal ocean acts as a disproportionate sink of atmospheric CO_2 (Chen & Borges, 2009; Fennel et al., 2019; Laruelle et al., 2010, 2014; Roobaert et al., 2019), subsequent studies painted a more complicated picture, as described in more detail in section Shelves.

The carbon cycle of coastal habitats, including saltmarshes, seagrass meadows, mangroves, and coral reefs, was a research theme for many decades before they were recognized as potentially important to the global carbon cycle. An early focus was on their potential for subsidizing coastal food webs, the so-called outwelling hypothesis (Odum, 1968, 2002). The central tenet of this hypothesis is that highly productive coastal vegetated habitats export organic matter that fuels secondary productivity in less-productive coastal areas. This hypothesis has been hotly debated

over the decades since the pioneering work of Odum and colleagues. While evidence is mounting that indeed a substantial amount of organic matter is exported from coastal vegetated habitats in both dissolved and particulate forms (Santos et al., 2021), the evidence that this organic matter sustains coastal secondary productivity is equivocal. The Odum brothers are also often credited with conducting the first study that measured the metabolism of a coral reef (Odum & Odum, 1955), although earlier studies exist (Sargent & Austin, 1949). Studies of coral reef carbon fluxes on different reef communities, types, and morphologies progressed further during the 1960s and 1970s (e.g., Kinsey & Davies, 1979; Smith, 1973; Smith & Pesret, 1974) and have seen a dramatic increase from 1990 to 2020 because of the negative impacts of global warming and ocean acidification on coral reef ecosystems.

History of Coastal Carbon Measurement Techniques

The complexity and variability of coastal systems require dense spatial and temporal measurements to quantify and understand sources and sinks of organic and inorganic carbon. Often these data sets can only be obtained with automated shipboard or autonomous in situ systems. Since necessity is the mother of invention, several important systems were developed, beginning in the 1980s and 1990s, as interest in the coastal carbon cycle intensified. Coastal waters have also served as a convenient instrument testbed because of their proximity to land. The highest-priority carbon-cycle measurements are on the list of Essential Ocean Variables compiled by the Global Ocean Observing System(Table 1).[2] These priorities focused efforts on instrument development, but the successful early autonomous instruments were also the low-hanging fruit of carbon-cycle parameters (Johnson et al., 2007).

The first chemical sensors widely used in oceanographic research were dissolved oxygen (O_2) sensors, developed in the mid-1980s. Based on modification of the existing O_2 Clark electrode design (Langdon, 1984), these sensors had features essential for autonomous measurements: low drift, low power demands, and a compact and reliable design. They were widely deployed in coastal areas to study hypoxia and for quantifying net community production, a critical carbon flux variable (Sanford et al., 1990). Two decades later, time-resolved fluorescence-based O_2 sensors (optodes) (Tengberg et al., 2006) have essentially replaced the electrochemical sensors because of their reduced drift and improved reliability.

Automated instruments and autonomous sensors for the measurement of inorganic carbon parameters were also a high-priority area (Table 1). The inorganic carbon system is comprised of dissolved CO_2, and bicarbonate and carbonate ions. Because of this complexity, and depending on the goal of the study, different inorganic carbon parameters might be measured. Laboratory methods have been developed for the four inorganic carbon parameters pH, pCO_2, total alkalinity (A_T), and total DIC. While these measurements all provide valuable information on their own, the combination of any two of them makes it possible to calculate the other parameters using equilibrium models (see Pierrot et al., 2006).

Table 1. A Carbon-Cycle-Focused Subset of the Essential Ocean Variables, a List of Priority Measurements Compiled by the Global Ocean Observing System[1]

Biogeochemical	Biological
Dissolved oxygen	Phytoplankton biomass and diversity
Nutrients	Zooplankton biomass and diversity
Dissolved inorganic carbon (also includes pCO_2, pH, and total alkalinity)	Microbe biomass and diversity
Particulate and dissolved organic carbon	
Stable carbon isotopes	

See the August 2019 Global Climate Report <https://www.ncdc.noaa.gov/sotc/global/201908> and The Global Ocean Observing System <https://www.goosocean.org/index.php?option=com_content&view=article&id=170&Itemid=114>.

Note: The table does not list critical physical parameters, while some other important parameters are subsets under the headings (e.g., primary productivity falls under phytoplankton biomass and diversity).

Of these methods, pCO_2 sensors were the first to follow the initial development of O_2 sensors in the mid-1990s (DeGrandpre et al., 1995; Friederich et al., 1995). The two methods, which are still widely used, employ pH indicator reagents (DeGrandpre et al., 1995) or equilibration of seawater with air and gas-phase infrared detection (Friederich et al., 1995). The systems departed from the simple, no-moving-parts design of the O_2 sensors, with pumps and valves necessary to achieve the accuracy and low drift essential for long-term deployments. Several in situ and automated shipboard pCO_2 systems have been commercialized, reflecting the importance of this variable for determining air–sea CO_2 fluxes. The instruments have revealed the short-term dynamics and long-term trends of pCO_2 in coastal waters (see Evans et al., 2011; McNeil et al., 2006; Reimer et al., 2017; Wesslander et al., 2011). The pCO_2 sensor technology was followed by the development of autonomous indicator-based pH instruments (Liu et al., 2006; Seidel et al., 2008) and, shortly thereafter, electrochemical pH measurements, based on ion-selective field effect transistors (Martz et al., 2010). These were timely innovations because of the increasing interest in pH for ocean acidification studies (Harris et al., 2013).

While these robust pCO_2 and pH sensors are providing valuable information about the inorganic carbon system in coastal waters, this combination of variables is not optimal for inorganic carbon system calculations (Cullison-Gray et al., 2011). Ideally, pH or pCO_2 is combined with measurements of A_T or DIC. Systems for measurement of A_T and DIC are inherently complex and pose significant challenges for in situ operation, but progress has also been made on them (Fassbender et al., 2015; Spaulding et al., 2014; Wang et al., 2015).

POC and DOC are also essential carbon-cycle variables (Table 1). Laboratory methods for determining them, using high-temperature combustion or ultraviolet photooxidation, are not adaptable for autonomous measurements because of their high power requirements. POC and DOC can, however, be indirectly quantified using optical proxy measurements, such as light

attenuation or backscatter for POC (Bishop, 1999; Bishop et al., 2016; Spinrad et al., 1983) and fluorescence for DOC (Cyr et al., 2017). A significant challenge is that the lack of a consistent correlation between carbon concentrations and optical signals requires regional calibrations using lab-based analysis of a sufficiently large number of water samples.

Another one of the big carbon-cycle challenges has been to connect plankton dynamics with air–sea CO_2 fluxes, carbon export, and respiration (Wassman, 1998). This challenge is more readily addressed with the availability of in situ bioanalytical instrumentation based on flow cytometry and other methods (Fischer et al., 2020; Hunter-Cevera et al., 2016;Olson & Sosik, 2007; Thyssen et al., 2008). Progress has also been made on autonomous nutrient analysis. The UV-based nitrate analyzers are commonly deployed on moorings and drifters (Ohman et al., 2013). Autonomous instruments for nitrate and phosphate based on lab-on-a-chip technology have also been developed (see Beaton et al., 2017), but these instruments are not yet routinely used.

While great advances have been made, significant challenges remain. The scarcity of inexpensive sensors that are reliable, accurate, and precise will continue to impair our ability to effectively study the coastal carbon cycle. Review articles that provide more in-depth information about sensors include Johnson et al. (2007), Lai et al. (2018), and Bushinsky et al. (2019). Ohman et al. (2013) and Chai et al. (2020) offered overviews of autonomous platforms.

Carbon Fluxes Along the LOAC

Rivers and estuaries, coastal oceans, and continental shelf systems are essential components connecting terrestrial and oceanic carbon-cycling processes. This sequence of systems is often referred to as the LOAC (Regnier et al., 2013).

Rivers and Estuaries (Including Tidal Freshwater Flows)

Rivers and estuaries (Figure 2) connect terrestrial to coastal carbon-cycling processes and form the first in the sequence of systems encapsulated by the LOAC. Depending on local conditions on land, including weather, lithology, vegetation, and human activities, carbon from soils and rocks enters the inland water network, where it is subject to transformations, including photosynthetic production of organic matter from inorganic carbon and degradation through respiration. Throughout its journey along the riverine network, a fraction of carbon is buried in lake and riverine sediments in the form of POC and a fraction of inorganic carbon is lost to the atmosphere in the form of CO_2, while the rest is ultimately transported to estuaries or the coastal ocean. Worldwide, rivers collect roughly 2.7 Gt C/year, of which 0.6 Gt C/year is buried in sediments, 1.1 Gt C/year is emitted to the atmosphere, and about 1 Gt C/year eventually reaches estuaries or the coastal ocean directly (Regnier et al., 2013). These fluxes are shown schematically in Figure 3.

Figure 2. Diverse examples of rivers and estuaries in the land–ocean aquatic continuum. Image credits clockwise from top left: Jessica Furtney, Kermit Nicou, Dan Meyers, Jack Anstey, Alejandro Pinero, Lex Zhao via Unsplash.

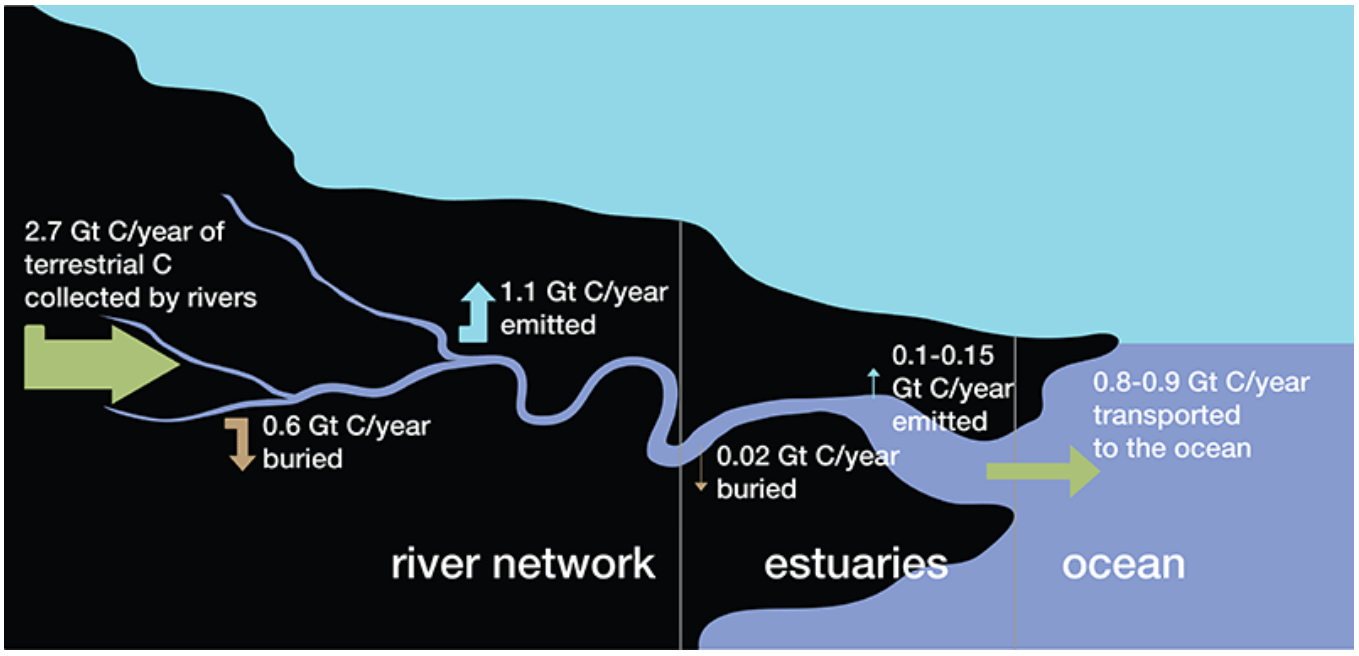

Figure 3. Sources and sinks of aquatic carbon along the land–ocean continuum. The width of arrows scales with the magnitude of the flux.

The next important component of the LOAC, connecting rivers and the coastal ocean, are estuaries. Estuaries are defined as water bodies under both marine and freshwater influence. Several definitions exist for the upstream and downstream limits of an estuary (Pritchard, 1967). The most upstream section of a tidal estuary is called the tidal river, where salinity is insignificant, but the influence of tides still exists. As the width of the estuary increases in the downstream direction, pronounced salinity gradients are present both horizontally and vertically due to dilution by seawater, until the mouth of the estuary is reached, where estuarine water flows into the coastal ocean. Geographically, the downstream limit of an estuary can be defined by the coastline (Dürr et al., 2011). With this definition, the surface area of estuaries amounts to 1 million km^2 globally. However, the influence of large rivers can be observed in the salinity and the water composition well past the coastline, because of their high river discharge. Such an "external estuary" is called a river plume and can spread tens to hundreds of kilometers over continental shelves. Although river plumes are limited to very large rivers with high water discharges, their cumulated surface area amounts to several times that of estuaries (Kang et al., 2013).

To account for their vast diversity and to offer insights into their functioning, several typologies have been designed over the years to better classify estuaries based on their hydrodynamic or geomorphological properties. For instance, the shape and geometry of an estuarine system will exert strong control over its water residence time as well as the lengths of its tidal and saline intrusion. In alluvial estuaries, this shape is the result of the trade-off between fresh sediments carried by rivers and deposited in the estuary and the tidal energy that removes these sediments. The geometry of other estuarine systems, such as fjords, is the result of processes acting over much longer timescales.

Usually, marine and riverine waters have very different concentrations of various chemical species. As a result, estuaries are characterized not only by salinity and tidal gradients, which decrease in the upstream direction, but also strong biogeochemical gradients. Because of the strong dilution of riverine water induced by the widening of the estuary toward the coast, nutrients and many other chemical species display concentration gradients that decrease from the riverine boundary to the marine boundary. This can be observed with organic carbon, particularly in systems under high anthropic pressure, where large amounts of organic matter may be released along the river network by agriculture. The amount of inorganic carbon in the river is largely constrained by the lithology of the watershed.

In terms of pCO_2, riverine waters are generally oversaturated with CO_2 compared to the atmosphere, while at the marine boundary of estuaries, coastal waters are closer to equilibrium with the atmosphere with respect to CO_2. While slightly oversaturated in tropical regions, coastal waters are generally undersaturated in temperate and polar regions. This results in a strong contrast in CO_2 saturation between the upstream and downstream boundaries of estuaries and implies that the exchange of CO_2 at the air–water interface changes significantly in intensity and sometimes direction along the main axis of estuarine systems. Like rivers, estuaries can also trap POC in their sediments. Consequently, they act as a filter between rivers and the coastal ocean that removes a fraction of the incoming riverine carbon through outgassing or burial. This removal is partly a function of the water residence time within the system. The outgassing of CO_2

from estuaries is estimated to amount to 0.10 to 0.15 Gt C/year globally (Chen et al., 2013; Laruelle et al., 2013). Carbon burial estimates within estuarine sediments are still poorly constrained at the global scale but a global synthesis suggests that 0.02 Gt C/year of organic carbon is buried in estuarine sediments (Smith et al., 2015). Because estuaries are disconnected from one another and each is shaped by its own morphological, physical, and biogeochemical characteristics, two neighboring estuaries can exhibit very different biogeochemical behaviors. It is thus difficult to extrapolate observations and estimates from the best-monitored estuaries to regional and global scales. Thus, large uncertainties are associated with these global estimates.

Shelves

Continental shelves, the flooded edges of continents at the transition between land and ocean, form the ultimate link for carbon moving along the LOAC before reaching the open ocean. Shelves vary considerably in their width, from several hundred kilometers along geologically passive margins to tens of kilometers along active subduction zones. Two major pathways of carbon flow, both mediated by the coastal ocean, are input of terrestrial carbon from rivers and estuaries, in both inorganic and organic forms, and uptake of CO_2 from the atmosphere. These carbon inputs are subsequently processed in coastal waters (e.g., by exchange between organic and inorganic forms through primary production, respiration, and other transformations) and are ultimately exported to the open ocean, with smaller fractions being buried in coastal sediments and accumulating in coastal waters.

Shelves receive significant inputs of organic and inorganic carbon and nutrients from rivers and estuaries. A fraction of the inputs are exported to the open ocean via river plumes and are subject only to minor biogeochemical processing on shelves. This export is most efficient for large rivers, where the shelves are narrow, and within ± 20 degrees latitude of the equator, because the influence of Earth's rotation on the circulation of river plumes varies with latitude (Izett & Fennel, 2018a; Sharples et al., 2017). The equatorial latitude band includes the two largest rivers, the Amazon and the Congo, which account for 20% of the global delivery of freshwater to the coastal ocean. Globally, 15% to 53% of freshwater is estimated to be exported to the open ocean within days of leaving the river mouth, most of it within ± 20 degrees of the equator. This export of river-plume water is especially relevant for DOC, a relatively refractory form of organic carbon. Global estimates for export of riverine DOC to the open ocean vary: for example, Rabouille et al. (2001) estimated 15% and Izett and Fennel (2018b) estimated 6% to 52%.

However, outside of the equatorial latitude band, the majority of continental shelf area is comprised of broad shelves, where water resides for weeks, months, and, in some regions, years (Bourgeois et al., 2016; Rutherford & Fennel, 2018). Biogeochemical constituents on these shelves undergo extensive transformations. The CSP has been proposed as a specific mechanism for how the shelves may contribute to the sequestration of carbon in the deep ocean (Tsunogai et al., 1999). While early work on this carbon-pump mechanism suggested a disproportionately large contribution by continental shelf regions to the oceanic uptake of atmospheric CO_2, a number of subsequent observation and modeling studies suggested that the early estimates were too high, and in some regions studies documented net outgassing of CO_2 (Cai et al., 2006; Shadwick et al.,

2010). Evidence that has accumulated since then indicates that continental shelves at mid to high latitudes tend to act as net sinks, and shelves at low latitudes as net sources, of atmospheric CO_2 (Laruelle et al., 2014; Roobaert et al., 2019), but there are exceptions. For example, the northwest North Atlantic shelf has regions with net outgassing (Rutherford & Fennel, 2022; Vandemark et al., 2011). These findings emphasize the large uncertainties in scaling up from limited measurements to shelfwide air–sea CO_2 fluxes and a need for more mechanistic understanding.

An assessment of carbon fluxes in the exclusive economic zone (EEZ) around the North American continent suggests that the Arctic and sub-Arctic, mid-latitude Atlantic, and mid-latitude Pacific portions of the EEZ, which make up 51%, 25%, and 24% of its area, respectively, account for 104, 62, and -3.7 Tg C/year of air–sea fluxes (Fennel et al., 2019). Combining this net uptake of 160 ± 80 Tg C/year with an estimated carbon input from land of 106 ± 30 Tg C/year minus an estimated burial of 65 ± 55 Tg C/year and an estimated accumulation of dissolved carbon in EEZ waters of 50 ± 25 Tg C/year implies a carbon export of 151 ± 105 Tg C/year to the open ocean (Fennel et al., 2019). This estimate of atmospheric carbon uptake in the North American EEZ amounts to 6.4% of the global ocean uptake of atmospheric CO_2 of 2,500 Tg C/year (Le Quéré et al., 2015). Thus, since the North American EEZ makes up about 4% of the surface area of the global ocean, its uptake of CO_2 is about 50% more efficient than the global average.

Overview of Carbon Cycling in Major Coastal Regions/Habitats

Located along and within the estuarine and shelf systems described above, vegetated, coral reef, and permafrost regions are of socioeconomic interest for providing species habitat and coastal protection and for supporting tourism and the blue economy. Some regions are important contributors to carbon cycling, while others are strongly affected by the changes in carbon cycling and global warming.

Mangroves, Seagrass, and Marshes

Mangroves, seagrass meadows, and saltmarshes (together known as coastal vegetated habitats; Figure 4) provide substantial societal benefits, including fisheries habitat and production, coastal protection, nutrient and sediment retention, and erosion control (Barbier et al., 2011). Coastal vegetated habitats are also among the most productive and carbon-rich ecosystems globally (Duarte et al., 2005; McLeod et al., 2011; Spivak et al., 2019). The ecosystem services provided by these habitats rank them as some of the most valuable habitats globally (Costanza et al., 1997).

Figure 4. Examples of vegetated habitats. Image credits clockwise from top left: Bre Smith, Sofia Wang, A. P. Djalu, Hayden Dunsel, Timothy K., Curioso Photography via Unsplash.

With increasing atmospheric CO_2, the potential role of natural carbon sinks has gained increasing attention, resulting in a significant shift in research effort in coastal vegetated habitats. As a result of a general lack of oxygen in their soils and high rates of sedimentation and primary productivity, carbon burial rates in coastal vegetated habitats are relatively high and can exceed terrestrial forest-soil carbon-sequestration rates by one to two orders of magnitude (McLeod et al., 2011). The high carbon sequestration capacity of coastal vegetated habitats has been called blue carbon (Nelleman et al., 2008). Research on understanding the drivers and magnitude of carbon storage and sequestration in coastal vegetated habitats has grown substantially from 2010 to 2020, making up ~20% of total publications on mangroves, seagrass, and saltmarshes at the end of the decade.

Despite significant advances in our understanding of the carbon cycle of coastal vegetated habitats, substantial knowledge gaps remain. For example, until recently, the fate of ~50% of the net primary productivity of mangroves could not be accounted for (Bouillon et al., 2008), the fate of seagrass net primary productivity remains highly uncertain (Duarte & Krause-Jensen, 2017), and the global saltmarsh carbon budget suffers from a lack of data on key processes (Alongi, 2020; Santos et al., 2021). Much of the uncertainty in constraining the carbon budget of coastal vegetated habitats stems from their position in the intertidal and subtidal zone, resulting in the need to quantify not only local carbon sources and sinks (primary productivity/respiration and soil carbon sequestration), but also horizontal or lateral fluxes of carbon in dissolved and particulate forms as well as inorganic and organic forms (Figure 5). Therefore, a multidisciplinary approach is required, incorporating traditional productivity measurements (e.g., chambers, gas

flux towers, and litterfall estimates), geochronology techniques to assess carbon burial in sediments (e.g., sediment dating, marker horizons, and surface elevation tables), and hydrological methods to determine lateral particulate and dissolved carbon fluxes in wetland streams, as well as mapping to measure changes in spatial extent.

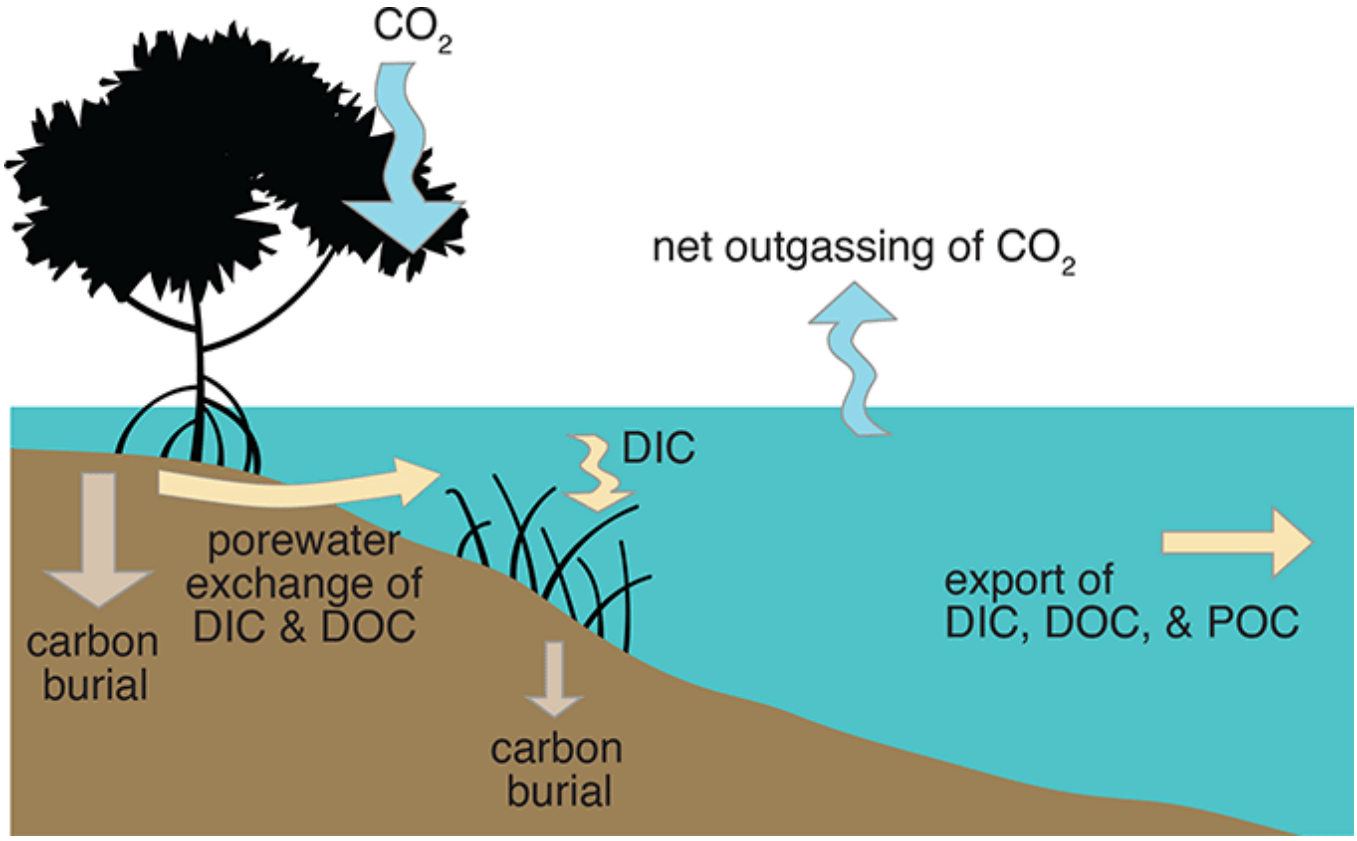

Figure 5. Net carbon fluxes in the subtidal and intertidal zone.

Recent evidence suggests that much of the uncertainty in the global carbon budget of mangroves and saltmarshes can be linked to the historical emphasis on measuring organic carbon fluxes at the expense of inorganic carbon fluxes. Several studies have highlighted that DIC export may be the dominant sink of saltmarsh and mangrove net primary productivity (Bouillon et al., 2008; Ho et al., 2017; Wang et al., 2016). Much of this DIC is produced in the sediments, which is efficiently flushed to surface waters through the effect of tides, a process known as tidal pumping. As a result of the anaerobic processes producing this DIC, much of the carbon is in the form of carbonate alkalinity, which may act as a long-term atmospheric carbon sink (Maher et al., 2018). A similar debate is currently underway about whether the extensive organic matter exports from seagrass meadows in the form of DOC and POC act as a long-term atmospheric carbon sink (Duarte & Krause-Jensen, 2017).

While coastal vegetated habitats clearly "punch above their weight" in terms of carbon sequestration and other societal values, they have experienced considerable decline in coverage. Coastal vegetated habitats are under increasing pressure from a range of anthropogenic

stressors, including urban, aquaculture, and agriculture development in the coastal zone, sea-level rise, and climate change (Spivak et al., 2019). For example, mangrove coverage is reported to have decreased by up to 35% since 1980 (Polidoro et al., 2010; Valiela et al., 2001), with much of the decline due to land-use change in the coastal zone (Goldberg et al., 2020). Similarly, saltmarsh area is believed to have decreased by up to 50% of historical coverage (Mcowen et al., 2017) and seagrass area has declined by ~29% since the late 19th century (Waycott et al., 2009).

Efforts to include blue carbon in government carbon accounting (e.g., the Emissions Reduction Fund in Australia), as well as an appetite for blue carbon projects in voluntary carbon markets (Sapkota & White, 2020), may ultimately be the savior for coastal vegetated ecosystems, with multiple benefits associated with healthy coastal habitats. Data on national inventories (see Serrano et al., 2019) have highlighted the value of carbon storage and sequestration in coastal vegetated habitats, stimulating the push toward method development for carbon credits associated with coastal wetland restoration. For example, Verra has developed a Verified Carbon Standard for coastal wetland restoration, and large corporations, such as Apple, have ventured into the blue carbon market through purchasing carbon offsets. How much coastal vegetated habitat will be restored through carbon credit schemes remains to be seen, but financial incentives for conservation and restoration may help stem the tide of destruction of these valuable carbon-cycling dynamos of the coastal zone.

Coral Reefs

Coral reefs are iconic ecosystems that provide goods and services to millions of people worldwide and support tremendous biodiversity (Moberg & Folke, 1999; Figure 6). Reefs are geological structures formed from the production and accumulation of calcium carbonate ($CaCO_3$) minerals by corals and other calcifying organisms (Hopley, 2011). The resulting complex three-dimensional reef structure provides habitat for over 30% of all marine species at some point during their life cycle (Fisher et al., 2015). In general, the two dominant carbon fluxes on reefs (i.e., production and calcification) are collectively referred to as coral reef metabolism.

Over long time frames and averaged across ecosystems, the production and destruction of organic carbon on coral reefs are thought to be relatively balanced (Gattuso et al., 1999; Takeshita et al., 2018). The fact that reefs exist in predominantly low-nutrient waters indicates that they are highly efficient at recycling carbon and nutrients. Most of the accumulated organic carbon is found as the thin veneer of coral tissue covering the $CaCO_3$ skeletons, and accumulation of organic matter in reef sediments is small (up to 3%, but generally less than 1% wt/wt), providing further indication that these systems are efficient recyclers of carbon. There is only minimal export and burial of organic carbon (Ingalls et al., 2004; Umezawa et al., 2008), while reefs accumulate large amounts of inorganic carbon as $CaCO_3$. Much less is known about the cycling of DOC on reefs, which is generally found in concentrations on orders of magnitude less than DIC (Tanaka, Miyajima, et al., 2011; Tanaka, Ogawa, & Miyajima, 2011). The uptake of DOC by sponges and its subsequent release as POC—referred to as the sponge loop—is thought to be a critical carbon pathway on some coral reefs that can recycle and retain organic carbon and nutrients within reef ecosystems (de Goeij et al., 2013; Pawlik et al., 2018).

Figure 6. Examples of reefs and corals. Image credits clockwise from top left: Ibrahim Mushan, Francesco Ungaro, Francesco Ungaro, Eva Tillmann, Milan Degraeve, Dustin Humes via Unsplash.

Coral reefs dominate the production and accumulation of $CaCO_3$ in shallow oceanic ecosystems. Estimates of global $CaCO_3$ accumulation rates for coral reefs range from 0.084 to 0.7 Pg C/year, with the most recent studies placing reefs at the low end of that range (Iglesias-Rodriguez et al., 2002; Milliman, 1993; O'Mara & Dunne, 2019). While modern reefs make up less than 0.1% of the seafloor, they contribute to over 50% of yearly neritic $CaCO_3$ accumulation, and nearly 25% of $CaCO_3$ accumulation across the global ocean (Milliman, 1993; O'Mara & Dunne, 2019). Modern $CaCO_3$ production and accumulation rates within coral reefs exhibit a wide range and are linked to habitat type (e.g., reef flat, fore reef) and benthic cover (Kinsey, 1983; Perry et al., 2012). In a geological context, $CaCO_3$ accretion is closely linked to changes in sea level, which can expand and shrink areas of the seafloor that are suitable for reef growth (Husson et al., 2018; Montaggioni, 2005; Montaggioni & Faure, 1997). In fact, past appearances and disappearances of reefs in the geological record since hard corals first evolved have been linked to broad changes in Earth's carbon cycle (Veron, 2008; Webb, 2001).

Coral reefs are self-perpetuating ecosystems, with $CaCO_3$ structure providing the critical function and role of habitat building. Therefore, maintaining positive rates of $CaCO_3$ production and accretion is essential for the survival of diverse and productive reef ecosystems (Perry & Alvarez-Filip, 2019). The three major impacts of anthropogenic climate change on the oceans (i.e., warming, sea-level rise, and acidification) all directly affect the formation and development of coral reef ecosystems. Therefore, modern climate change is likely to dramatically disrupt the carbon cycle in coral reefs (Hoegh-Guldberg, 2011; Kleypas et al., 2001).

Modern reefs are already experiencing impacts due to ocean warming, with temperature-driven mass bleaching events (i.e., the expulsion of algal symbionts) occurring more frequently (Hughes et al., 2017). The bleaching events can lead to widespread coral death and transform the ecology and benthic assemblages of entire reef ecosystems (Hughes et al., 2018). The transformation of reefs from coral to algal domination will dramatically impact their carbon cycle by changing rates of photosynthesis, respiration, and calcification (Roth et al., 2021). Range shifts of corals have also been attributed to warming, suggesting that climate change may expand habitat suitable for coral growth (Kumagai et al., 2018; Price et al., 2019; Yamano et al., 2011).

Changes in sea level will likely change the geomorphological evolution of reefs by providing more vertical space for reefs to grow, as long as $CaCO_3$ accretion can keep up (Perry & Alvarez-Filip, 2019; Webster et al., 2004, 2018). Sea-level rise could also impact local variability of environmental conditions, including the carbonate chemistry, in shallow reef ecosystems (Cyronak et al., 2020; Lowe et al., 2016).

Last, ocean acidification is expected to reduce biogenic coral calcification (Chan & Connolly, 2013) and increase $CaCO_3$ dissolution (Eyre et al., 2014), which will critically affect reef $CaCO_3$ budgets and accretion rates (Albright et al., 2016). Overall, coral reefs are facing numerous threats from both global and local anthropogenic change that will greatly impact their carbon cycle.

Permafrost

A third of Earth's coastlines is made up of permafrost, defined as ground on land or in the marine seabed that remains frozen for at least two years consecutively. Permafrost has not historically been a focus of coastal carbon budgets, but as global warming is increasingly mobilizing carbon stored in permafrost, it is receiving more attention.

Permafrost contains ~1,300 Gt of organic carbon, about twice as much carbon as the atmosphere (Hugelius et al., 2014; Tarnocai et al., 2009; Zimov et al., 2006). As the upper decimeters to meters of these frozen grounds thaw, organic matter decomposes, and the resulting CO_2 and CH_4 are emitted into the atmosphere, rivers, groundwater, and ocean. The thaw may occur seasonally, but it is increasing with warming temperatures. In Russia, for example, the maximum thaw depth increased by about 20 cm vertically between 1956 and 1990 (Frauenfeld et al., 2004). While the extent of organic matter decomposition following thaw remains poorly quantified, with 1% to 76% of material undergoing microbial degradation under laboratory conditions over a decade, permafrost environments likely are a growing source of carbon to the atmosphere and ocean (Schuur et al., 2015; Tanski et al., 2019; Vonk et al., 2012; and references therein).

One major pathway for the delivery of carbon mobilized from permafrost to the coastal ocean is via rivers and groundwater. The five largest Arctic rivers, for instance, contribute over 16 Tg per year of DOC (Raymond et al., 2007). POC is estimated to contribute 5 to 7 Tg per year (McClelland et al., 2016; McGuire et al., 2009; Ping et al., 2011). Given that these inputs are related to river discharge, future changes are expected to depend on changes in the hydrological cycle. Dissolved carbon export to the coastal ocean, for example, is correlated with water discharge, which is strongly related to permafrost active-layer thickness, the depth to which soils thaw seasonally

(Mu et al., 2019), and is therefore expected to increase as permafrost thaws. In addition to river input, increased thaw of subsea permafrost may also enhance decomposition of organic matter and allow for diffusion of CO_2 and CH_4 from the seabed into ocean waters (Shakhova et al., 2014).

Coastal carbon budgets in regions with permafrost have also included carbon fluxes from permafrost to the ocean via shoreline erosion (Moon et al., 2019). Ping et al. (2011) estimated that coastal erosion contributes about 15% of the total terrigenous organic carbon flux to the Arctic Ocean (41 Tg per year). Moreover, changes in environmental conditions (e.g., warmer temperatures, reduced sea ice, higher sea level, and stronger waves) have increased shoreline erosion rates. Along the coast of the Alaskan Beaufort Sea, for example, mean annual erosion rates increased from 6.8 m per year (1955–1979) to 8.7 m per year (1979–2002), to 13.6 m per year (2002–2007; Jones et al., 2009), increasing the delivery of carbon to the coast.

Given the rapidly changing nature of permafrost, Arctic regions generally, and their relatively remote location, estimating baseline and future carbon inputs into the coastal ocean remains difficult. Yet, the projected impacts of climate change on permafrost systems imply that these regions are important components of coastal carbon budgets.

Summary

Coastal regions host a diverse set of valuable and vulnerable habitats that also play an important role in the global carbon cycle. Thus, quantification of coastal carbon fluxes and a mechanistic understanding of the processes underpinning the fluxes are important for two main reasons: the carbon cycle is a major driver of climate change, and fixation and respiration of carbon are central to life and the functioning of coastal ecosystems. In the context of climate change, an accurate accounting of exchanges of carbon between its mobile reservoirs on land and in the ocean is imperative for predicting and mitigating climate change. Regarding coastal ecosystems, anthropogenic activities are exerting several compounding pressures that threaten the services they provide.

Quantification of coastal reservoirs and fluxes is an active research area with many remaining unknowns and uncertainties. Challenges and sources of uncertainty include the variability and diversity of estuarine, coastal, and shelf systems, both in terms of spatial and temporal scales and in terms of differences in functioning due to the specific geography and hydrography of each system. The high variability relative to typically observable scales makes it difficult to accurately quantify reservoirs and fluxes, and to scale up local observations to the global scale. The great heterogeneity of coasts around the globe results in distinct questions in different systems and distinct local issues. Despite these difficulties, quantification of these pathways and their rates is needed for global and national carbon accounting and for assessment, and possibly mitigation, of deleterious impacts.

References

Albright, R., Caldeira, L., Hosfelt, J., Kwiatkowski, L., Maclaren, J. K., Mason, B. M., Nebuchina, Y., Ninokawa, A., Pongratz, J., Ricke, K. L., Rivlin, T., Schneider, K., Sesboüé, M., Shamberger, K., Silverman, J., Wolfe, K., Zhu, K., & Caldeira, K. (2016). Reversal of ocean acidification enhances net coral reef calcification. *Nature*, *531*, 362.

Alley, R. B. (2000). *The two-mile time machine: Ice cores, abrupt climate change, and our future*. Princeton University Press.

Alongi, D. M. (2020). Carbon balance in salt marsh and mangrove ecosystems: A global synthesis. *Journal of Marine Science and Engineering*, *8*(10).

Atwood, T. B., Witt, A., Mayorga, J., Hammill, E., & Sala, E. (2020). Global patterns in marine sediment carbon stocks <https://doi.org/10.3389/fmars.2020.00165>. *Frontiers in Marine Science*, *7*, 165.

Barbier, E. B., Hacker, S. D., Kennedy, C., Koch, E. W., Stier, A. C., & Silliman, B. R. (2011). The value of estuarine and coastal ecosystem services. *Ecological Monographs*, *81*(2), 169–193.

Barnola, J., Raynaud, D., Korotkevich, Y. S., & Lorius, C. (1987). Vostok ice core provides 160,000-year record of atmospheric CO_2 <https://doi.org/10.1038/329408a0>. *Nature*, *329*, 408–414.

Bauer, J. E., Cai, W.-J., Raymond, P. A., Bianchi, T. S., Hopkinson, C. S., & Regnier, P. A. G. (2013). The changing carbon cycle of the coastal ocean <https://doi.org/10.1038/nature12857>. *Nature*, *504*, 61–70.

Beaton, A. D., Wadham, J. L., Hawkings, J., Bagshaw, E. A., Lamarche-Gagnon, G., Mowlem, M. C., & Tranter, M. (2017). High-resolution in situ measurement of nitrate in runoff from the Greenland ice sheet <https://doi.org/10.1021/acs.est.7b03121>. *Environmental Science & Technology*, *51*(21), 12518–12527.

Bishop, J. K. B. (1999). Transmissometer measurement of POC. *Deep-Sea Research I*, *46*, 353369.

Bishop, J. K. B., Fong, M. B., & Wood, T. J. (2016). Robotic observations of high wintertime carbon export in California coastal waters <https://doi.org/10.5194/bg-13-3109-2016>. *Biogeosciences*, *13*, 3109–3129.

Bouillon, S., Borges, A. V., Castaneda, E., Diele, K., Dittmar, T., Duke, N. C., Kristensen, E., Lee, S. Y., Marchand, C., Middelburg, J. J., Rivera-Monroy, V. H., Smith, T. J., & Twilley, R. R. (2008). Mangrove production and carbon sinks: A revision of global budget estimates. *Global Biogeochemical Cycles*, *22*, GB2013.

Bourgeois, T., Orr, J. C., Resplandy, L., Terhaar, J., Ethá, C., Gehlen, M., & Bopp, L. (2016). Coastal-ocean uptake of anthropogenic carbon <https://doi.org/10.5194/bg-13-4167-2016>. *Biogeosciences*, *13*, 4167–4185.

Broecker, W. S. (1982). Glacial to interglacial changes in ocean chemistry. *Progress in Oceanography*, *11*, 151–197.

Bushinsky, S. M., Takeshita, Y., & Williams, N. L. (2019). Observing changes in ocean carbonate chemistry: Our autonomous future. *Current Climate Change Reports*, *5*, 207–220.

Cai, W.-J., Dai, M., & Wang, Y. (2006). Air-sea exchange of carbon dioxide in ocean margins: A province-based synthesis <https://doi.org/10.1029/2006GL026219>. *Geophysical Research Letters*, *33*(12), L12603.

Chai, F., Johnson, K. S., Claustre, H., Xing, X., Wang, Y., Boss, E., Riser, S., Fennel, K., Oscar Schofield, O., Sutton, A. (2020). Monitoring ocean biogeochemistry with autonomous platforms <https://doi.org/10.1038/s43017-020-0053-y>. *Nature Reviews Earth & Environment*, *1*(6), 315–326.

Chan, N. C. S., & Connolly, S. R. (2013). Sensitivity of coral calcification to ocean acidification: A meta-analysis. *Global Change Biology*, *19*, 282–290.

Chen, C. T. A., & Borges, A. V. (2009). Reconciling opposing views on carbon cycling in the coastal ocean: Continental shelves as sinks and near-shore ecosystems as sources of atmospheric CO_2. *Deep Sea Research Part II Topical Studies in Oceanography*, *56*(8–10), 578–590.

Chen, C.-T. A., Huang, T.-H., Chen, Y.-C., Bai, Y., He, X., & Kang, Y. (2013). Air–sea exchanges of CO_2 in the world's coastal seas <https://doi.org/10.5194/bg-10-6509-2013>. *Biogeosciences*, *10*, 6509–6544.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R. B., Piao, S., & Tornton, P. (2013). Carbon and other biogeochemical cycles. In T. F. Stocker, D. Qin, G. K. Platner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Climate change 2013: The physical science basis* (pp. 465–570). Cambridge University Press.

Costanza, R., d'Arge, R., de Groot, R., Farber, S., Grasso, M., Hannon, B., Limburg, K., Naeem, S., O'Neill, R. V., Paruelo, J., Raskin, R. G., Sutton, P., & van den Belt, M. (1997). The value of the world's ecosystem services and natural capital. *Nature*, *387*, 253–260.

Cullison-Gray, S. E., DeGrandpre, M. D., Moore, T. M., Martz, T. R., Friederich, G. E., & Johnson, K. S. (2011). Applications of in situ pH measurements for inorganic carbon calculations. *Marine Chemistry*, *125*, 82–90.

Cyr, F., Tedetti, M., Besson, F., Beguery, L., Doglioli, A. M., Petrenko, A. A., & Goutx, M. (2017). A new glider-compatible optical sensor for dissolved organic matter measurements: Test case from the NW Mediterranean Sea <https://doi.org/10.3389/fmars.2017.00089>. *Frontiers in Marine Science*, *4*, 89.

Cyronak, T., Takeshita, Y., Courtney, T. A., DeCarlo, E. H., Eyre, B. D., Kline, D. I., Martz, T., Page, H., Price, N. N., Smith, J., Stoltenberg, L., Tresguerres, M., & Anderssonland, A. J. (2020). Diel temperature and pH variability scale with depth across diverse coral reef habitats. *Limnology and Oceanography Letters*, *5*, 193–203.

de Goeij, J. M., van Oevelen, D., Vermeij, M. J. A., Osinga, R., Middelburg, J. J., de Goeij, A. F. P. M., & Admiraal, W. (2013). Surviving in a marine desert: The sponge loop retains resources within coral reefs. *Science*, *342*, 108–110.

DeGrandpre, M. D., Hammar, T. R., Smith, S. P., & Sayles, F. L. (1995). In situ measurements of seawater pCO_2. *Limnology & Oceanography*, *40*, 969–975.

Duarte, C. M., & Krause-Jensen, D. (2017). Export from seagrass meadows contributes to marine carbon sequestration. *Frontiers in Marine Science*, *4*, 13.

Duarte, C. M., Middleburg, J. J., & Caraco, N. (2005). Major role of marine vegetation on the oceanic carbon cycle. *Biogeosciences*, *2*, 1–8.

Dürr, H. H., Laruelle, G. G., Van Kempen, C. M., Slomp, C. P., Maybeck, M., & Middelkoop, H. (2011). World-wide typology of nearshore coastal systems: Defining the estuarine filter of river inputs to the oceans. *Estuaries Coasts*, *34*, 441–458.

Evans, W., Hales, B., & Strutton, P. G. (2011). Seasonal cycle of surface ocean pCO_2 on the Oregon shelf <https://doi.org/10.1029/2010JC006625>. *Journal of Geophysical Research*, *116*, C05012.

Eyre, B. D., Andersson, A. J., & Cyronak, T. (2014). Benthic coral reef calcium carbonate dissolution in an acidifying ocean. *Nature Climate Change*, *4*, 969–976.

Falkowski, P., Scholes, R. J., Boyle, E., Canadell, J., Canfield, D., Elser, J., Gruber, N., Hibbard, K., Högberg, P., Linder, S., Mackenzie, F. T., Moore, B., 3rd, Pedersen, T., Rosenthal, Y., Seitzinger, S., Smetacek, V., & Steffen, W. (2000). The global carbon cycle: A test of our knowledge of Earth as a system. *Nature*, *290*, 291–296.

Fassbender, A. J., Sabine, C. L., Lawrence-Slavas, N., De Carlo, E. H., Meinig, C., & Maenner Jones, S. (2015). Robust sensor for extended autonomous measurements of surface ocean dissolved inorganic carbon <https://doi.org/10.1021/es5047183>. *Envrironmental Science & Technology*, *49*, 3628–3635.

Fennel, K., Alin, S., Barbero, L., Evans, W., Bourgeois, T., Cooley, S., Dunne, J., Feely, R. A., Hernandez-Ayon, J. M., Hu, X., Lohrenz, S., Muller-Karger, F., Najjar, R., Robbins, L., Shadwick, E., Siedlecki, S., Steiner, N., Sutton, A., Turk, D., . . . Wang, Z. A. (2019). Carbon cycling in the North American coastal ocean: A synthesis <https://doi.org/10.5194/bg-16-1281-2019>. *Biogeosciences*, *16*, 1281–1304.

Fischer, A. D., Hayashi, K., McGaraghan, A., & Kudela, R. (2020). Return of the “age of dinoflagellates” in Monterey Bay: Drivers of dinoflagellate dominance examined using automated imaging flow cytometry and long-term time series analysis. *Limnology and Oceanography*, *9999*, 1–17

Fisher, R., O’Leary, R. A., Low-Choy, S., Mengersen, K., Knowlton, N., Brainard, R. E., & Julian Caley, M. (2015). Species richness on coral reefs and the pursuit of convergent global estimates. *Current Biology*, *25*, 500–505.

Fourier, J-B. F. (1827). On the temperatures of the terrestrial sphere and interplanetary space. *Memoires de l’Academie Royale des Sciences*, *7*, 569–604.

Frauenfeld, O. W., Zhang, T., Barry, R. G., & Gilichinsky, D. (2004). Interdecadal changes in seasonal freeze and thaw depths in Russia <https://doi.org/10.1029/2003JD004245>. *Journal of Geophysical Research*, *109*, D05101.

Friederich, G. E., Brewer, P. G., Herlien, R., & Chavez, F. P. (1995). Measurements of sea surface partial pressure of CO_2 from a moored buoy. *Deep-Sea Research I*, *42*, 1175–1186.

Friedlingstein, P., Jones, M. W., O’Sullivan, M., Andrew, R. M., Hauck, J., Peters, G. P., Peters, W., Pongratz, J., Sitch, S., Le Quéré, C., Bakker, D. C. E., Canadell, J. G., Ciais, P., Jackson, R. B., Anthoni, P., Barbero, L., Bastos, A., Bastrikov, V., Becker, M., . . . Zaehle, S. (2019). Global carbon budget 2018. *Earth System Science Data*, *11*, 1783–1838.

Gattuso, J.-P., Allemand, D., & Frankignoulle, M. (1999). Photosynthesis and calcification at cellular, organismal and community levels in coral reefs: A review on interactions and control by carbonate chemistry. *American Zoologist*, *39*, 160–183.

Gattuso, J. P., Frankignoulle, M., & Wollast, R. (1998). Carbon and carbonate chemistry in coastal aquatic ecosystems <https://doi.org/10.1146/annurev.ecolsys.29.1.405>. *Annual Review of Ecology and Systematics*, *29*, 405–434.

Goldberg, L., Lagomasino, D., Thomas, N., & Fatoyinbo, T. (2020). Global declines in human-driven mangrove loss. *Global Change Biology*, *26*(10), 5844–5855.

Hansell, D. A., Carlson, C. A., Repeta, D. J., & Schlitzer, R. (2009). Dissolved organic matter in the ocean: A controversy stimulates new insights <https://doi.org/10.5670/oceanog.2009.109>. *Oceanography*, *22*(4), 202–211.

Harris, K. E., DeGrandpre, M. D., & Hales, B. (2013). Aragonite saturation state dynamics in a coastal upwelling zone <https://doi.org/10.1002/grl.50460>. *Gephysical Research Letters*, *40*(11), 2720–2725.

Ho, D. T., Ferrón, S., Engel, V. C., Anderson, W. T., Swart, P. K., Price, R. M., & Barbero, L. (2017). Dissolved carbon biogeochemistry and export in mangrove-dominated rivers of the Florida Everglades <https://doi.org/10.5194/bg-14-2543-2017>. *Biogeosciences*, *14*, 2543–2559.

Hoegh-Guldberg, O. (2011). Coral reef ecosystems and anthropogenic climate change. *Regional Environmental Change*, *11*, 215–227.

Hopley, D. (2011). *Encyclopedia of modern coral reefs: Structure, form and process*. Springer.

Hugelius, G., Strauss, J., Zubrzycki, S., Harden, J. W., Schuur, E. A., Ping, C.-L., Schirrmeister, L., Grosse, G., Michaelson, G. J., Koven, C. D., O'Donnell, J. A., Elberling, B., Mishra, U., Camill, P., Yu, Z., Palmtag, J., & Kuhry, P. (2014). Estimated stocks of circumpolar permafrost carbon with quantified uncertainty ranges and identified data gaps. *Biogeosciences*, *11*, 6573–6593.

Hughes, T. P., Kerry, J. T., Álvarez-Noriega, M., Álvarez-Romero, J. G., Anderson, K. D., Baird, A. H., Babcock, R. C., Beger, M., Bellwood, D. R., Berkelmans, R., Bridge, T. C., Butler, I. R., Byrne, M., Cantin, N. E., Comeau, S., Connolly, S. R., Cumming, G. S., Dalton, S. J., Diaz-Pulido, G., . . . Wilson, S. K. (2017). Global warming and recurrent mass bleaching of corals. *Nature*, *543*, 373–377.

Hughes, T. P., Kerry, J. T., Baird, A. H., Connolly, S. R., Dietzel, A., Eakin, C. M., Heron, S. F., Hoey, A. S., Hoogenboom, M. O., Liu, G., McWilliam, M. J., Pears, R. J., Pratchett, M. S., Skirving, W. J., Stella, J. S., & Torda, G. (2018). Global warming transforms coral reef assemblages. *Nature*, *556*, 492–496.

Hunter-Cevera, K. R., Neubert, M. G., Olson, R. J., Solow, A. R., Shalapyonok, A., & Sosik, H. M. (2016). Physiological and ecological drivers of early spring blooms of a coastal phytoplankter <https://doi.org/%2010.1126/science.aaf8536>. *Science*, *354*, 326–329.

Husson, L., Pastier, A.-M., Pedoja, K., Elliot, M., Paillard, D., Authemayou, C., Sarr, A.-C., Schmitt, A., & Cahyarini, S. Y. (2018). Reef carbonate productivity during quaternary sea level oscillations. *Geochemistry, Geophysics, Geosystems*, *19*, 1148–1164.

Iglesias-Rodriguez, M. D., Armstrong, R., Feely, R., Hood, R., Kleypas, J., Milliman, J. D., Sabine, C., & Sarmiento, J. (2002). Progress made in study of ocean's calcium carbonate budget. *Eos, Transactions American Geophysical Union*, *83*, 365–375.

Ingalls, A. E., Aller, R. C., Lee, C., & Wakeham, S. G. (2004). Organic matter diagenesis in shallow water carbonate sediments. *Geochimica et Cosmochimica Acta*, *68*, 4363–4379.

Izett, J., & Fennel, K. (2018a). Estimating the cross-shelf export of riverine materials, Part 1: General relationships from an idealized numerical model. *Global Biogeochemical Cycles*, *32*, 160–175.

Izett, J., & Fennel, K. (2018b). Estimating the cross-shelf export of riverine materials, Part 2: Estimates of global freshwater and nutrient export. *Global Biogeochemical Cycles*, *32*, 176–186.

Johnson, K. S., Needoba, J. A., Riser, S. C., & Showers, W. J. (2007). Chemical sensor networks for the aquatic environment. *Chemical Reviews*, *107*, 623−640.

Jones, B. M., Arp, C. D., Jorgenson, M. T., Hinkel, K. M., Schmutz, J. A., & Flint, P. L. (2009). Increase in the rate and uniformity of coastline erosion in Arctic Alaska <https://doi.org/10.1029/2008GL036205>. *Geophysical Research Letters*, *36*,L03503.

Kang, Y., Pan, D., Bai, Y., He, X., Chen, X., Chen, C.-T. A., & Wang, D. (2013). Areas of the global major river plumes <https://doi.org/10.1007/s13131-013-%200269-5>. *Acta Oceanologica Sinica*, *32*, 79–88.

Kinsey, D. W. (1983). *Standards of performance in coral reef primary production and carbon turnover*. Australian Institute of Marine Science.

Kinsey, D., & Davies, P. (1979). *Carbon turnover, calcification and growth in coral reefs*. Elsevier.

Kleypas, J. A., Buddemeier, R. W., & Gattuso, J.-P. (2001). The future of coral reefs in an age of global change. *International Journal of Earth Sciences*, *90*, 426–437.

Kumagai, N. H., García Molinos, J., Yamano, H., Takao, S., Fujii, M., & Yamanaka, Y. (2018). Ocean currents and herbivory drive macroalgae-to-coral community shift under climate warming. *Proceedings of the National Academy of Sciences*, *115*, 8990–8995.

Lai, C.-Z., DeGrandpre, M., & Darlington, R. (2018). Autonomous optofluidic chemical analyzers for marine applications: Insights from the Submersible Autonomous Moored Instruments (SAMI) for pH and pCO_2 <https://doi.org/10.3389/fmars.2017.00438>. *Frontiers in Marine Science*, *4*, 438.

Langdon, C. (1984). Dissolved oxygen monitoring system using a pulsed electrode: Design, performance, and evaluation. *Deep Sea Research Part A. Oceanographic Research Papers*, *31*, 1357–1367.

Laruelle, G. G., Dürr, H. H., Lauerwald, R., Hartmann, J., Slomp, C. P., Goossens, N., & Regnier, P. A. G. (2013). Global multi-scale segmentation of continental and coastal waters from the watersheds to the continental margins <https://doi.org/10.5194/hess-17-2029-2013>. *Hydrology and Earth System Sciences*, *17*, 2029–2051.

Laruelle, G. G., Durr, H. H., Slomp, C. P., & Borges, A. V. (2010). Evaluation of sinks and sources of CO_2 in the global coastal ocean using a spatially explicit typology of estuaries and continental shelves <https://doi.org/10.1029/2010GL043691>. *Geophysical Research Letters*, *37*, L15607.

Laruelle, G. G., Lauerwald, R., Pfeil, B., & Regnier, P. (2014). Regionalized global budget of the CO_2 exchange at the air–water interface in continental shelf seas <https://doi.org/10.1002/2014GB004832>. *Global Biogeochemical Cycles*, *28*(11), 1199–1214.

Le Quéré, C., Moriarty, R., Andrew, R. M., Canadell, J. G., Sitch, S., Korsbakken, J. I., Friedlingstein, P., Peters, G. P., Andres, R. J., Boden, T. A., Houghton, R. A., House, J. I., Keeling, R. F., Tans, P., Arneth, A., Bakker, D. C. E., Barbero, L., Bopp, L., Chang, J., . . . Zeng, N. (2015). Global carbon budget. *Earth System Science Data*, *7*, 349–396.

Liu, X., Want, Z. A., Byrne, R. H., Kaltenbackher, E. A., & Bernstein, R. E. (2006). Spectrophotometric measurements of pH in-situ: Laboratory and field evaluations of instrumental performance. *Environmental Science and Technology*, *40*, 5036–5044.

Lowe, R. J., Pivan, X., Falter, J., Symonds, G., & Gruber, R. (2016). Rising sea levels will reduce extreme temperature variations in tide-dominated reef habitats. *Science Advances*, *2*.

Maher, D. T., Call, M., Santos, I. R., & Sanders, C. J. (2018). Beyond burial: Lateral exchange is a significant atmospheric carbon sink in mangrove forests. *Biology Letters*, *14*(7), 20180200.

Maier-Reimer, E., & Hasselmann, K. (1987). Transport and storage of CO_2 in the ocean—An inorganic ocean-circulation carbon cycle model. *Climate Dynamics*, *2*, 63–90.

Martz, T. R., Connery, J. G., & Johnson, K. S. (2010). Testing the Honeywell Durafet for seawater pH applications. *Limnology & Oceanography Methods*, *8*, 172–184.

McClelland, J. W., Holmes, R. M., Peterson, B. J., Raymond, P. A., Striegl, R. G., Zhulidov, A. V., Zimov, S. A., Zimov, N., Tank, S. E., Spencer, R. G., Staples, R., Gurtovaya, T. Y., & Griffin, C. G. (2016). Particulate organic carbon and nitrogen export from major Arctic rivers <https://doi.org/10.1002/2015GB005351>. *Global Biogeochemical Cycles*, *30*, 629–643.

McGuire, A. D., Anderson, L. G., Christensen, T. R., Dallimore, S., Guo, L., Hayes, D. J., Heimann, M., Lorenson, T. D., Macdonald, R. W., & Roulet, N. (2009). Sensitivity of the carbon cycle in the Arctic to climate change. *Ecological Monographs*, *79*(4), 523–555.

McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Björk, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H., & Silliman, B. R. (2011). A blueprint for blue carbon: Toward an improved understanding of the role of vegetated coastal habitats in sequestering CO_2. *Frontiers in Ecology and the Environment*, *9*(10), 552–560.

McNeil, C. L., Ward, B., McGillis, W. R., DeGrandpre, M. D., & Marcinowski, L. (2006). Fluxes of N_2, O_2 and CO_2 in nearshore waters off Martha's Vineyard. *Continental Shelf Research*, *26*, 1281–1294.

Mcowen, C. J., Weatherdon, L. V., Bochove, J. V., Sullivan, E., Blyth, S., Zockler, C., Stanwell-Smith, D., Kingston, N., Martin, C. S., Spalding, M., & Fletcher, S. (2017). A global map of saltmarshes <https://doi.org/10.3897/BDJ.5.e11764>. *Biodiversity Data Journal*, *5*, e11764.

Milliman, J. D. (1993). Production and accumulation of calcium carbonate in the ocean: Budget of a nonsteady state. *Global Biogeochemical Cycles*, *7*, 927–957.

Moberg, F., & Folke, C. (1999). Ecological goods and services of coral reef ecosystems. *Ecological Economics*, *29*, 215–233.

Montaggioni, L. F. (2005). History of Indo-Pacific coral reef systems since the last glaciation: Development patterns and controlling factors. *Earth-Science Reviews*, *71*, 1–75.

Montaggioni, L. F., & Faure, G. (1997). Response of reef coral communities to sea-level rise: A Holocene model from Mauritius (Western Indian Ocean). *Sedimentology*, *44*, 1053–1070.

Moon, T. A., Overeem, I., Druckenmiller, M., Holland, M., Huntington, H., Kling, G., Lovecraft, A. L., Miller, G., Scambos, T., Schädel, C., Schuur, E. A., Trochim, E., Wiese, F., Williams, D., & Wong, G. (2019). The expanding footprint of rapid Arctic change <https://doi.org/10.1029/2018EF001088>. *Earth's Future*, *7*, 212–218.

Mu, C., Zhang, F., Chen, X., Ge, S., Mu, M., Jia, L., Wu, Q., & Zhang, T. (2019). Carbon and mercury export from the Arctic rivers and response to permafrost degradation <https://doi.org/10.1016/j.watres.2019.05.082>. *Water Resources*, *161*, 54–50.

Muller-Karger, F. E., Varela, R., Thunell, R., Luerssen, R., Hu, C., & Walsh, J. J. (2005). The importance of continental margins in the global carbon cycle. *Geophysical Research Letters*, *32*, L01602.

Nelleman, C., Corcoran, E., Duarte, C. M., Valdés, L., De Young, C., Fonseca, L., & Grimsditch, G. (Eds.). (2008). *Blue carbon: The role of healthy oceans in binding carbon*. A Rapid Response Assessment. United Nations Environment Programme, GRID-Arendal.

O'Mara, N. A., & Dunne, J. P. (2019). Hot spots of carbon and alkalinity cycling in the coastal oceans. *Scientific Reports*, *9*, 4434.

Odum, E. P. (1968). *A research challenge: Evaluating the productivity of coastal and estuarine water* [Conference session]. In proceedings of the Second Sea Grant Conference, University of Rhode Island, pp. 63–64.

Odum, E. P. (2002). Tidal marshes as outwelling/pulsing systems. In M. P. Weinstein & D. A. Kreeger (Eds.), *Concepts and controversies in tidal marsh ecology* (pp. 3–7). Springer.

Odum, H. T., & Odum, E. P. (1955). Trophic structure and productivity of a windward coral reef community on Eniwetok Atoll. *Ecological Monographs*, *25*, 291–320.

Ohman, M. D., Rudnick, D. L., Chekalyuk, A., Davis, R. E., Feely, R. A., Kahru, M., Kim, H.-J., Landry, M. R., Martz, T. R., Sabine, C. L., & Send, U. (2013). Autonomous ocean measurements in the California Current Ecosystem <http://dx.doi.org/10.5670/oceanog.2013.41>. *Oceanography*, *26*(3), 18–25.

Olson, R. M., & Sosik, H. M. (2007). A submersible imaging-in-flow instrument to analyze nano- and microplankton: Imaging FlowCytobot <https://doi.org/10.4319/lom.2007.5.195>. *Limnology & Oceanography Methods*, *5*, 195–203.

Pawlik, J. R., Loh, T.-L., & McMurray, S. E. (2018). A review of bottom-up vs. top-down control of sponges on Caribbean fore-reefs: What's old, what's new, and future directions. *PeerJ*, *6*, e4343.

Perry, C. T., & Alvarez-Filip, L. (2019). Changing geo-ecological functions of coral reefs in the Anthropocene. *Functional Ecology*, *33*, 976–988.

Perry, C. T., Edinger, E. N., Kench, P. S., Murphy, G. N., Smithers, S. G., Steneck, R. S., & Mumby, P. J. (2012). Estimating rates of biologically driven coral reef framework production and erosion: A new census-based carbonate budget methodology and applications to the reefs of Bonaire. *Coral Reefs*, *31*, 853–868.

Pierrot, D., Lewis, E., & Wallace, D. W. R. (2006). *MS Excel Program Developed for CO_2 System Calculations* <https://doi:%2010.3334/CDIAC/otg.CO2SYS_XLS_CDIAC105a>. ORNL/CDIAC-105a. Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, U.S. Department of Energy.

Ping, C.-L., Michaelson, G. J., Guo, L., Jorgenson, M. T., Kanevskiy, M., Shur, Y., Dou, F., & Liang, J. (2011). Soil carbon and material fluxes across the eroding Alaska Beaufort Sea coastline <https://doi.org/2010.1029/2010JG001588>. *Journal of Geophysical Research*, *116*(G02004).

Polidoro, B. A., Carpenter, K. E., Collins, L., Duke, N. C., Ellison, A. M., Ellison, J. C., Farnsworth, E. J., Fernando, E. S., Kathiresan, K., Koedam, N. E., Livingstone, S. R., Miyagi, T., Moore, G. E., Ngoc Nam, V., Ong, J. E., Primavera, J. H., Salmo, S. G., Sanciangco, J. C., Sukardjo, S., . . . Yong, J. W. (2010). The loss of species: Mangrove extinction risk and geographic areas of global concern. *PLOS ONE*, *5*, Article e10095.

Price, N. N., Muko, S., Legendre, L., Steneck, R., van Oppen, M. J. H., Albright, R., Ang, P., Jr., Carpenter, R. C., Chui, A. P. Y., Fan, T.-Y., Gates, R. D., Harii, S., Kitano, H., Kurihara, H., Mitarai, S., Padilla-Gamiño, J. L., Sakai, K., Suzuki, G., & Edmunds, P. J. (2019). Global biogeography of coral recruitment: Tropical decline and subtropical increase <https://doi.org/10.3354/meps12980>. *Marine Ecology Progress Series*, *621*, 1–17.

Pritchard, D. W. (1967). Observations of circulation in coastal plain estuaries. In G. H. Lauf (Ed.), *Estuaries* (pp. 37–44). American Association for the Advancement of Science.

Rabouille, C. F., Mackenzie, T., & Ver, L. M. (2001). Influence of the human perturbation on carbon, nitrogen, and oxygen on biogeochemical cycles in the global coastal ocean <https://doi.org/10.1016/S0016-7037(01)00760-8>. *Geochimica et Cosmochimica Acta*, *65*(21), 3615–3641.

Raymond, P. A., McClelland, J. W., Holmes, R. M., Zhulidov, A. V., Mull, K., Peterson, B. J., Striegl, R. G., Aiken, G. R., & Gurtovaya, T. Y. (2007). Flux and age of dissolved organic carbon exported to the Arctic Ocean: A carbon isotopic study of the five largest Arctic rivers <https://doi.org/10.1029/2007GB002934>. *Global Biogeochemical Cycles*, *21*(BG4011).

Regnier, P., Friedlingstein, P., Ciais, P., Mackenzie, F. T., Gruber, N., Janssens, I. A., Laruelle, G. G., Lauerwald, R., Luyssaert, S., Andersson, A. J., Arndt, S., Arnosti, C., Borges, A. V., Dale, A. W., Gallego-Sala, A., Goddéris, Y., Goossens, N., Hartmann, J., Heinze, C., . . . Thullner, M. (2013). Anthropogenic perturbation of the carbon fluxes from land to ocean. *Nature Geoscience*, *6*, 597–606.

Reimer, J. J., Wang, H., Vargas, R., & Cai, W.-J. (2017). Multidecadal fCO_2 increase along the United States southeast coastal margin <https://doi.org/10.1002/2017JC013170>. *Journal of Geophysical Research: Oceans*, *122*, 10,061–10,072.

Roobaert, A., Laruelle, G. G., Landschützer, P., Gruber, N., Chou, L., & Regnier, P. (2019). The spatiotemporal dynamics of the sources and sinks of CO_2 in the global coastal ocean <https://doi.org/10.1029/2019GB006239>. *Global Biogeochemical Cycles*, *33*(12), 1693–1714.

Roth, F., R̈adecker, N., Carvalho, S., Duarte, C. M., Saderne, V., Anton, A., Silva, L., Call-eja, M. L. L., Moŕan, X. A. G., Voolstra, C. R., K̈urten, B., Jones, B. H., & Wild, C. (2021). High summer temperatures amplify functional differences between coral- and algae-dominated reef communities. *Ecology*, *102*(2), e03226.

Rutherford, K., & Fennel, K. (2018). Diagnosing transit times on the northwestern North Atlantic continental shelf. *Ocean Science*, *14*, 1207–1221.

Rutherford, K., & Fennel, K. (2022). Elucidating coastal ocean carbon transport processes: A novel approach applied to the northwest North Atlantic Shelf <https://doi.org/10.1029/2021GL097614>. *Geophysical Research Letters*, *49*, e2021GL097614.

Rutherford, K., Fennel, K., Atamanchuk, D., Wallace, D., & Thomas, H. (2021). A modeling study of temporal and spatial pCO_2 variability on the biologically active and temperature-dominated Scotian Shelf <https://doi.org/10.5194/bg-18-6271-2021>. *Biogeosciences*, *18*, 6271–6286.

Sanford, L. P., Sellner, K. G., & Breitburg, D. L. (1990). Covariability of dissolved oxygen with physical processes in the summertime Chesapeake Bay. *Journal of Marine Research*, *48*, 567–590.

Santos, I. R., Burdige, D. J., Jennerjahn, T. C., Bouillon, S., Cabral, A., Serrano, O., Wernberg, T., Filbee-Dexter, K., Guimond, J. A., & Tamborski, J. J. (2021). The renaissance of Odum's outwelling hypothesis in "blue carbon" science <https://doi.org/10.1016/j.ecss.2021.107361>. *Estuarine, Coastal and Shelf Science*, *255*, 107361.

Sapkota, Y., & White, J. R. (2020). Carbon offset market methodologies applicable for coastal wetland restoration and conservation in the United States: A review. *Science of the Total Environment*, *701*, 134497.

Sargent, M. C., & Austin, T. S. (1949). Organic productivity of an Atoll. *Eos, Transactions American Geophysical Union*, *30*, 245–249.

Sarmiento, J. L., & Toggweiler, J. R. (1984). A new model for the role of the oceans in determining atmospheric pCO_2. *Nature*, *308*, 621–624.

Schuur, E. A. G., McGuire, A. D., Schädel, C., Grosse, G., Harden, J. W., Hayes, D. J., Hugelius, G., Koven, C. D., Kuhry, P., Lawrence, D. M., Natali, S. M., Olefeldt, D., Romanovsky, V. E., Schaefer, K., Turetsky, M. R., Treat, C. C., & Vonk, J. E. (2015). Climate change and the permafrost carbon feedback <https://doi.org/10.1038/nature14338>. *Nature*, *520*(7546), 171–179.

Seidel, M. P., DeGrandpre, M. D., & Dickson, A. G. (2008). A sensor for in situ indicator-based measurements of seawater pH. *Marine Chemistry*, *109*, 18–28.

Serrano, O., Lovelock, C. E., Atwood, T. B., Macreadie, P. I., Canto, R., Phinn, S., Arias-Ortiz, A., Bai, L., Baldock, J., & Bedulli, C. (2019). Australian vegetated coastal ecosystems as global hotspots for climate change mitigation. *Nature Communications*, *10*(1), 1–10.

Shadwick, E. H., Thomas, H., Comeau, A., Craig, S. E., Hunt, C. W., & Salisbury, J. E. (2010). Air–sea CO_2 fluxes on the Scotian Shelf: Seasonal to multi-annual variability <https://doi.org/10.5194/bg-7-3851-2010>. *Biogeosciences*, *7*(11), 3851–3867.

Shakhova, N., Semiletov, I., Leifer, I., Sergienko, V., Salyuk, A., Kosmach, D., Chernykh, D., Stubbs, C., Nicolsky, D., Tumskoy, V., & Gustafsson, Ö. (2014). Ebullition and storm-induced methane release from the East Siberian Arctic Shelf <https://doi.org/10.1038/NGEO2007>. *Nature Geoscience*, *7*(1), 64–70.

Sharples, J., Middelburg, J. J., Fennel, K., & Jickells, T. D. (2017). What proportion of riverine nutrients reaches the open ocean? <https://doi.org/10.1002/2016GB00548> *Global Biogeochemical Cycles*, *31*, 39–58.

Siegenthaler, U., Monnin, E., Kawamura, K., Spahni, R., Schwander, J., Stauffer, B., Stocker, T. F., Barnola, J.-M., & Fischer, H. (2005). Supporting evidence from the EPICA Dronning Maud Land ice core for atmospheric CO_2 changes during the past millennium <https://doi.org/10.1111/j.1600-0889.2005.00131.x>. *Tellus Series B-Chemical and Physical Meteorology*, *57*(1), 51–57.

Siegenthaler, U., & Wenk, T. (1984). Rapid atmospheric CO_2 variations and ocean circulation. *Nature*, *308*, 624–626.

Smith, R., Bianchi, T., Allison, M., Savage, C., & Galy, V. (2015). High rates of organic carbon burial in fjord sediments globally <https://doi.org/10.1038/ngeo2421>. *Nature Geoscience*, *8*, 450–453. .

Smith, S. (1973). Carbon dioxide dynamics: A record of organic carbon production, respiration, and calcification in the Eniwetok reef flat community. *Limnology and Oceanography*, *18*, 106–120.

Smith, S., & Pesret, F. (1974). Processes of carbon dioxide flux in the Fanning Island lagoon. *Pacific Science*, *28*, 225–246.

Smith, S. V., & Hollibaugh, J. T. (1993). Coastal metabolism and the oceanic organic carbon balance. *Reviews of Geophysics*, *31*, 75–89.

Smith, S. V., & Mackenzie, F. T. (1987). The ocean as a net heterotrophic system: Implications from the carbon biogeochemical cycle. *Global Biogeochemical Cycles*, *1*, 187–198.

Spaulding, R. S., DeGrandpre, M. D., Beck, J. C., Hart, R. D., Peterson, B., DeCarlo, E. H., Drupp, P. S., & Hammar, T. R. (2014). Autonomous in situ measurements of seawater alkalinity *<https://doi.org/10.1021/es501615x>*. *Environmental Science & Technology*, *48*, 9573–9581,.

Spinrad, R. W., Zaneveld, J. R. V., & Kitchen, J. C. (1983). A study of the optical characteristics of the suspended particles in the benthic nepheloid layer of the Scotian Shelf. *Journal of Geophysical Research*, *88*, 7641–7645.

Spivak, A. C., Sanderman, J., Bowen, J. L., Canuel, E. A., & Hopkinson, C. S. (2019). Global-change controls on soil-carbon accumulation and loss in coastal vegetated ecosystems *<https://doi.org/10.1038/s41561-019-0435-2>*. *Nature Geoscience*, *12*, 685–692.

Takeshita, Y., Cyronak, T., Martz, T. R., Kindeberg, T., & Andersson, A. J. (2018). Coral reef carbonate chemistry variability at different functional scales. *Frontiers in Marine Science*, *5*, 175.

Tanaka, Y., Miyajima, T., Watanabe, A., Nadaoka, K., Yamamoto, T., & Ogawa, H. (2011). Distribution of dissolved organic carbon and nitrogen in a coral reef. *Coral Reefs*, *30*, 533–541.

Tanaka, Y., Ogawa, H., & Miyajima, T. (2011). Production and bacterial decomposition of dissolved organic matter in a fringing coral reef. *Journal of Oceanography*, *67*, 427–437.

Tanski, G., Tanski, G., Wagner, D., Knoblauch, C., Fritz, M., Sachs, T., Lantuit, H. (2019). Rapid CO_2 release from eroding permafrost in seawater *<https://doi.org/10.1029/2019GL084303>*. *Geophysical Research Letters*, *46*(11), 244–252.

Tarnocai, C., Canadell, J. G., Schuur, E. A. G., Kuhry, P., Mazhitova, G., & Zimov, S. (2009). Soil organic carbon pools in the northern circumpolar permafrost region *<https://doi.org/10.1029/2008GB003327>*. *Global Biogeochemical Cycles*, *23*(GB2023).

Tengberg, A., Hovdenes, J., Andersson, J. H., Brocandel, O., Diaz, R., Hebert, D., Arnerich, T., Huber, C., Körtzinger, A., Khripounoff, A., Rey, F., Rönning, C., Schimanski, J., Sommer, S., & Stangelmayer, A. (2006). Evaluation of a life time based optode to measure oxygen in aquatic systems. *Limnology & Oceanography Methods*, *4*, 7–17.

Thomas, H., Bozec, Y., Elkalay, K., & de Baar, H. J. W. (2004). Enhanced open ocean storage of CO_2 from shelf sea pumping. *Science*, *304*, 1005–1008.

Thyssen, M., Mathieu, D., Garcia, N., & Denis, M. (2008). Short-term variation of phytoplankton assemblages in Mediterranean coastal waters recorded with an automated submerged flow cytometer *<https://doi.org/10.1093/plankt/fbn054>*. *Journal of Plankton Research*, *30*, 1027–1040.

Tsunogai, S., Watanabe, S., & Sato, T. (1999). Is there a “continental shelf pump” for the absorption of atmospheric CO_2? *Tellus*, *51B*, 701–712.

Umezawa, Y., Miyajima, T., & Koike, I. (2008). Stable nitrogen isotope composition in sedimentary organic matter as a potential proxy of nitrogen sources for primary producers at a fringing coral reef. *Journal of Oceanography*, *64*, 899–909.

Valiela, I., Bowen, J. L., & York, J. K. (2001). Mangrove forests: One of the world’s threatened major tropical environments: At least 35% of the area of mangrove forests has been lost in the past two decades, losses that exceed those for tropical rain forests and coral reefs, two other well-known threatened environments. *Bioscience*, *51*, 807–815.

Vandemark, D., Salisbury, J. E., Hunt, C. W., Shellito, S. M., Irish, J. D., McGillis, W. R., Sabine, C. L., & Maenner, S. M. (2011). Temporal and spatial dynamics of CO_2 air–sea flux in the Gulf of Maine <https://doi.org/10.1029/2010JC006408>. *Journal of Geophysical Research: Oceans*, *116*(C1), C01012.

Veron, J. E. N. (2008). Mass extinctions and ocean acidification: Biological constraints on geological dilemmas. *Coral Reefs*, *27*, 459–472.

Volk, T., & Hoffert, M. I. (1985). Ocean carbon pumps: Analysis of relative strengths and efficiencies in ocean-driven atmospheric CO_2 changes <https://doi.org/10.1029/GM032p0099>. In E. T. Sundquist &W. S. Broecker (Eds.), *The carbon cycle and atmospheric CO_2: Natural variations archean to present* (Vol. 32). American Geophysical Union; Geophysical Monograph 32.

Vonk, J. E., Sánchez-García, L., van Dongen, B. E., Alling, V., Kosmach, D., Charkin, A., Semiletov, I. P., Dudarev, O. V., Shakhova, N., Roos, P., Eglinton, T. I., Andersson, A., & Gustafsson, Ö. (2012). Activation of old carbon by erosion of coastal subsea permafrost in Arctic Siberia <https://doi.org/10.1038/nature11392>. *Nature*, *489*(7414), 137–140.

Wang, Z. A., Kroeger, K. D., Ganju, N. K., Gonneea, M. E., & Chu, S. N. (2016). Intertidal salt marshes as an important source of inorganic carbon to the coastal ocean. *Limnology & Oceanography*, *61*, 1916–1931.

Wang, Z. A., Sonnichsen F. N., Bradley, A. M., Hoering, H. A., Lanagan, T. M., Chu, S. N., Hammar, T. R., & Camilli, R. (2015). An in-situ sensor technology for simultaneous spectrophotometric measurements of seawater total dissolved inorganic carbon and pH <https://doi.org/%2010.1021/es504893n>. *Environmental Science & Technology*, *49*(7), 4441–4449.

Wassmann, P. (1998). Retention versus export food chains: Processes controlling sinking loss from marine pelagic ecosystems <https://doi.org/10.1023/A:1003113403096>. *Hydrobiologia*, *363*, 29–57.

Waycott, M., Duarte, C. M., Carruthers, T. J. B., Orth, R. J., Dennison, W. C., Olyarnik, S., Calladine, A., Fourqurean, J. W., Heck, K. L., Hughes, A. R., Kendrick, G. A., Kenworthy, W. J., Short, F. T., & Williams, S. L. (2009). Accelerating loss of seagrasses across the globe threatens coastal ecosystems. *Proceedings of the National Academy of Sciences*, *106*(30), 12377–12381.

Webb, G. E. (2001). Biologically induced carbonate precipitation in reefs through time. In G. D. Stanley (Ed.), *The history and sedimentology of ancient reef systems* (pp. 159–203). Springer US.

Webster, J. M., Clague, D. A., Riker-Coleman, K., Gallup, C., Braga, J. C., Potts, D., Moore, J. G., Winterer, E. L., & Paull, C. K. (2004). Drowning of the 150 m reef off Hawaii: A casualty of global meltwater pulse 1A? *Geology*, *32*, 249–252.

Webster, J. M., Braga, J. C., Yokoyama, Y., Fujita, K., Humblet, M., Potts, D. C., Iryu, Y., Bourillot, R., Esat, T. M., Fallon, S., Thompson, W. G., Thomas, A. L., Kan, H., McGregor, H. V., Hinestrosa, G., Obrochta, S. P., & Lougheed, B. C. (2018). Response of the Great Barrier Reef to sea-level and environmental changes over the past 30,000 years. *Nature Geoscience*, *11*, 426–432.

Wesslander, K., Hall, P., Hjalmarsson, S., Lefevre, D., Omstedt, A., Rutgersson, A., Sahlee, E., & Tengberg, A. (2011). Observed carbon dioxide and oxygen dynamics in a Baltic Sea coastal region. *Journal of Marine Systems*, *86*, 1–9.

Yamano, H., Sugihara, K., & Nomura, K. (2011). Rapid poleward range expansion of tropical reef corals in response to rising sea surface temperatures <https://doi.org/10.1029/2010GL046474>. *Geophysical Research Letters*, *38*, L04601.

Yool, A., & Fasham, M. J. A. (2001). An examination of the "continental shelf pump" in an open ocean general circulation model. *Global Biogeochemical Cycles*, *15*, 831–844.

Zimov, S. A., Shuur, E. A. G., & Chapin, F. S. (2006). Permafrost and the global carbon budget <https://doi.org/10.1126/science.1126279>. *Science*, *312*(5780), 1612–1613.

Notes

1. NOAA Global Climate Report August 2019 <https://www.ncdc.noaa.gov/sotc/global/201908>

2. Global Ocean Observing System Essential Ocean Variables <https://www.goosocean.org/index.php?option=com_content&view=article&id=170&Itemid=114>

Related Articles

Climate and Coast: Overview and Introduction

Perceptions of and Resilience to Coastal Climate Risks