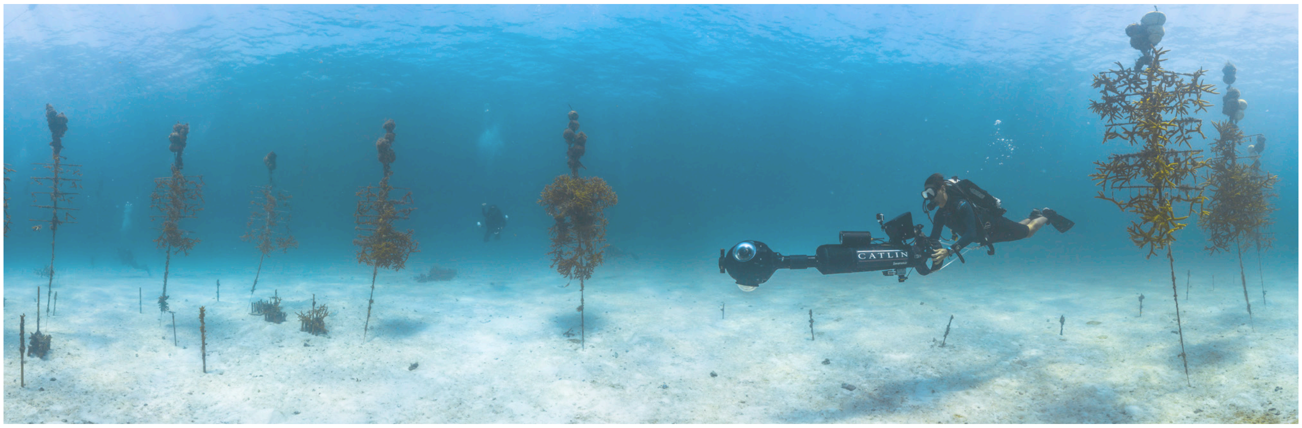

8. Florida Keys and Caribbean Region Acidification Research

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Abstract

This region encompasses the Florida Keys and coastal waters of south Florida, as well as Puerto Rico, the U.S. Virgin Islands, and the surrounding areas between the Gulf of Mexico and Atlantic Ocean. Processes driving acidification in this region range from global incorporation of anthropogenic carbon in surface waters to localized alteration of seawater chemistry by natural ecosystems, as well as human activities. Fluctuations in seawater carbon dioxide (CO_2) manifest on timescales ranging from decades to hours, making holistic characterization a challenging task. The region is home to especially sensitive coral reef ecosystems and commercially important fisheries, which are all inexorably linked to coastal communities and economies. NOAA's Florida Keys and Caribbean research goals are to:

- Enhance the temporal and spatial resolution of ocean acidification (OA) monitoring to capture the ecologically-relevant variability of this dynamic region;
- Monitor responses to OA on scales ranging from individuals to ecosystems, specifically targeting those that have been previously identified as susceptible to or threatened by OA;
- Experimentally investigate the sensitivity and resilience of ecologically and economically important species, as well as the underlying molecular mechanisms that drive their differential responses to OA; and
- Develop interdisciplinary tools that integrate socioeconomic data with ecological outcomes.

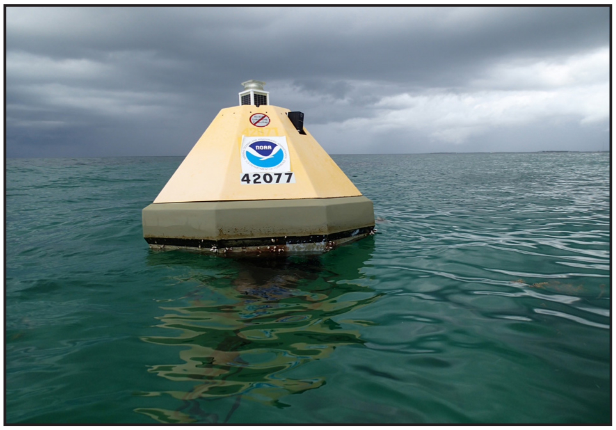
Acidification in the Florida Keys and Caribbean Region

The Florida Keys and wider Caribbean region contain numerous shallow-water ecosystems, including coral reefs, seagrasses, mangrove habitats, as well as sand and hard bottom communities. These systems support economically important fisheries, active tourism industries, and fulfill important roles for coastal protection. Numerous taxa that occupy and form these habitats are sensitive to elevated CO_2 and associated OA, further threatening systems that are already degraded due to warming, disease, overfishing, and eutrophication (e.g., Gardner et al., 2003). These ecosystems' heightened sensitivity to stress and their close relationship with carbonate chemistry serve to underscore the importance of OA in the region. The Caribbean exhibits some of the highest carbonate mineral saturations states in the world, but has experienced among the most rapid rates of decline since pre-industrial times (Gledhill et al., 2009). The carbonate chemistry of the Florida Keys and Caribbean is spatially variable and driven by interconnected ecosystems and waterways. For example, seagrass communities sequester CO_2 via photosynthesis and influence the chemistry of surrounding waters in the Florida Keys (Manzello et al., 2012) and navigational inlets and urbanized waterways lead to localized hotspots of acidification in southeast Florida (Enochs et al., 2019). These spatial patterns are temporally dynamic. For example, seagrasses have a pronounced growing season with elevated rates of productivity during the spring and early summer that can significantly increase seawater pH, possible alleviating OA stress (Manzello et al., 2012). On a more episodic basis, tropical cyclones contribute to periods of undersaturation as a result of reduced photosynthesis and stress-driven increases in respiration (Manzello et al., 2013). The relative importance of these dynamic processes varies greatly across the region, which represents a large geographic area that encompasses both islands and continentally influenced coasts.

Over the last decade NOAA-supported OA research has made great strides in establishing a monitoring program to characterize carbonate chemistry across space and time, as well as the status of closely-related biological processes such as calcification and bioerosion on coral reefs. This has been done in a highly leveraged manner, through close collaboration with existing monitoring programs, chief among them the National Coral Reef Monitoring Program (NCRMP, coris.noaa.gov/monitoring). NOAA has also supported several experiments on the OA sensitivity of key coral taxa, three associated with coral reefs and two that are important in local fisheries. Despite these advances, significant gaps remain that are crucial to the management and persistence of economically important marine resources within the region.

Environmental Change in the Florida Keys and Caribbean Region

Climate-quality geochemical surveys have historically not taken place in much of the region because it is a marginal sea, rather than an open ocean, and has therefore been of lower priority to carbon inventory studies. However, extensive underway and ship-of-opportunity efforts have occurred for more than a decade at NOAA with support from partnering programs to expand surface observations in this region. Two quadrennial OA surveys have conducted repeated transects of climate-quality full-water column measurements of OA and affiliated biogeochemical sampling within the region since 2007. The Gulf of Mexico Ecosystems and Carbon Cruise (GOMECC) has sampled waters offshore of the Florida Keys, while the East Coast OA (ECOA) cruise has sampled the east coast down to Miami. Monthly Caribbean-wide estimates of carbonate mineral saturation state, derived from satellite measurements and models are available from the Ocean Acidification Product Suite (OAPS, https://www.coral.noaa.gov/accrete/oaps.html; Gledhill et al., 2009).



An ocean acidification buoy at Cheeca Rocks, an inshore patch reef within the Florida Keys National Marine Sanctuary. Credit: NOAA

NOAA's NCRMP was established to collect biological, physical, and socioeconomic information needed to gauge changing conditions of U.S. coral reef ecosystems. NOAA conducts sustained, long-term measurements of the chemical progression of OA and associated ecological impacts in and around coral reefs. OA monitoring on reefs throughout the Keys and Caribbean has been a highly leveraged collaboration with numerous academic, state, and federal partners.

NOAA utilizes a tiered approach of monitoring classes whereby seawater CO_2 measurements are made with very high frequency at a few locations, and at lower frequency across many locations (150 per year). There are presently two fully operational Class III, or sentinel OA monitoring sites on coral reefs at La Parguera, Puerto Rico (since January 2009) and Cheeca Rocks, Florida Keys (since December 2011). These sites each have a Moored Autonomous pCO_2 ($MApCO_2$) buoy providing high-resolution time-series data of xCO_2 and pH, accompanied by bi-weekly discrete measurements of total alkalinity (TA) and TCO_2. Flower Garden Banks is a third Class III location installed in 2015, but is not fully operational because it lacks a $MApCO_2$ buoy or comparable instrumentation that provide climate-quality, long-term CO_2 measurements. Class II sites (Dry Tortugas, St. Croix, and St. Thomas) include the same metrics as the class III sites, but lack the $MApCO_2$ buoy. Diurnal CO_2 measurements are obtained from the Class II sites using subsurface automatic samplers (SAS) every three years. Class I sites provide fixed *in situ* temperature data, whereas Class 0 sites represent discrete seawater collections for carbonate chemistry, obtained by the NCRMP biological teams, from stratified random reef locations in each jurisdiction once every two years. In association with NCRMP carbonate chemistry monitoring, a suite of eco-response measurements are made once every three years at Class III sites. These includes *ReefBudget* census-based carbonate budget monitoring (Perry et al., 2012), Calcification Accretion Units (CAUs, Vargas-Ángel et al., 2015), Bioerosion Monitoring Units (BMUs, Enochs et al., 2016a), and cores to elucidate coral calcification rates. CAUs and BMUs were recently added to all 15 m class I sites to increase spatial resolution. Higher frequency seawater sampling in southeast Florida (quarterly, 2014-2015, Enochs et al., 2019) and the Florida Keys (bimonthly, 2010-2012, 2014-present), accomplished via program leveraging, has led to a more thorough understanding of carbonate chemistry variability.

Research Objective 8.1: Characterize spatial carbonate chemistry patterns

Considerable seawater CO_2 variability has been measured throughout the region and current monitoring efforts are likely limited in their ability to detect ecologically important patterns across spatial and temporal scales.

Action 8.1.1: Improve the spatial resolution of existing carbonate chemistry monitoring in order to better detect regional and local patterns.

Action 8.1.2: Improve upon the deficiency in measurements taken at depth on coral reefs.

Action 8.1.3: Initiate routine sampling in understudied ecosystems (e.g., seagrass beds, mesophotic coral reefs, mangroves, and soft-bottom communities).

Action 8.1.4: Expand Ship of Opportunity Program (SOOP) coverage into the Caribbean.

Action 8.1.5: Explore the use of advanced autonomous systems (e.g., carbon Waveglider, Saildrone, glider) to achieve improved constraint of OA conditions.

Research Objective 8.2: Characterize temporal carbonate chemistry patterns

Spatial gradients in carbonate chemistry can be dramatic, but are often linked to temporal variability driven by processes such as seasonally-enhanced seagrass productivity. Infrequent sampling may not detect these patterns.

Action 8.2.1: Improve the frequency of carbonate chemistry measurements to better understand diel and seasonal oscillations, and capture episodic events.

Research Objective 8.3: Better understand ecosystem response to OA through paired monitoring of carbonate (and ancillary) chemistry and biological/community-scale metrics

Establishing causation between stressors and responses can be difficult and is complicated by the high variability of coastal CO_2, diverse ecological interactions, and the subtle but steady progression of global OA. Regardless, real-world biological responses to OA are central to understanding how ecosystem services are presently and will be impacted.

Action 8.3.1: Monitor individual responses of species with documented sensitivities, especially those that have ramifications for ecosystem health (e.g., calcifying and bioeroding species).

Action 8.3.2: Evaluate the importance of biogeochemistry within sediment pore waters (e.g., dissolution, Cyronak et al., 2013; Eyre et al., 2014, 2018) and improve understanding of how this relates to ecosystem function and services, particularly for coral reefs.

Action 8.3.3: Cross-validate, standardize, and establish best-practices for techniques to quantify net community calcification (NCC) and net community productivity (NCP) and integrate them into monitoring programs (Cyronak et al., 2018).

Research Objective 8.4: Ecosystem modeling that integrates multiple functional groups

There is an urgent need to develop modeling tools to gauge present day reef state and forecast their persistence in future OA conditions.

Action 8.4.1: Develop a habitat persistence (e.g., carbonate budget) model that incorporates the species-specific sensitivities of key calcifying and bioeroding taxa to forecast reef habitat permanence under OA scenarios (Perry et al., 2012; Kennedy et al., 2013).

Action 8.4.2: Apply spatiotemporal patterns in carbonate chemistry to OA-sensitive carbonate budget models to identify hotspots and refugia.

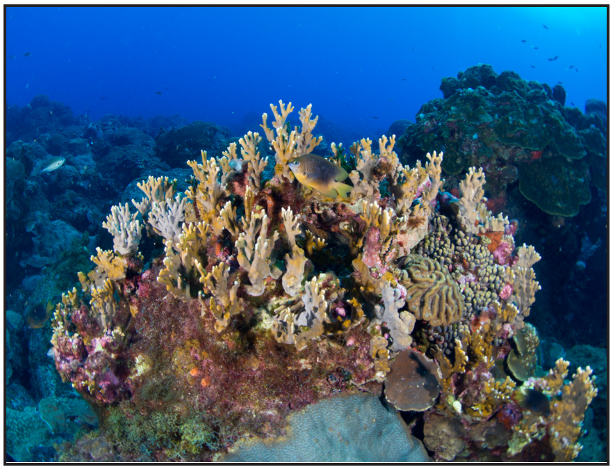
Biological Sensitivity in the Florida Keys and Caribbean Region

Over the last decade, NOAA has supported experimental investigation of Caribbean taxa and their responses to OA. To date, OA sensitivity research has been conducted by NOAA on three species of reef-dwelling animals from different functional groups: a stony coral (*Acropora cervicornis*, listed as threatened under the Endangered Species Act; Hogarth, 2006), a soft coral (*Eunicea flexuosa*), and a bioeroding sponge (*Pione lampa*). *A. cervicornis* responds to OA stress with reduced calcification and skeletal density (Enochs et al., 2014), but exhibits accelerated growth rates in more-variable contemporary CO_2 environments (Enochs et al., 2018). By contrast, soft corals such as *E. flexuosa* are apparently resilient to OA and may be competitively favored in the future (Enochs et al., 2016b). Caribbean bioeroding sponges such as *P. lampa* have accelerated rates of biological dissolution under moderate OA scenarios (Enochs et al., 2015b). In addition to reef species, NOAA has supported experimentation with commercially important Caribbean taxa. For instance, elevated CO_2 resulted in morphological alteration of the ear stones of larval cobia (*Rachycentron canadum*), which could alter their hearing ability and detrimentally influence dispersal and recruitment (Bignami et al., 2013). OA and warming conditions reduced the survivorship of larval stone crabs (*Menippe mercenaria*), with implications for stock size maintenance and the sustainability of the fishery (Gravinese et al., 2018).

Periodic exposures to extremes (high vs. low CO_2) are relevant to the calcification of *A. cervicornis*, resulting in higher growth rates in more-variable contemporary conditions (Enochs et al., 2018). Carbonate chemistry fluctuations are expected to increase due to global OA (Shaw et al., 2013) and land use changes may result in regional alteration of CO_2 dynamics, including the magnitude of seasonal changes (Wallace et al., 2014; Duarte et al., 2013). While data are scarce (Rivest et al., 2017), this variability likely has strong ramifications for other ecologically important taxa and should be investigated further.

The potential for intraspecific variability in OA responses also requires attention. Different genotypes within a single species can have significantly different rates of calcification and thermal tolerance (Dixon et al., 2015; Parkinson et al., 2015). It is of vital importance to determine if there are genes or molecular mechanisms that confer OA resilience. It may be possible to selectively breed for these traits in coral nurseries as is being done for resistance to heat stress (e.g., Dixon et al., 2015; van Oppen et al., 2015).

Relative to calcifying species, the influence of OA on the more biodiverse community of bioeroding flora and fauna is poorly understood (Schönberg et al., 2017). These organisms act in opposition to calcifiers and the balance of the two processes (bioerosion vs. calcification) is ultimately what determines the fate of reef habitat. Experimental studies, primarily from the Pacific, suggest that OA will accelerate chemical dissolution of reef carbonate by clionaid sponges (Wisshak et al., 2012) as well as endolithic algae (Tribollet et al., 2009; Reyes-Nivia et al., 2013). Preliminary evidence from the Caribbean supports these findings (Enochs et al., 2015b; Stubler et al., 2015). As coral cover continues to decline throughout the Caribbean (Gardner et al., 2003), the relative impact of bioeroders is increasing, shifting many reefs into erosional states and making bioerosion the primary driver of reef carbonate budgets (Alvarez-Filip et al., 2009; Kennedy et al., 2013; Perry et al., 2013; Enochs et al., 2015b).



Flower Garden Banks National Marine Sanctuary is home to some of the most healthy and vibrant coral reefs, like the ones shown here, in the northern Gulf of Mexico. Credit: GP Schmahl/NOAA

Several key taxa are of particular importance to the ecology, economies, and cultures of the region yet their OA sensitivities remain largely unexplored. Lobster (*Panuliris argus*) supports the single most valuable fishery in Florida and the greater Caribbean (Phillips & Kittaka, 2000). In addition to the numerous impacts of OA documented for related crustacean species (e.g., Whiteley, 2011), a single study found that warmer, more saline, and lower pH environments impacted the chemosensory habitat selectivity of *P. argus* (Ross & Behringer, 2019). Stone crabs (*M. mercenaria*) are also an important commercial and recreational fishery in Florida. Studies have demonstrated the sensitivity of early life stages, which could have damaging effects on the fishery by limiting population growth and dispersal (Gravinese, 2018; Gravinese et al., 2018). The queen conch (*Lobatus gigas*) fishery is the second largest benthic fishery in the Caribbean, yet decades of overfishing and habitat degradation have led to Caribbean-wide declines and fishery closures (CITES, 2003). Preliminary data from Mexico indicate warming and OA decrease larval survival and calcification, as well as increase the development rate of veligers, resulting in a faster settlement and shorter dispersal (Aranda, presented at 69th GCFI meeting, Nov. 2016). Finally, while larval cobia have been shown to be sensitive to future OA (Bignami et al., 2013), it is unknown if other commercially important fishes will be similarly impacted (e.g., snappers, groupers). Further work is needed to isolate the direct OA impacts on the physiology of multiple life stages of these species.

Other marine species in the region are not directly fished, but should be prioritized due to their ecological influence. For instance, unprecedented blooms and mass strandings of floating *Sargassum* have been reported along Caribbean and Florida coasts since 2011. These strandings have major implications for nearshore areas as they can increase nutrients, fuel hypoxic events, and trigger fish and invertebrate kills (e.g., van Tussenbroek et al., 2017). *Sargassum* from a temperate habitat has been shown to thrive in naturally acidified environments (Kumar et al., 2017) and similar studies are needed for tropical species. Finally, the urchin *Diadema* was once extremely abundant throughout the Caribbean and was instrumental in algae control on reefs, as well as framework erosion. Since the 1980s it has experienced a stark decline in abundance due to a Caribbean-wide die-off (Lessios, 2016). *Diadema* has potentially soluble, high magnesium calcite structures and OA could be a contributing factor in the limited recovery of this species (Dery et al., 2017; Uthicke et al., 2013).

As research progresses, it is imperative to incorporate ecological complexity into the evaluation of the impacts of OA. This involves the collection of multi-species community response data, rather than changes in the physiology (e.g., growth rates) of a single or small number of species. Natural ecosystems reflect ecological complexity orders of magnitude higher than that replicated in even the most biodiverse artificial mesocosm studies and interacting species that are differentially influenced by OA stress can give rise to unexpected outcomes

(Enochs et al., 2016a). Similarly, environmental complexity and multiple stressors can exacerbate (e.g., nutrients, warming) or ameliorate (feeding) the influences of OA. Communities presently existing in naturally high CO_2 environments provide insights into real-world community response to OA. While naturally acidified ecosystems are known from the Caribbean (e.g., vents, McCarthy et al., 2005; inlets, Enochs et al., 2019; ojos, Crook et al., 2013), they remain understudied relative to the Pacific (e.g., Manzello, 2010; Fabricius et al., 2011; Shamberger et al., 2014; Enochs et al., 2015a, 2016a). As such, the identification of new high-CO_2 analogs within the region is of paramount importance, along with detailed investigation of how OA-like conditions alter the ecology of surrounding biota.

Research Objective 8.5: Improve understanding of the responses of bioeroding communities

Understanding the responses of bioeroders to OA and co-occurring stressors is critically important for determining reef persistence, yet this relationship is poorly understood in the Caribbean.

Action 8.5.1: Conduct experiments to assess the responses of Caribbean bioeroding organisms to OA and co-occurring stressors (e.g., temperature and land-based sources of pollution).

Research Objective 8.6: Evaluate the influence of carbonate chemistry variability on ecosystem engineering taxa such as bioeroding and calcifying species

Further work is necessary to understand how real-world diel and seasonal fluctuations in carbonate chemistry influence ecologically, and economically important species.

Action 8.6.1: Conduct laboratory experiments to assess the responses of key Caribbean taxa to fluctuating carbonate chemistry.

Action 8.6.2: Compare the biological responses of species living in environments with different carbonate chemistry dynamics.

Research Objective 8.7: Evaluate differences in OA-sensitivity within coral species and molecular mechanisms associated with OA resilience

An understanding of different genotypic responses to OA will lead to science-based restoration practices that incorporate the threat of OA.

Action 8.7.1: Incorporate genotypes as a factor when designing OA response experiments.

Action 8.7.2: Conduct experiments to assess how the transcriptomes and proteomes of key taxa are influenced by OA, prioritizing comparisons between sensitive and resilient individuals.

Action 8.7.3: Examine the genome and gene expression of key taxa living in OA hotspots.

Research Objective 8.8: Investigate the direct response of understudied ecosystems, as well as iconic, invasive, endangered, and commercially important species to OA

Ecosystems are chemically and biologically interconnected, and their persistence is therefore interdependent. The OA sensitivities of many ecologically, economically, and culturally important species remain relatively unknown.

Action 8.8.1: Assess the sensitivity of seagrass and mangrove ecosystems to OA using field studies and laboratory experiments.

Action 8.8.2: Assess the sensitivity of key understudied taxa (e.g., Lobster, Conch, Stone crabs, fishes, *Sargassum* and *Diadema*) to OA.

Research Objective 8.9: Identification and investigation of natural high-CO_2 analogs

Naturally high CO_2 systems provide a means of investigating complex ecosystem-level responses to OA, where long-term exposure (decades to centuries) can reveal the implications of subtle responses, as well as acclimatization.

Action 8.9.1: Identify and characterize new high-CO_2 analogs within the region.

Action 8.9.2: Leverage naturally high-CO_2 ecosystems to better understand and predict real-world responses to OA.

Human dimensions in the Florida Keys and Caribbean Region

Focusing solely on biological and chemical research and monitoring can lead to ineffective management of coastal resources. Many key drivers of ecosystem decline are linked to human behavior and activities. Therefore, management can benefit from an approach that recognizes people and society as part of the ecosystem, addressing their interrelationship, important ecosystem services, and perceived ecosystem values. Ultimately, this deeper understanding of the human connections helps managers assess the social and economic consequences of management policies, interventions, and activities. The socioeconomic component of NCRMP presently includes survey questions on knowledge, perception, and awareness of a few key climate and OA related topics, but NOAA-supported work within the region is limited.

Fishermen out for a trip in Florida Keys National Marine Sanctuary. Photo: Nick Zachar/NOAA

A new report led by the U.S. Department of the Interior U.S. Geological Survey has evaluated the role of U.S. coral reefs in coastal hazard risk reduction. Coral reefs can substantially reduce coastal flooding and erosion by dissipating shoreline wave energy. The annual value of flood risk reduction by U.S. coral reefs is more than 18,000 lives and $1.805 billion (2010 USD, Storlazzi et al., 2019). In Florida alone, over $319 million (2010 USD) of economic activity is of economic activity is preserved due to flood protection from coral reefs, while in Puerto Rico and the U.S. Virgin Islands reef protection has been valued at $117 million and greater than $25 million, respectively (Storlazzi et al., 2019). Coupling these valuations with OA-specific forecasts for loss of coral reef structural integrity and rugosity may provide increased clarity for decision makers on the economic cost of OA-related reef degradation.

On a limited basis, other projects are beginning to address ecosystem services through economic valuation. Again, coupling this approach with OA-relevant ecosystem forecasts can lead to the tangible measurement of the economic impact of OA within the region. Providing these data to agencies, decision makers, and lawmakers (local, state and national) aids with budget allocations, environmental mitigation, and research support prioritization. This should be done for important fisheries, which in Florida alone have been estimated to generate $28.7 billion, and support 177,000 jobs (NOAA's Fisheries Economics of the United States 2015 Report). With respect to ecotourism, NOAA's Florida Keys National Marine Sanctuaries and CRCP suggest that coral reefs in southeast Florida have an asset value of $8.5 billion, generating $4.4 billion in local sales, $2 billion in local income, and 70,400 full and part-time jobs, much of which will be threatened due to OA's effects on reef-building corals. Additional assessments are needed to quantify the economic impact of accelerated reef structure erosion leading to less protected coastal infrastructure and property. This is particularly relevant for the Florida Keys and Caribbean that rely heavily on Blue Economy drivers such as coastal tourism and shipping.

Combining natural and social science data by mapping indicators is an approach that could be utilized to prioritize management and inform policy (Pendleton et al., 2016). For example, an interdisciplinary approach might involve comparing chemical and ecological monitoring with public perception of reef health or OA awareness. Some of these data may be gleaned from NCRMP and other related social science efforts (Gorstein et al., 2016, 2017). At the global scale, there are pre-existing tools that have been developed to assess human vulnerability and resilience to climate impacts (Wongbusarakum and Loper, 2011). These tools can be adapted for this region, and for development of a set of socioeconomic indicators related to ocean and climate change. These could then be included into a socioeconomic assessment of any site for which ocean and climate change impacts are an important issue. The resulting information can then inform coastal management needs and adaptive management practices.

Research Objective 8.10: Economic assessment of the impact of OA in region

By coupling ecosystem forecasts with economic valuations, OA impacts can be assessed, providing important information and projections to decision makes and lawmakers.

Action 8.10.1: Quantify the economic impact of OA-accelerated reef structure erosion leading to less protected coastal infrastructure and property.

Action 8.10.2: Quantify the economic impact of OA on recreational and commercial fisheries through direct physiological and behavioral alteration of fished species, as well as degradation of essential habitat.

Research Objective 8.11: Interdisciplinary and integrated socio-ecological approaches

Spatially-explicit economic indicators and visual mapping tools are an effective means to clearly communicate risk.

Action 8.11.1: Develop mapping tools and socio-economic indicators related to OA.

Action 8.11.2: Use indicators to communicate risk, and inform management and adaptation.

References

[INTRO] = Introduction;

[NAT] = National Ocean & Great Lakes;

[OO] = Open Ocean Region;

[AK] = Alaska Region;

[ARC] = Arctic Region;

[WC] = West Coast Region;

[PAC] = U.S. Pacific Islands Region;

[SAG] = Southeast Atlantic & Gulf of Mexico Region;

[FLC] = Florida Keys and Caribbean Region;

[MAB] = Mid-Atlantic Bight Region;

[NE] = New England Region;

[GL] = Great Lakes Region

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