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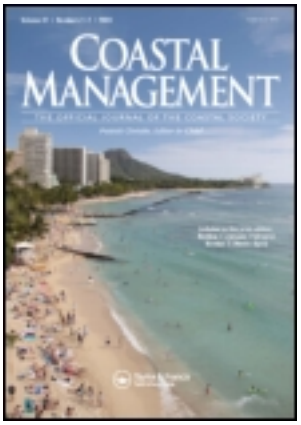

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Integrating Climate and Ocean Change Vulnerability into Conservation Planning

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Integrating Climate and Ocean Change Vulnerability into Conservation Planning

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Tropical coastal and marine ecosystems are particularly vulnerable to ocean warming, ocean acidification, and sea-level rise. Yet these projected climate and ocean change impacts are rarely considered in conservation planning due to the lack of guidance on how existing climate and ocean change models, tools, and data can be applied. Here, we address this gap by describing how conservation planning can use available tools and data for assessing the vulnerability of tropical marine ecosystems to key climate threats. Additionally, we identify limitations of existing tools and provide recommendations

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for future research to improve integration of climate and ocean change information and conservation planning. Such information is critical for developing a conservation response that adequately protects these ecosystems and dependent coastal communities in the face of climate and ocean change.

Keywords climate change, conservation planning, increasing sea-surface temperature, marine conservation, marine protected area (MPA), ocean acidification, sea-level rise

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Introduction

The ecological impacts of climate change are well documented for polar to tropical systems (Walther et al. 2002; Parmesan and Yohe 2003; Rosenzweig et al. 2008). For tropical coastal and marine ecosystems, climate-driven changes have been observed due to increasing sea-surface temperatures (SSTs), sea-level rise, and ocean acidification (Glynn 1993; Short and Neckles 1999; Hoegh-Guldberg et al. 2007; Lovelock and Ellison 2007; Pandolfi et al. 2011). Despite the recognition of the severity of climate impacts, few conservation planning efforts incorporate these impacts (Hannah, Midgley, and Millar 2002; Araujo et al. 2004; McClanahan et al. 2008). Currently, conservation planning focuses predominantly on static spatial planning, including establishing protected areas and corridors of connectivity, and designation of critical habitat (Hansen et al. 2010). Landscapes and seascapes are changing dramatically due to climate impacts, yet the identification and prioritization of conservation areas is still based largely on current conditions, ranges, and environmental parameters (Hansen et al. 2010; Poiani et al. 2011).

The anticipated severity of climate and ocean change impacts on natural and social systems has triggered a reevaluation of current conservation strategies and plans, with the aim of proposing solutions that will meet long-term conservation objectives in a high CO_2 world (e.g., McClanahan et al. 2008). In addition, regional initiatives have developed over the past decade to protect marine and coastal resources through the establishment of networks of marine protected areas (MPAs) that are resilient to potential climate change impacts (e.g., the Micronesia Challenge, the Caribbean Challenge, and the Coral Triangle Initiative); such efforts require conservation planners to incorporate climate change vulnerability into conservation planning.

Challenges Facing Conservation Planners in Addressing Climate Change

Conservation planners face a number of challenges integrating potential climate change impacts into their conservation strategies. Many planners lack access to climate experts or climate models and tools and also lack access to regional and local projections relevant for site-based planning (Poiani et al. 2011). Additionally, much of the available climate data has a high level of uncertainty, and is therefore challenging to interpret (Lawler et al. 2010). Conservation planners lack guidance on how to identify and apply the most appropriate tools for assessing climate impacts. Finally, the ability of existing conservation approaches, such as marine protected areas (MPAs) to protect ecosystems and species in the face of climate change is debated (Graham et al. 2007; McClanahan 2008; Selig and Bruno 2010).

Some studies suggest that MPAs do not protect biodiversity from climate impacts better than unmanaged areas (Jones et al. 2004; Graham et al. 2007; McClanahan 2008; Côté and Darling 2010; Darling, McClanahan, and Côté 2010). Other studies support the notion that species and habitats within reserves are more resilient than those outside (Lafferty and Behrens 2005; Mumby et al. 2006; Babcock et al. 2010). While the ability of MPAs to support resilience in response to climate change requires improved

science-based verification, planners and legislators will need to use the best available science to inform policies guiding MPA selection. Such policies include regional initiatives (e.g., the Micronesia Challenge, the Caribbean Challenge, and the Coral Triangle Initiative) and global commitments established at international meetings such as the World Summit on Sustainable Development (2002), the World Parks Congress (2003), and the Convention on Biological Diversity (2004).

Strategies to Support Resilience to Climate Change

The recognition of the importance of climate change to the conservation community has led to the identification of key strategies to integrate resilience into conservation plans (Mcleod et al. 2009; Hansen et al. 2010; Lawler et al. 2010; Groves et al. 2012; Poiani et al. 2011). Ecosystem resilience refers to the ability of an ecosystem to maintain key functions and processes in the face of stresses or pressures, either by resisting or adapting to change (Holling 1973; Nyström and Folke 2001). Some strategies expected to support the resilience of tropical marine ecosystems to climate and ocean change impacts are generic (e.g., reducing local anthropogenic stressors that exacerbate such impacts) and do not rely on precise predictions about the nature of these impacts (but see Anthony and Maynard 2011). However, other proposed solutions, such as the identification and protection of areas likely to be least impacted by climate change (West and Salm 2003; Game et al. 2008), require that spatially explicit models of vulnerability to climate change and ocean acidification are incorporated into conservation planning.

Marine managers seek to identify and protect areas that are expected to be least impacted by climate change (often called climate refugia) and incorporate these into MPAs. Historical physical observations and climate change projections provide data necessary for identifying these areas. Geographic predictors of species mortality and recovery (such predictors for coral reefs include local thermal history, acclimation history, existence of and proximity to refuges) have been identified as critical for identifying climate refuges and for marine conservation efforts more broadly (Maina et al. 2008; Graham et al. 2011). This information helps planners to identify areas less likely to be exposed to climate and ocean change and/or better able to cope with these changes.

While the identification of strategies to support resilience to climate change, and specifically strategies to integrate climate change adaptation into conservation plans is essential (Mcleod et al. 2009; Hansen et al. 2010; Lawler et al. 2010; Groves et al. 2012; Poiani et al. 2011), such recommendations would be more useful if they included a discussion of tradeoffs involved in their application, assumptions implicit in their use, and a description of data required for their implementation (Groves et al. 2012).

Incorporating Vulnerability into Conservation Planning

Conservation planners and policymakers need to understand and incorporate the ecological, biophysical, and socioeconomic impacts of climate change into coastal zone planning and management. To achieve this, they will need to understand how coastal ecosystems are likely to change in response to sea-level rise and how increasing sea-surface temperature and ocean acidification are likely to affect coral reef ecosystems. Assessing the vulnerability of these coastal and marine ecosystems is an important first step in planning to maintain the goods and services that they provide.

However, conservation planners lack guidance on the advantages, limitations, and most appropriate uses of data and tools to assess the vulnerability of tropical marine

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ecosystems to key global threats including: increases in sea-surface temperature, sea-level rise, and ocean acidification. Here, we discuss conservation planning objectives that address these key global threats. We also discuss the conditions under which existing climate and ocean change models and data can best be used in marine conservation planning to assess the vulnerability of marine ecosystems to these threats. Finally, we include discussion of tradeoffs in the application of such models and data. While not exhaustive, the tools discussed below represent viable options to support conservation planning in the face of climate and ocean change.

Incorporating Sea-Surface Temperature Vulnerability into Tropical Marine Conservation

Conservation Planning Objectives that Address Increasing SSTs

Conservation planners addressing increasing SSTs can prioritize marine ecosystems that are less exposed and/or less sensitive to thermal stress or that have high adaptive capacity for protection in MPA networks. Such areas include: (1) reefs where thermal history and projections indicate lack of exceedence of coral bleaching thresholds; (2) reefs where thermal variability is high because such areas may be more resistant and/or resilient to coral bleaching (McClanahan et al. 2007; Donner 2010; Oliver and Palumbi 2011); (3) corals pre-exposed to high temperatures (corals subjected to warmer than average temperatures prior to a thermal stress event sufficient to cause bleaching can be more thermally tolerant compared to corals that have not been pre-stressed; Middlebrook, Hoegh-Guldberg, and Leggat 2008); and (4) coral communities that have experienced bleaching and subsequently recovered.

Current Tools to Assess Vulnerability to Increasing SSTs

Current tools to address these objectives include: general circulation models (GCMs), satellite SST data, *in situ* sensors, and coral bleaching field data (Table 1). GCM outputs can be used to develop projections of thermal stress at regional scales andidentify coral reefs areas least likely to exceed coral bleaching thresholds (Donner 2009). Satellite SST data (e.g., Advanced Very High Resolution Radiometer Pathfinder data) and derived products are available from 1981 until present and provide historical patterns of thermal stress at a variety of scales (2–50 km). They can be used to identify areas of low thermal stress and where thermal variability is high (McClanahan et al. 2007; Mcleod et al. 2010a). *In situ* sensors can be used to identify reef-specific bleaching temperature thresholds, patterns of thermal stress at scales relevant to coral colonies, and to validate satellite SST data. However, because they can only provide data where the sensor is located, they are most useful when multiple sensors are deployed, enabling comparison among sites to inform conservation planning. Coral bleaching field data provide patterns of bleaching at various scales (e.g., from local to global) and can include important information on coral reef recovery patterns following a bleaching event.

Conservation planners and policymakers who want to assess coral reef vulnerability to increasing SSTs but have limited budgets and technical capacity may want to consider using a combination of freely available satellite SST data and coral bleaching field data to identify historical patterns of thermal stress and impacts. Expertise is needed to determine coral bleaching thresholds and to process the satellite data. Coral bleaching data can be accessed from international monitoring networks (Global Coral Reef Monitoring Network, Reef Check) and databases (e.g., www.Reefbase.org). Bleaching data is particularly important

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Table 1
Summary of tools to assess vulnerability of coral reef ecosystems to increasing SSTs

Data/Tools	Scale	Application	Advantages	Limitations
Coupled atmosphere-ocean general circulation models (CGCMs)	Global, regional	Identify broad homogenous patterns of thermal stress and thermal variability Prioritize areas of low thermal stress and high thermal variability for inclusion in MPA networks Ensure representation of MPAs across variety of thermal regimes	Can perform multiple simulations using different greenhouse gas emissions scenarios Can be integrated into GIS and other conservation planning tools to inform decision making	Uncertainties associated with model projections Cannot capture smaller-scale climate features or local patterns of thermal stress Not appropriate for site selection of MPAs Unable to project thermal stress near-shore High cost and expertise required to process model outputs
2, 4, 5, and 50 km satellite SST data	Global, regional	Identify broad homogenous patterns of thermal stress Identify reef areas in stable and unstable temperature regimes Identify coral reef areas pre-exposed to high temperatures Prioritize areas of low thermal stress and high thermal variability for inclusion in MPA networks Ensure representation of MPAs across variety of thermal regimes	Freely available from the internet Can be validated using in situ temperature observations Can be integrated into GIS and other conservation planning tools to inform decision making	Cannot capture reef/sub-reef patterns of thermal variability and thermal stress Cannot capture reef/sub-reef scale factors that affect bleaching susceptibility (e.g., species composition, zooxanthellae type, hydrodynamics around individual coral reefs) Unable to calculate thermal stress near-shore Not appropriate for site selection of MPAs Expertise required to analyze satellite data and identify bleaching thresholds

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Table 1
Summary of tools to assess vulnerability of coral reef ecosystems to increasing SSTs *(Continued)*

Data/Tools	Scale	Application	Advantages	Limitations
Bleaching data	Global, regional, local	Identify bleaching impact (and recovery where available) patterns in response to thermal stress at various scales Identify locally relevant thermal thresholds for corals Validate bleaching predictions for particular reefs derived from historical SST data	Can include data on coral reef recovery following bleaching event Can be freely accessed from international monitoring networks (Global Coral Reef Monitoring Network, Reef Check) and databases (Reefbase) Can support local to global analyses of patterns of coral reef health	Bleaching data are often temporally and spatially limited Long-term monitoring of bleaching and recovery patterns are labor intensive and expensive Capacity to analyze monitoring data is often lacking
In situ sensors (e.g., temperature loggers)	Local	Identify patterns of thermal stress at scales relevant to coral colonies Identify reef-specific bleaching temperature thresholds Identify coral reef areas pre-exposed to high temperatures Validate satellite SST data and hydrodynamic models	Temperature loggers are inexpensive easy to deploy Can provide temperature data for a variety of depths Can be used to develop reef-specific bleaching temperature thresholds	Temperature loggers only provide data for one site and results cannot be extrapolated to larger areas Not useful for comparing among sites for conservation planning
High-resolution hydrodynamic modeling	Local	Integrate temperature data from other sources Identify patterns of thermal stress at reef and sub-reef scale	Can provide spatially explicit information in three-dimensions over the model domain, filling gaps between data acquisition sites Can provide additional information on currents, salinity, chemistry, etc.	Development and calibration needed for each site which can be costly and requires expertise Not useful for comparing among sites outside the spatial domain of the model to inform conservation planning

to include in analyses of vulnerability to increasing SSTs to determine locally relevant thermal thresholds for corals, to identify impact and recovery patterns in response to thermal stress, and to support global and regional analyses of patterns of coral reef health.

While such analyses provide an initial assessment of vulnerability to thermal stress, they suffer from a number of limitations. For example, satellite data are often too coarse for assessing patterns of thermal stress at local extents and cannot capture local factors that affect bleaching susceptibility (Selig, Casey, and Bruno 2010). Satellite SST data and derived products vary in resolution from 2–50 km (ReefTemp, the Coral Reef Temperature Anomaly Database—CoRTAD, National Oceanic and Atmospheric Administration [NOAA]'s Coral Reef Watch). The Pathfinder SST data (Kilpatrick, Podesta, and Evans 2001) are on a ∼4 km grid and are too coarse for discerning patterns of thermal stress at local extents (i.e., <16 km^2). Therefore, these data are limited for assessing thermal stress in many MPAs, because the SST data do not capture the variability of temperature anomalies at sufficiently fine spatial resolution. Satellite SST data also cannot capture local factors that affect bleaching susceptibility (e.g., species composition, zooxanthellae type, hydrodynamics around individual coral reefs) or calculate thermal stress near shore, and are inappropriate for site selection of smaller MPAs. However, 4 km and 50 km resolution SST data are appropriate for assessing regional and global patterns of thermal stress (e.g., Mcleod et al. 2010a; Peñaflor et al. 2009), or across large MPAs (e.g., Chagos MPA, Phoenix Islands Protected Area, Papahānaumokuākea Marine National Monument, Great Barrier Reef Marine Park). Maina et al. (2008) developed a methodology combining historical SST data with field observations of coral bleaching, and known relationships between the environment and bleaching (e.g., surface currents, wind velocity, UV radiation, photosynthetically active radiation (PAR), and chlorophyll-a concentration) to predict susceptibility of corals to bleaching and climate change in the Western Indian Ocean.

Additionally, although coral bleaching data are accessible from international monitoring networks and databases, they are often temporally and spatially limited. Coral bleaching data are critical to identify coral communities that have experienced bleaching, yet long-term monitoring of bleaching and recovery patterns are labor intensive and expensive. Even when monitoring is conducted regularly, the capacity to analyze the data is often lacking. Despite these challenges, bleaching data are essential to validate the bleaching predictions for particular reefs derived from historical SST data, particularly in areas where acclimation and/or reorganization of the coral community have occurred due to past bleaching events (McClanahan et al. 2007).

If conservation planners have access to climate modelers and model outputs, then analyses combining GCM outputs and satellite SST data can provide valuable information to improve the design of MPA networks at regional scales. Mcleod et al. (2010a) combined these data with anthropogenic impacts to assess vulnerability to both global (thermal) and local (e.g., pollution, development, overfishing) stressors for ecoregions in the Coral Triangle. They identified specific management recommendations for MPA networks based on the levels of vulnerability to thermal and local stress.

However, managers and policymakers need to understand the limitations of climate models and outputs. Because GCMs have a horizontal resolution of about 250–600 km, it is only possible to discriminate between locations that are ∼600 km apart. This means that current GCMs are only able to identify broad patterns of thermal stress (i.e., at global and regional extents), thus only useful at regional scales. While downscaling approaches can increase the resolution of bleaching projections using historical observations of satellite data (e.g., Donner et al. 2005), outputs of downscaling should be interpreted with caution and are inappropriate for individual site selection of MPAs. Additionally, GCMs are unable

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to capture smaller-scale climate features or local patterns of thermal stress, and are thus unable to project thermal stress near shore.

Research Needs to Assess Vulnerability to Increasing SSTs

Researchers from government agencies (e.g., NOAA) and universities are making GCM outputs and analyses of decades of satellite SST data more widely available to conservation planners, nongovernmental organizations (NGOs), and government agencies. Also, efforts to build accessible online databases of ecological, socioeconomic, and biophysical data including climate layers (e.g., Coral Triangle Atlas; http://ctatlas.reefbase.org/) are addressing a critical need for managers attempting to integrate climate vulnerability into their conservation planning. However, planners and managers need guidance on which datasets to use for assessing bleaching risk and how these should be combined. For example, it remains unclear whether and how climate projections of thermal stress and historical patterns of thermal stress based on satellite SST data should be weighted. Mcleod et al. (2010a), for example, weighted these layers equally, but others may argue that the projections of thermal stress should be given a lower weight than the historical data due to greater uncertainties in the GCM outputs. Another challenge facing planners is identification of bleaching thresholds, although van Hooidonk and Huber (2009) provide some guidance.

The development of improved SST remote sensing tools at intermediate and fine resolutions is a priority for conservation planners. Future research needs to improve understanding of thermal stress patterns nearshore, thermal variability, local factors affecting bleaching susceptibility, and correlation between satellite data and coral reef response. CSIRO and the Australian Institute of Marine Science have developed a three-dimensional hydrodynamic model (1 km spatial resolution) for the Great Barrier Reef that includes processes that control temperature, currents, mixing, and salinity (Brinkman et al. 2011); a similar scale model has been developed for South Florida (Kourafalou and Kang 2012). High-resolution hydrodynamic models integrating remotely-sensed and *in situ* temperature data can provide detailed temperature, currents, and ocean chemistry data, but their conservation application is limited by the cost and expertise needed to parameterize, verify, and operate the models, and the lack of available field data needed for validation. Research is needed on the potential rates of biological adaptation in corals to improve projections of coral reef vulnerability in response to increasing SSTs (Pandolfi et al. 2011). Evolutionary studies will become increasingly important in understanding past climate variability and ecosystem responses, such as acclimatization and adaptation (Budd and Pandolfi 2010).

Finally, socioeconomic factors must be integrated into to ecological assessments of vulnerability to increasing SSTs, yet guidance on how to do so is lacking (but see Combest-Friedman, Christie, and Miles 2012 who combined socioeconomic data with physical data to assess community vulnerability to climate change). Case studies are needed to help conservation planners integrate socioeconomic, physical, and ecological factors into such assessments. Currently most efforts to assess the vulnerability of coral reefs to increasing SSTs incorporate ecological and oceanographic factors, but do not consider socioeconomic factors. Socioeconomic factors such as land-use changes, changing demographic patterns (e.g., population increases in coastal areas) and fishing practices (e.g., overfishing of herbivores which can reduce coral reef recovery following disturbance; Mumby and Harborne 2010) can lead to changes in sedimentation and pollution in the coastal zone and altered fish communities, which can affect coral reef health and vulnerability to increasing SSTs.

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Incorporating Sea-Level Rise Vulnerability into Tropical Marine Conservation

Conservation Planning Objectives that Address Changes in Sea Level

Conservation planners and policymakers are increasingly concerned with the vulnerability of coastal habitats (e.g., mangroves, barrier islands, beaches) and species (e.g., sea turtles, nesting birds) to sea-level rise. Vulnerability assessments of coastal ecosystems to sea-level rise are useful to inform land-use and conservation planning. For example, conservation and land-use planners can prioritize the preservation of buffer zones adjacent to coastal ecosystems with high projected rates of sea-level rise to enable inland expansion. Conservation planners could also prioritize areas likely to be less vulnerable to sea-level rise for protection or restoration. Restoration of coastal ecosystems, such as mangroves, can help buffer the coastline from sea-level rise, in some cases trapping sediment, thus increasing the adaptive capacity of these ecosystems and associated human communities. Such areas could include mangroves which have room to move to higher ground in response to sea-level rise, and areas where human communities demonstrate a high degree of social resilience (e.g., capacity to adapt livelihood/industry).

Current Tools to Assess Vulnerability to Changes in Sea Level

Coastal impact models, such as inundation models (e.g., Rowley et al. 2007), SLAMM (Park, Armentano, Cloonan 1986), DIVA (DINAS-COAST 2006), and SimCLIM (Warrick et al. 2005) are useful for predicting environmental responses to changes in sea level and the impacts of alternative management policies on ecosystem structure and productivity (Table 2). Such tools enable planners and policymakers to plan proactively for sea-level rise, and take immediate actions to ensure the security of coastal communities and the persistence of ecosystem services by reserving lands less vulnerable to sea-level rise (Mcleod et al. 2010b).

For conservation planners and policymakers with limited budgets and technical capacity and requiring a quick assessment of coastal vulnerability to sea-level rise, an inundation model using Geographic Information Systems (GIS) is the most efficient option (Rowley et al. 2007; Mcleod et al. 2010b). Potentially inundated areas can be calculated (e.g., in GIS) based on both elevation and proximity to shoreline from local to global extents (Rowley et al. 2007). Two recent approaches for assessing vulnerability to sea-level rise involved producing raster GIS layers showing the world's shorelines using sea-level increases from 1 to 6 m, calculating inundation zones for each incremental sea-level rise, and estimating area of land inundated and population affected in each scenario (Rowley et al. 2007; Weiss, Overpeck, and Strauss 2011). Such inundation models provide useful communication tools for policymakers, coastal communities, and conservation practitioners; but are unlikely to represent future conditions accurately because they do not account for the full range of biophysical or socioeconomic factors and associated feedbacks, specifically adaptation responses. Consequently, these models are useful for conservation planning decisions regionally, but should not be used to project how ecosystems or human communities will respond to changes in sea level over local extents.

If a conservation planner requires a detailed local or regional scale assessment of coastal ecosystem vulnerability to prioritize less vulnerable coastal ecosystems for protection in coastal zone management plans, then SLAMM (Sea Level Affecting Marshes Model) is a good choice. SLAMM simulates the dominant processes involved in wetland conversions and shoreline modifications during long-term sea-level rise. It produces

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Table 2
Summary of tools to assess vulnerability of coastal habitats and communities to sea-level rise (SLR)

Data/Tools	Scale	Application	Advantages	Limitations
DIVA SimCLIM	Global, regional	Identify coastal habitats and communities at broad scales likely to be more/less vulnerable to sea-level rise impacts Inform development of national adaptation responses Compare regional vulnerability to sea-level rise within or among countries Prioritize vulnerable areas requiring more in-depth studies Prioritize vulnerable local communities to support climate change adaptation initiatives	Can be completed quickly and efficiently with minimal data collection required Includes socioeconomic data and can be used to inform adaptation responses Allows users to explore sea-level rise impacts on coastal environments and societies, and assess costs and benefits of adaptation options Model results may be used to support government commitments to reduce vulnerability to climate change (e.g., under UNFCCC) and to raise public awareness of the impacts of sea-level rise	Uncertainties associated with model projections of global rates of sea level change May lack drivers that can significantly influence changes in sea level (e.g., human-induced subsidence, tectonic movements, and accretion, storm frequency and intensity) Includes faulty assumptions regarding coastal evolution (“Bruun Rule”) Cannot be used to develop adaptation strategies at local scales Requires cost and expertise to run and apply models
Inundation models	Global, regional	Identify coastal habitats and communities vulnerable to inundation based on both elevation and proximity to shoreline Provide useful communication tools for policymakers, coastal communities, and conservation practitioners	Can be completed cheaply and efficiently with minimal data collection and expertise required (GIS experience needed) Provides quick assessment of coastal vulnerability to sea-level rise	Unlikely to represent future conditions accurately because do not account for the full range of biophysical or socioeconomic factors and associated feedbacks, specifically adaptation responses Should not be used to project ecosystem or human communities response to changes in sea level over local extents

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SLAMM SimCLIM	Regional, local	Assess vulnerability of coastal habitats, species, and coastal people and resources Produce maps of projected changes in coastal habitats under accelerated sea-level rise Prioritize key coastal habitats of less vulnerability for inclusion in MPA networks Model outputs may be used to inform development of adaptation strategies Prioritize most vulnerable local communities to support climate change adaptation initiatives	SimCLIM includes socioeconomic data needed for developing adaptation responses May provide more robust estimates of sea-level rise vulnerability because local factors can be included (e.g., human-induced subsidence, tectonic movements, and accretion) if such data are available Provide high-resolution information regarding how coastal habitats may be affected by changes in sea level SimCLIM can be used to inform development of adaptation strategies (e.g., ecosystem-based adaptation)	Lack of available data (socioeconomic, high resolution elevation) Lack of knowledge on the driving forces affecting coastal change Lack of feedback mechanisms between hydrodynamic and ecological systems affected by changes in sea level SLAMM does not include socioeconomic component thus cannot be used to inform adaptation strategies Requires cost and expertise to run and apply models

maps of projected changes in wetland habitat under accelerated sea-level rise, is useful for local or regional scale studies that assess the vulnerability of coastal habitats and species, and can provide detailed information regarding how habitats may shift in response to sea-level rise. Such information can be used to identify potential future conflicts among communities and coastal habitats based on migration and uses of habitats (Mcleod et al. 2010b), important information influencing land-use policies and plans. SLAMM can also be used to raise awareness of the potential impacts of sea-level rise. It has been applied to assess coastal habitat change in response to sea-level rise in Washington, Florida, Georgia, Alaska, California, South Carolina, Louisiana, and Maryland (http://warrenpinnacle.com/prof/SLAMM/SLAMM_Projects.html). Recently, SLAMM was used to predict how sea-level rise will change the delivery of ecosystem services in Georgia estuaries and to project changes in shoreline protection potential of tidal marshes (Craft et al. 2009). It has also been used to assess the impacts of sea-level rise on habitats and species in Australia (Traill et al. 2011). However, SLAMM lacks feedback mechanisms between hydrodynamic and ecological systems that may be affected by changes in sea level (Kirwan and Guntenspergen 2009), and it does not include a socioeconomic component that can estimate costs in response to changes in sea level, thus is not useful for informing adaptation policies (Mcleod et al. 2010b). Despite these limitations, the SLAMM model provides useful, high-resolution information regarding how coastal habitats may be impacted by changes in sea level, thus providing a useful tool to land-use and conservation planners and legislators concerned with related policies.

Conservation planners or policymakers may require information to support the development of mitigation and adaptation policies and strategies. In such cases, an integrated assessment, incorporating social, ecological, and economic impacts of sea-level rise, can help identify the vulnerability of coastal habitats, species, and coastal people and resources. These assessments are necessary to inform development of local level adaptation strategies and national adaptation plans. DIVA and SimCLIM are appropriate for these applications as they both allow users to explore sea-level rise impacts on coastal environments and communities and assess costs and benefits of adaptation options. SimCLIM (http://www.climsystems.com) is a software modeling system that simulates, temporally and spatially, biophysical impacts and socioeconomic effects of climatic variability and change (Warrick et al. 2005). SimCLIM allows users to generate scenarios of future climate and sea-level changes and examine sectoral impacts from local to global scales. DIVA (Dynamic Interactive Vulnerability Assessment) is an integrated research model of coastal systems that assesses biophysical and socioeconomic consequences of sea-level rise and socioeconomic development as well as costs and benefits of adaptation to these impacts (http://www.diva-model.net). DIVA produces quantitative information on a range of ecological, social, and economic coastal vulnerability indicators from sub-national to global scales (Vafeidis et al. 2008). DIVA considers a wider range of impacts than SimCLIM, including coastal flooding, wetland change, and salinity intrusion. DIVA is a research model and requires funding to hire a consultant to run the model and develop the outputs. By contrast, SimCLIM is a commercial tool for which licenses and training courses are available. It also has a flexible structure that allows users to customize the model to meet their specific objectives.

Research Needs to Assess Vulnerability to Changes in Sea Level

Research priorities to support sea-level rise assessments include improved high-resolution global elevation data, socioeconomic data (particularly for local assessments), and improved

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understanding of coastal processes affecting changes in sea level. High-resolution elevation data is essential because sea level is projected to increase by 1–2 m by 2100; thus elevation data must have a vertical error of less than 0.5 m, preferably several centimeters, to provide projections useful for spatial planning. Unfortunately, the most widely available global elevation data (Shuttle Radar Topographic Mission) have 90 m horizontal resolution in most areas, and 30 m horizontal resolution available for some areas such as the United States. The SRTM maximum vertical error is about 16 m (http://srtm.csi.cgiar.org), but has been reported at values ranging from 1.5–6.0 m depending on location, terrain, and surface features (e.g., vegetation).

Improved understanding of coastal processes is critical because the complexity and dynamics of these limits the ability of existing models to accurately predict shoreline change in response to sea-level rise. Particularly, data on changes in storm frequency and intensity due to climate change are lacking (but see Walsh and Ryan 2000). This information would help planners and policymakers develop more realistic projections of future shoreline change and associated flooding and erosion scenarios. These data are essential for predicting impacts because tropical cyclones and storm surges can lead to significant increases in coastal flooding and erosion and will be exacerbated by higher sea levels. However, these changes are challenging to model, mainly because of large uncertainty in predictions and lack of scientific consensus (IPCC 2007). Other important factors that can exacerbate sea-level rise impacts include human-induced subsidence (e.g., groundwater/oil extraction) and tectonic movements (e.g., subsidence), although such data are often unavailable.

Finally, the development of a simple global model of shoreline retreat to predict shoreline change in response to sea-level rise is a high priority to replace the widespread use of the "Bruun Rule," which has been shown to be invalid (Cooper and Pilkey 2004; Harvey and Woodroffe 2008). The "Bruun Rule" suggests a beachface will build vertically but retreat landward maintaining an equilibrium profile. The "Bruun Rule" underlies many of the automated tools available to assess coastal vulnerability (e.g., DIVA, SimCLIM) and has seen near global application, despite its applicability being questioned (Cooper and Pilkey 2004). Clearly, understanding the response of the shoreline to changes in sea level is a critical area for collaboration among scientists, planners, and policymakers, and development of a universally applicable model of shoreline retreat under sea-level rise is a research priority.

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Incorporating Ocean Acidification Vulnerability into Tropical Marine Conservation

Conservation Planning Objectives that Address Ocean Acidification

Conservation planners addressing vulnerability to ocean acidification will need to identify and protect marine ecosystems that will be less exposed or sensitive to changes in ocean carbonate chemistry, or which have a high adaptive capacity. Such areas include coral reef communities with physiologically resistant species (Fabricius et al. 2011). Additionally, because local processes can cause local variation in carbonate chemistry, some coral reef areas are likely to experience less change in seawater chemistry as oceans acidify (e.g., due to their ability to modify the seawater chemistry via high rates of photosynthesis and local drawdown of CO_2; Anthony, Kleypas, and Gattuso 2011). Coral reefs in areas already experiencing naturally high fluctuations in pH or aragonite saturation state (Ω_a), perhaps due to high benthic carbon exchange and high water residence times (e.g., Santos

et al. 2011), could have adapted to deal with these conditions, and might thus represent priorities for protection. Although the science is developing, uncertainties exist regarding how marine species and communities will respond to ocean acidification and which reefs are more or less vulnerable to ocean acidification (e.g., does high variability in Ω_a and/or stable low Ω_a lead to improved performance of corals?) (Pandolfi et al. 2011). Due to these uncertainties, it is important to apply a "bet-hedging approach" (i.e., protect ecosystems likely to experience a variety of ocean chemistry regimes such as high and low Ω_a, high variability of Ω_a).

Current Tools to Assess Vulnerability to Ocean Acidification

The conservation planning and management implications of ocean acidification have only recently been explored (Mcleod et al. 2008; Kelly et al. 2011). Data on changes in ocean carbonate chemistry (e.g., pH, carbonate ion concentration, and aragonite saturation state), and ecological responses to such changes can be provided by GCMs, ecological and hydrodynamic models, moored instruments, and environmental proxy studies (e.g., coral coring, sediment coring, isotope analysis). Such tools are useful to identify carbonate chemistry regimes and ecological responses that can be used to inform conservation planning (Table 3).

Currently, for many planners, the ability to incorporate the threat of ocean acidification into conservation planning is limited. GCMs (e.g., coupled carbon cycle models) can provide projections of changes in ocean chemistry and the identification of patterns of natural variability of $\Omega_{a,}$ but most conservation planners in tropical coral reef areas do not have access to such outputs. Even if they did have access, results from GCMs (e.g., Cao and Caldeira 2008; Friedrich et al. 2012), while useful for helping to support urgent emissions reduction policies, are not relevant for local conservation planning. Their relevance for coastal areas is limited because ocean-based models do not capture the variability of nearshore carbon chemistry, nor do they adequately capture the ecological complexity needed to predict ecosystem response. Further, model validation is limited by sparse observational records of ocean carbon chemistry, particularly in coral-rich regions (e.g., Micronesia, Southeast Asia).

Remote sensing data can be used to monitor historical variation in ocean chemistry parameters. Once scientific understanding improves regarding how such variation affects vulnerability to ocean acidification, planners will be able to use these data to identify sites with potentially reduced/increased vulnerability to ocean acidification and support representation of MPAs across a variety of ocean chemistry regimes. A recent tool utilizing remote sensing data was developed to produce 25 km maps of the CO_2-system parameters for the Greater Caribbean (http://coralreefwatch.noaa.gov/satellite/oa/; Gledhill et al. 2008). While this tool provides useful historical information, it requires regional-scale data for calibration. The methodology is based on significant amounts of at-sea ocean chemistry data which are not available in many data-poor regions. Also, as the tool uses atmospheric pCO_2, sea-surface temperature, and salinity as key input variables, its application is limited in coastal or shallow-water reef areas where benthic carbon fluxes can overwhelm the air-sea carbon exchange (Anthony, Kleypas, and Gattuso 2011).

At local extents, carbonate chemistry in reef waters varies widely both spatially and temporally, as photosynthesis-respiration and calcification-dissolution by the reef communities themselves can cause significant diurnal changes in the ocean carbonate chemistry (Anthony, Kleypas, and Gattuso 2011). Moored instruments are increasingly used on reefs to capture this variability as they provide high-resolution time series measurements of ocean carbon chemistry and variability. Moored instrument data can be used to validate

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Table 3
Summary of tools to assess vulnerability of coral reef ecosystems to ocean acidification (OA)

Data/Tools	Scale	Application	Advantages	Limitations
GCMs (e.g., coupled carbon cycle models)	Global, regional	Project changes in ocean chemistry Identify patterns of natural variability of Ω_a Regional comparisons of changes in ocean chemistry	Highlight potential changes to OA parameters that may be experienced on reefs Identify natural vs. climate-induced changes	Uncertainties associated with model projections of changes in ocean chemistry Do not include coastal processes Do not adequately capture ecological complexity needed to predict ecosystem response Model validation limited by sparse observational record of ocean carbon chemistry, particularly in coral-rich regions (e.g., Micronesia, Southeast Asia) Requires cost and expertise to run and apply models
25 km satellite products	Regional	Monitoring of historical variation and recent conditions in ocean chemistry parameters Identify sites with reduced/increased vulnerability to OA Ensure representation of MPAs across variety of ocean chemistry regimes Prioritize areas of lower vulnerability to OA for inclusion in MPAs	Establish seasonal variability and trends across region Can be integrated into GIS/other planning tools to inform decision making	Requires regional-scale data for calibration Too coarse to capture local patterns of ocean carbon chemistry Links between open ocean environment and on-reef chemistry are complex

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Table 3
Summary of tools to assess vulnerability of coral reef ecosystems to ocean acidification (OA) *(Continued)*

Data/Tools	Scale	Application	Advantages	Limitations
Ecological/ hydrodynamic models with carbon chemistry capability	Local	Identify reefs likely to be more/ less vulnerable to OA Identify processes influencing vulnerability to OA Estimate biological response of reefs to OA Test reef sensitivity to variability in water chemistry	Determine how reef type, reef community composition, hydrodynamics, and bathymetry affect OA impacts on reefs Ability to include multiple variables affecting calcification rates (e.g., saturation state, light, temperature, and nutrients)	Scarcity of data establishing reef response to ocean chemistry Incorporation of OA in reef models is in development and thus guidance on these techniques is not broadly available Lack of ocean chemistry data to validate models Lack of data on natural variability of ocean chemistry Lack of guidance regarding what scales of ocean chemistry variability are most relevant for coral reefs Requires cost and expertise to run and apply models
Moored instruments	Local	Provide high-resolution time series measurements of ocean carbon chemistry and variability	Data can be used to validate model projections	Moored instruments can only be used for site specific data and must be maintained over time for long-term datasets Expensive and requires expertise to process data
Historical studies (e.g., coral/sediment coring, isotopic analysis)	Local	Provide climatological histories regarding response of reefs to environmental change (e.g., changes in calcification rates)	Identify long-term changes in coral growth rates, skeletal density	Historical studies can be time consuming and expensive to process Uncertainties noted in some dating techniques and proxies (e.g., boron isotopic ratio) Expensive and requires expertise to collect and analyze coral cores/sediment

model projections, but require major infrastructure investments and technical expertise, and therefore are not widely used.

Combined ecological and hydrodynamic models are increasingly used by researchers to understand local interactions between the carbonate chemistry of water overlying coral reefs and their community composition (Anthony, Kleypas, and Gattuso 2011; Kleypas, Anthony, and Gattuso 2011) because they provide insight into what reef characteristics (in terms of community composition, hydrodynamic regime, and water depth) could counter or exacerbate ocean acidification. Combined ecological and hydrodynamic models are useful to support the identification of processes influencing vulnerability to acidification, and estimation of the biological response of reefs to acidification. These models are able to include multiple variables affecting calcification rates (e.g., saturation state, light, temperature, and nutrients). However, limitations include the lack of ocean chemistry data to validate models, data on natural variability of ocean chemistry, and guidance regarding the scales of ocean chemistry variability most relevant to coral reefs. Lessons from observational studies in areas of natural reef acidification (cold gas seeps) provide insight into potential expected changes in reef community structure under ocean acidification (Fabricius et al. 2011).

Environmental proxy studies (e.g., coral and sediment coring, isotope analysis; Lough and Barnes 2000; Pelejero et al. 2005) provide climatological histories that can be directly compared with multiple measures of reef responses to environmental change (e.g., changes in calcification rates or community structure). In particular, studies identifying long-term changes in coral growth rates and skeletal density (e.g. Cantin et al. 2010; Cooper, O'Leary, and Lough 2012; Tanzil et al. 2009) can help managers to understand how acidification and other stressors have affected corals over time. Substantial progress has been made in minimizing the main limitations of these studies including increased temporal resolution (Zhao et al. 2009), and reduction in uncertainties of geochemical interpretation of potential proxies (e.g. boron isotropic ratio; Pagani et al. 2005) but the time, expense, and expertise required to collect and analyze data are still considerable.

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Research Needs to Assess Vulnerability to Ocean Acidification

Limited guidance exists for conservation planners to plan for and assess the impacts of ocean acidification on coral reefs. Global and regional models provide useful information to raise awareness of the ocean acidification threat to coral reefs and to support mitigation efforts, such as setting specific atmospheric CO_2 emissions targets, but are unable to inform local conservation planning due to the limitations noted above. Global and regional projections of aragonite saturation state can be used to help conservation planners understand differences in regional vulnerability to ocean acidification. These differences can influence decisions for where to allocate limited funding to monitor the impacts of ocean acidification at local scales, such as through supporting deployment of mooring buoys, the application of ecological/hydrodynamic models and environmental proxy studies.

Due to the significant variation in ocean and reef water carbon chemistry across habitats and individual reefs (Anthony et al. 2008), coarse-resolution studies are of limited use for conservation planning of individual MPAs. However, the application of mooring buoys, ecological/hydrodynamic models, and environmental proxy studies can provide information for scales at which management decisions are made and thus are encouraged in high priority coral reef conservation areas. Collaboration between conservation planners and scientists specializing in ocean acidification is essential to support the application and interpretation of these methods. As conservation planners and policymakers support the development of ocean acidification risk models, oceanographic and benthic processes

contributing to seawater carbonate chemistry variability must be integrated, particularly for high priority coral reef regions. Understanding feedbacks between seawater carbon chemistry, benthic carbon flux processes, and ecological and evolutionary responses under ocean acidification will facilitate comprehension of the vulnerability of coral reef ecosystems to ocean acidification within and among MPAs.

Conclusion

Climate and ocean change has shifted focus from conserving individual species to strategies aimed at maintaining ecological structure, processes, and function and securing the goods and services provided by marine ecosystems (Hughes et al. 2005). This shift is reflected in regional government commitments to protect marine ecosystems and their benefits to coastal communities. Conservation planners recognize that protecting ecosystem structure, processes, and function requires managing marine ecosystems for multiple and potentially synergistic stressors. However, their ability to address vulnerability to climate change specifically is limited by a lack of guidance on the most appropriate data and tools. Tables 1, 2, and 3 summarize available tools and data to help conservation planners assess the vulnerability of coral reef ecosystems to increasing SSTs, and changes in sea level and ocean chemistry. They include information regarding the application, advantages, and limitations of such tools and the appropriate scale at which the tools can meaningfully be applied.

Despite limitations in existing data and tools for projecting climate and ocean change impacts, policymakers and planners will make decisions using the best available knowledge, underscoring the need for close collaboration among scientists, conservation planners, and legislators. To address uncertainties in climate projections and ecological responses to related impacts, conservation planners and managers will need to implement strategies that address a range of impacts on at-risk ecosystems and communities.

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