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A multidisciplinary coastal vulnerability assessment for local government focused on ecosystems, Santa Barbara area, California

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ABSTRACT

Incorporating coastal ecosystems in climate adaptation planning is needed to maintain the well-being of both natural and human systems. Our vulnerability study uses a multidisciplinary approach to evaluate climate change vulnerability of an urbanized coastal community that could serve as a model approach for communities worldwide, particularly in similar Mediterranean climates. We synthesize projected changes in climate, coastal erosion and flooding, watershed runoff and impacts to two important coastal ecosystems, sandy beaches and coastal salt marshes. Using downscaled climate models along with other regional models, we find that temperature, extreme heat events, and sea level are expected to increase in the future, along with more intense rainfall events, despite a negligible change in annual rainfall. Consequently, more droughts are expected but the magnitude of larger flood events will increase. Associated with the continuing rise of mean sea level, extreme coastal water levels will occur with increasingly greater magnitudes and frequency. Severe flooding will occur for both natural (wetlands, beaches) and built environments (airport, harbor, freeway, and residential areas). Adaptation actions can reduce the impact of rising sea level, which will cause losses of sandy beach zones and salt marsh habitats that support the highest biodiversity in these ecosystems, including regionally rare and endangered species, with substantial impacts occurring by 2050. Providing for inland transgression of coastal habitats, effective sediment management, reduced beach grooming and removal of shoreline armoring are adaptations that would help maintain coastal ecosystems and the beneficial services they provide.

1. Introduction

The world is experiencing a growing set of impacts from a warming climate that include sea level rise (SLR), coastal flooding, fires, erosion and changes in weather patterns that threaten coastal communities and ecosystems (IPCC, 2013). These impacts are projected to increase throughout future decades, depending on the amount of greenhouse gas emissions (IPCC, 2013, 2018). Communities across the world are assessing their vulnerability to climate change and preparing for future impacts through a variety of planning avenues including land use, emergency response, hazard mitigation, climate adaptation plans, and infrastructure investments (Measham et al., 2011 (Australia); Heidrich et al., 2013 (UK); IPCC, 2013; Reckien et al., 2018 (EU); Kantamaneni et al., 2018 (UK); Keenan, 2018 (US); Kantamaneni et al., 2019 (India); Serafim et al., 2019 (Brazil). While there are constraints to local governments' abilities to adapt to climate change (Moser and Luers, 2007; Tribbia and Moser, 2008; Measham et al., 2011; Baker et al., 2012) and climate change adaptation cannot solely be addressed at the local level (Lindseth, 2004), local government and regional adaptation is recognized as an important avenue to large-scale climate adaptation planning (Shi, 2019; Rauken et al., 2015; Roberts, 2008; Heidrich et al., 2013).

Generally, local adaptation planning addresses the built and/or natural physical environment, with little attention to ecosystems (Wilson, 2006; Guyadeen et al., 2019). While certain ecosystems, such as wetlands, are afforded special status at the federal, state or local

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levels, most ecosystems are only protected by local statutes. The fate of ecosystems thus is largely dependent on local government decisions. When planning for a future with an altered climate, changes to ecosystems should be part of the purview of local governments, along with impacts to the built and natural physical environments.

Local government officials often have inadequate access to information on climate change and ecosystem functioning (Pasquini et al., 2013; Pasquini and Cowling, 2015) or an understanding of how ecosystems will respond to climate change (Reid, 2016). Local governments need multidisciplinary scientific information to plan climate change adaptation, including projections of physical impacts and an understanding of ecosystem response to climate change. Providing local governments with information for adaptation at the scale of the area they manage (Bourne et al., 2016), and enabling close collaboration between scientists and municipal staff (Wamsler et al., 2014) are vital to achieving practical implementation of ecosystem-based management.

Coastal ecosystems are among the most threatened by humans (Worm et al., 2006; Halpern et al., 2008). Major losses of coastal Mediterranean ecosystem services have occurred as a result of urbanization (Santana-Cordero et al., 2016), with climate change increasingly adding to adverse impacts (Gitay et al., 2002; Lovejoy and Hannah, 2005; IPCC, 2013). In urban areas, coastal ecosystems are often surrounded by coastal development on the landward side and rising sea level, so subject to increasingly shrinking and modified habitat (Defeo et al., 2009; Mooney et al., 2009; Moeslund et al., 2011; Valiela et al., 2018).

There is a need to incorporate coastal ecosystems in local government climate vulnerability assessments and adaptation plans as part of the broader societal adaptation process (Mawdsley et al., 2009; Runting et al., 2017). This will prevent loss of biodiversity and ecosystem services while helping communities adapt to climate change (Ojea, 2015; Reid, 2016) and promote a shift from infrastructure to ecosystem-based adaptation (EbA) - defined as 'the use of biodiversity and ecosystem services to help people adapt to the adverse effects of climate change as part of an overall adaptation strategy' (CBD, 2009) - as a way of preparing coastlines for climate change (Jones et al., 2012).

EbA solutions, which utilize the natural environment to provide an adaptation benefit (Jones et al., 2012; Munroe et al., 2012), provide a sustainable, ecologically sound and economically feasible approach to coastal defense with the potential to protect cities at risk of flooding (Temmerman et al., 2013). Maintaining ecosystems as 'green infrastructure' for EbA purposes, in addition to providing similar flood protection benefits as grey infrastructure, has multiple benefits including: greenhouse gas mitigation, water purification, sediment trapping, conservation of biodiversity, provision of natural recreational areas, and improved well-being of human communities. (Roberts et al., 2012; Munang et al., 2013; IPCC, 2013). Although no community has reported a comprehensive EbA approach, a variety of EbA measures are in use (Zölch et al., 2018). Shifting from grey infrastructure to ecosystem-based adaptation is recognized as key to achieving a future with sustainable development (Jones et al., 2012; Scarano, 2017).

We present the results of a multidisciplinary vulnerability study of climate change impacts to watersheds, shorelines and ecosystems in Santa Barbara County, California aimed at informing EbA for local governments in this region. In this case study, we assess projected changes in climate, coastal erosion and flooding, watershed runoff and impacts to beaches and a coastal salt marsh ecosystem.

1.1. Study area

The focal study region is in Santa Barbara County, California (USA), and lies in a narrow coastal plain, bordered to the north by the Santa Ynez Mountains, a steep east-west trending mountain range (> 1200 m), and to the south by the Santa Barbara Channel (Fig 1). The study region includes the cities of Goleta (population 31,100), Santa Barbara (population 92,100), and Carpinteria (population 13,600) and unincorporated areas in southeast Santa Barbara County (US Census Bureau, 2017).

The Santa Barbara region is characterized by a Mediterranean climate with mild intermittently wet winters and moderately warm, generally rainless summers (Ryan, 1994). Winter storms provide the majority of freshwater input to rivers, streams, and the nearshore marine environments. The coastal ecosystems of the Santa Barbara region are exposed to highly variable rainfall and to periodic El Niño Southern Oscillation (ENSO) and other short period climate variations that affect stream runoff and ocean conditions in the Santa Barbara Channel, including water temperature, wave height and period, and sea level (Wolter, 1987). Atmospheric and oceanic conditions that develop during El Niño create elevated sea levels that can persist for several months; these shorter period fluctuations will exacerbate the effects of longer term SLR. In addition, enhanced rainfall driven by El Niño and other atmospheric patterns may increase terrestrial runoff and the associated transport of sediments, nutrients, and pollutants to the coastal zone (Storlazzi et al., 2000).

Large scale patterns of ocean circulation also change, and storm disturbance from waves is often considerable, which coupled with elevated sea level increases the risk of coastal hazards across the entire U.S. West Coast (Barnard et al., 2015). El Niño events can drive elevated sea levels and more powerful waves without increased precipitation. This was the case during the El Niño winter 2015–2016, when ocean levels reached or exceeded 10 cm above normal and wave conditions were 50% more energetic than the average winter despite a continuing drought in the Santa Barbara region (Barnard et al., 2017).

The region has diverse watersheds, which vary widely in the proportion of natural, agricultural and urban development (Aguilera and Melack, 2018). Steep montane slopes composed of readily eroded fractured sedimentary rock and strongly seasonal, often intense, episodic rainfall, result in large sediment loads to the ocean (Warrick et al., 2015). The intermittent occurrence of fire in the catchments further enhances temporal variation in flooding and the export of sediments and nutrients.

1.2. Sandy beach and coastal wetland ecosystems

Typical of much of the world's coasts, most of the study area's shoreline is composed of sandy beaches (> 70%) (Habel and Armstrong, 1977). Coastal wetlands, lagoons, coastal dunes, vegetated coastal strand zones, rocky intertidal reefs and creeks and riparian areas are present in smaller proportions in the study area.

Sandy beaches are composed of unconsolidated sand from watersheds and coastal bluffs that are shaped by wind, waves and tides (McLachlan and Defeo, 2018). Sandy beach ecosystems are affected by wave action and sediment transport and thus vulnerable to climate change and SLR (Fig. 2). Ecosystem services and functions of beaches and dunes in the study area include absorption of wave energy, the filtration of large volumes of seawater, nutrient recycling, rich endemic invertebrate communities that are important prey resources for shorebirds and fish, and the provision of critical habitat for pinnipeds, and declining and endangered wildlife, such as shorebirds, as well as beach-nesting fish (Martin, 2015; Dugan and Hubbard, 2016). Wider beaches in the study area also can support sand-trapping pioneering vegetation, including unique plants and coastal strand communities (Dugan and Hubbard, 2010). Beaches in the study area exhibit considerable seasonal and interannual variation in profile and width (Revell and Griggs, 2006; Revell et al., 2011; Barnard et al., 2012). Episodic storms and El Niño events can strongly influence the morphodynamics of local beaches due to erosion from increased wave energy (Barnard et al., 2009a, 2011, 2017).

Beach ecosystems are generally not well protected by local regulations and their ecological function is rarely considered in climate adaptation planning. The widespread practices of shoreline armoring,

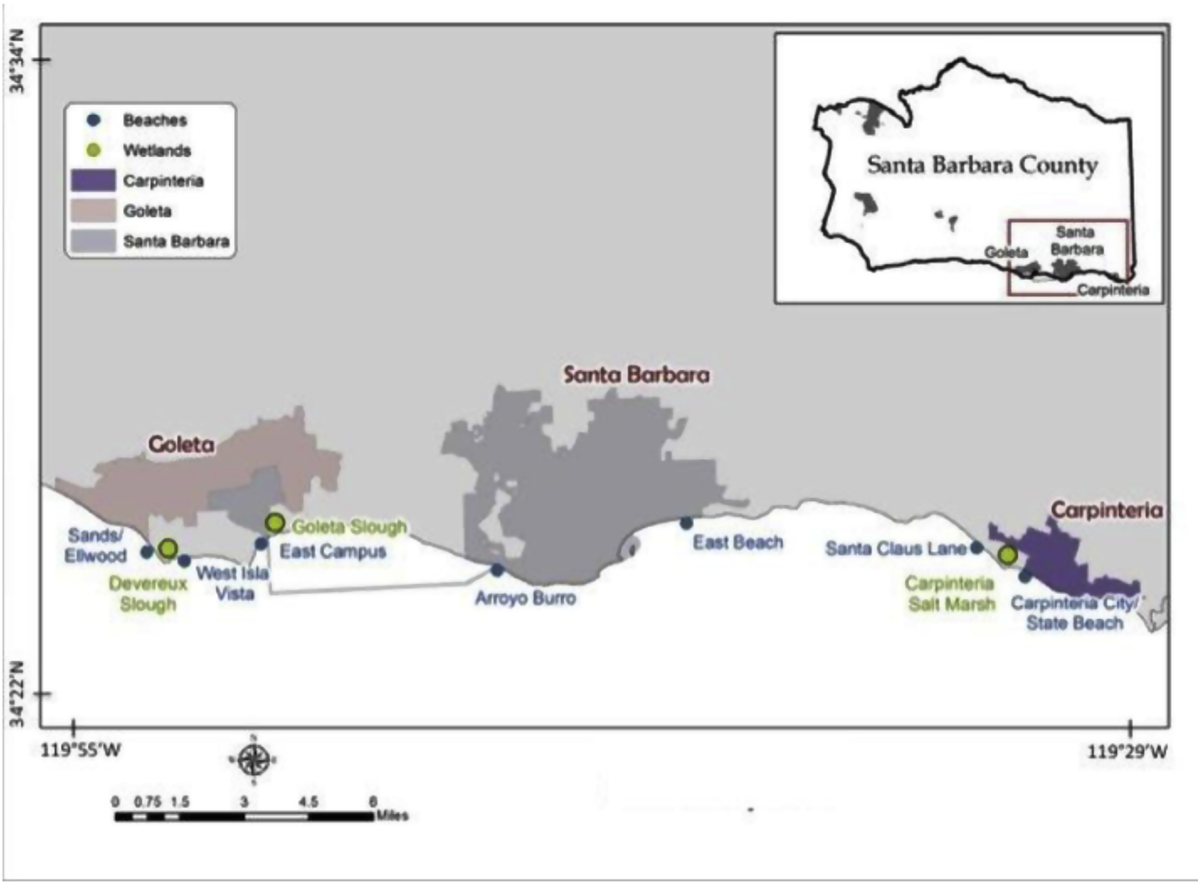

Fig. 1. Study area (for watershed map see Fig. 8).

beach grooming, beach filling, winter berm building, and vehicle use that degrade these ecosystems (Defeo et al., 2009) impact sandy beaches in the Santa Barbara study region.

Sixty-two percent of estuarine wetlands in the study region have been lost since 1850 (Stein et al., 2014). Those estuaries that remain are small, isolated systems that provide valuable ecosystem functions including: the preservation of native estuarine-dependent biodiversity, habitat for regionally rare and endangered plants and animals, food chain support for fish and birds, and the provision of habitat for recreationally and commercially important fish. They can provide storm protection, and buffering of coastal development from coastal erosion, surface water runoff filtration and attenuation, and carbon sequestration. Estuarine wetlands also provide socioeconomic values that include their use by the public and educational institutions for bird watching, nature walks, research and teaching (Onuf et al., 1979; Ferren et al., 1997).

Sandy beaches and wetlands are important to the economy, culture and character of the Santa Barbara area, contributing open space, aesthetic qualities, recreational opportunities, tourism support and spiritual and cultural values (King et al., 2018). The services provided by coastal ecosystems that mitigate physical impacts of climate change (e.g., carbon sequestration, storm buffering, runoff attenuation), can provide the basis of ecosystem-based adaptation for coastal communities.

2. Materials and Methods

This manuscript is derived from the Santa Barbara Area Coastal Ecosystem Vulnerability Assessment (SBA CEVA), a regional study conducted to inform climate change adaptation of both human and natural communities of Santa Barbara County, California, USA, with local government officials as the target audience (Myers et al., 2017). Five multidisciplinary research components included: downscaled climate projections, shoreline change and coastal hazards, watershed runoff, estuarine ecosystems and sandy beach ecosystems. Regional downscaled climate projections and models of shoreline change and coastal hazards informed local level impacts to watersheds and coastal ecosystems. The relationship between global datasets, regional downscaling and local ecosystem vulnerability is represented in Fig. 3. Methods for study components are summarized in Table 1.

2.1. Climate change projections

Downscaled global model projections were employed to provide an envelope of possible climate changes for the Santa Barbara region over the 21st Century. This study utilized ten global climate models (GCMs) from the Fifth Assessment (IPCC AR5, 2013) that were selected as best representing the historical climate of California (Climate Change Technical Advisory Committee, California Department of Water Resources, 2015; Pierce et al., 2018). Downscaled daily maximum temperature (Tmax), minimum temperature (Tmin) and precipitation using the Localized Constructed Analogs (LOCA) statistical technique (Pierce et al., 2014) were employed for two sets of GCM simulations, based on the RCP4.5, a moderate greenhouse gas emission scenario, and RCP8.5 a relatively high emissions scenario. The LOCA downscaled data covered the Santa Barbara region at ~6-km (1/16th degree) resolution covering the period extending from 1950 to 2100.

Projections of sea level were produced using modeled short period sea level variations superimposed on selected 21st Century SLR scenarios. Modeled hourly coastal water levels along the Santa Barbara County coastline included astronomical tide, meteorological and influences of short period climate variability, and long-term global SLR,

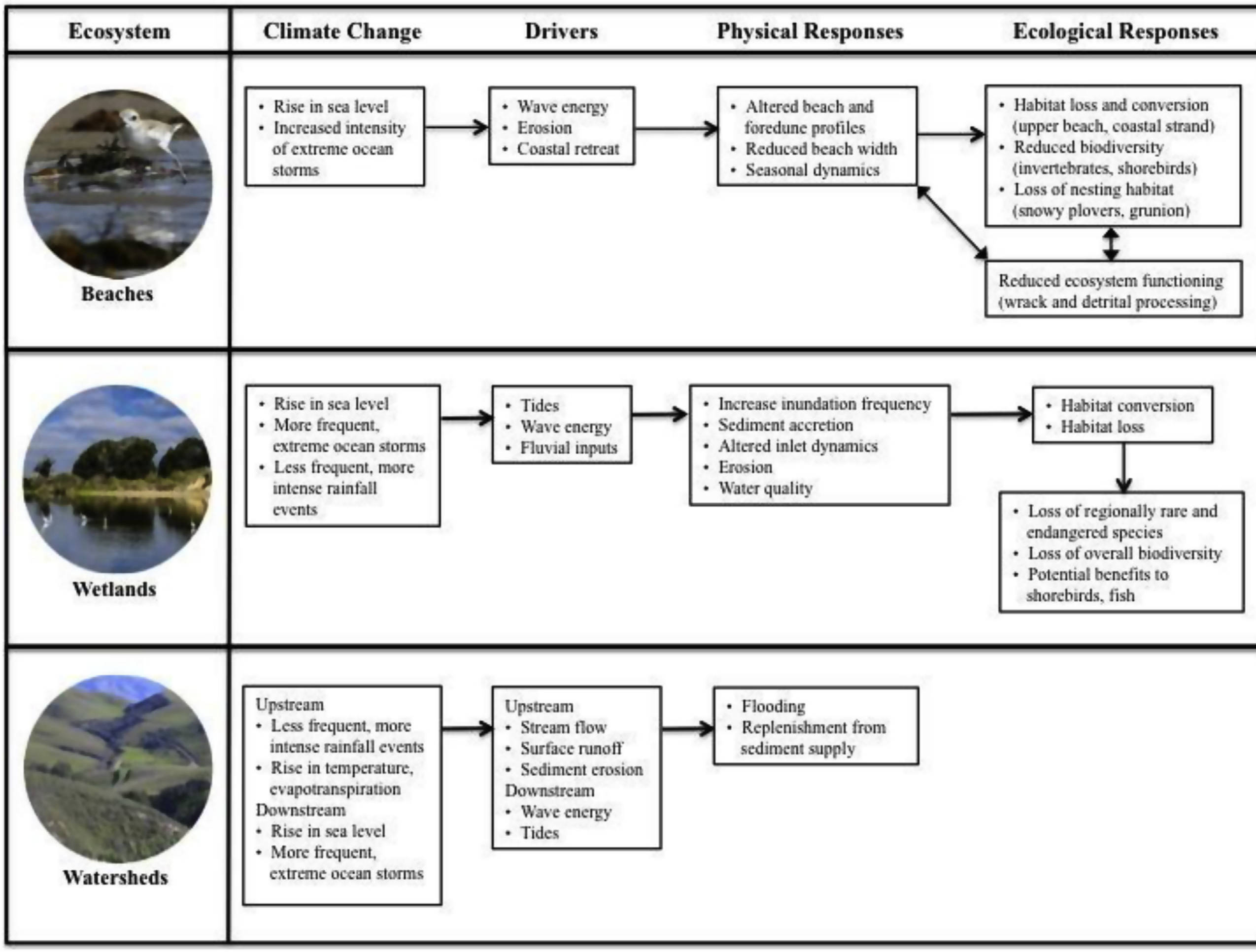

Fig. 2. Concept diagram representing the interaction of climate change, physical drives and responses and ecological responses.

following the method described in Cayan et al., 2008. This study employed low-, mid-, and high-range estimates of SLR from the National Research Council (NRC) report (2012), covering the 2005–2100 period. The short period sea level fluctuation (the meteorological component of residual water level) is estimated using multi-linear regression model following Cayan et al. (2008), constructed with water level observations at Santa Barbara Harbor and historical NCEP meteorological reanalysis data. Input to the model consisted of non-tide variables, including daily climate model data, local surface pressure and (together called H_{MET}) local offshore surface wind stresses, local sea surface temperature (SST), and SST in the central tropical Pacific Ocean as a measure of El Niño variability. The climate model data were first bias corrected with the method used by the Localized Constructed Analogue (LOCA) downscaling technique (Pierce et al., 2014). Local and equatorial Pacific Niño 3.4 regional average SST were detrended since large-scale global SLR arising from long-term temperature change is included as a separate term in the projection of the total water level. To produce hourly regressed estimates of H_{MET}, the daily forcing data from the CMIP5 climate models is disaggregated to hourly values using the method described in Cayan et al. (2008). Historical and future values of the non-tide water level residuals were projected for each of eight GCMs, which supplied the necessary meteorological and ocean temperature variables. The non-tide estimates were superimposed upon predicted astronomical tides and projected long-term SLR scenarios to produce values of total water level at each of the sites.

2.2. Watershed runoff modeling

Watershed runoff was simulated using the Hillslope River Routing (HRR) model (Beighley et al., 2009), which utilizes an irregular computational grid and parallel computing to simulate water fluxes and energy balance through vegetation and soil layers, lateral hydraulic transport from upland areas and channel hydraulics. Daily precipitation and temperature are the meteorological forcings for runoff generation in HRR. A binary-runoff-coefficient approach is used to simulate surface runoff, which assumes that runoff is proportional to precipitation rate and the runoff coefficient switches between dry and wet modes based on soil moisture conditions. Subsurface runoff is estimated as a function of soil moisture and saturation hydraulic conductivity. Potential evapotranspiration (PET) was used to quantify evaporation from land surface and transpiration through vegetation, which was estimated using Priestley and Taylor method (Priestley and Taylor, 1972) with the Food and Agriculture Organization of the United Nations (FAO) limited climate data approximations (Raoufi and Beighley, 2017). After the runoff excess was generated from each grid, it is transported over hillslopes using a kinematic approximation approach; after the runoff reaches channels, diffusion wave routing is used to simulate the hydraulics of channel flow.

A Monte Carlo-based calibration procedure was implemented to estimate the optimal model parameters in HRR. Gridded precipitation and temperature estimates derived from gauged observations (Livneh et al., 2015) were used as model forcings. In situ discharge measurements obtained from five USGS gauge stations were used for model performance evaluation. Based on the availability of streamflow data,

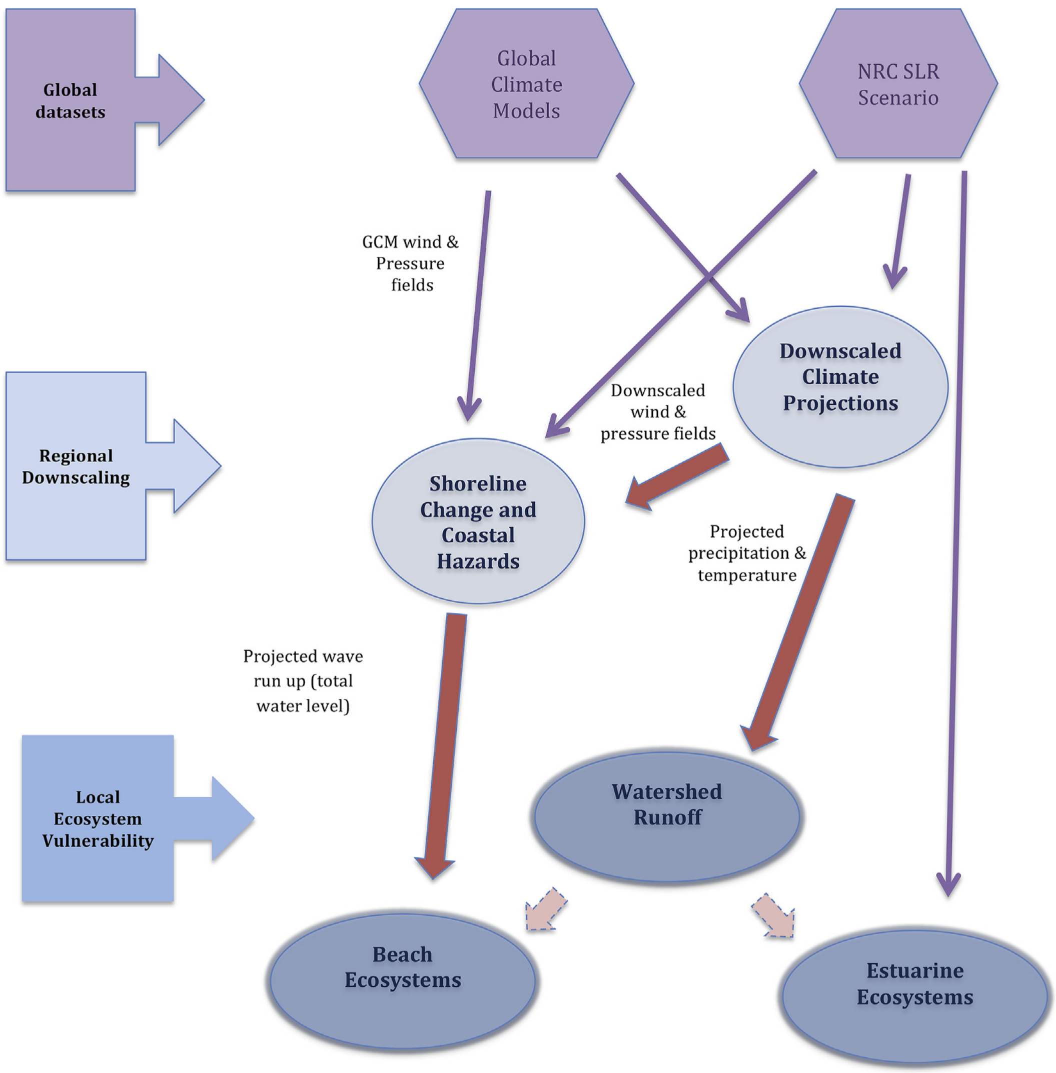

Fig. 3. Relationship between global, regional and local vulnerability study components. Circles and ovals represent the five research components of the study. Hexagons represent global datasets that informed regional models.

the calibration period was 1984–2013. Six parameters governing lateral and vertical transport and surface runoff generation processes were calibrated (the definition and description of these parameters can be found in Feng et al., 2019). During calibration, thousands of parameter sets are randomly selected from predefined parameter ranges. The best parameter set for each gauged-watershed was selected based on objective functions at each gauge location. To estimate the model parameters at non-calibrated watersheds, the optimal values from each gauge were then related to upstream watershed characteristics (e.g., land cover features). For those that are not significantly correlated with any hydrogeologic characteristics, their values are estimated when the overall cost function (i.e., average of error metrics from all calibrated watersheds) is minimized.

After HRR was calibrated, it was forced with downscaled daily precipitation and temperature from hindcast simulations and future projections of 10 GCMs to simulate watershed runoff during historical (1961–2000) and future (2021–2100) periods. The differences in streamflow volumes and extremes and seasonality between historical (1961–2000) and future (2021–2060 and 2061–2100) periods under both emission scenarios were quantified. The Mann-Whitney *U* test was applied to detect the significance of the changes in these variables.

2.3. Coastal hazards

To assess the exposure of ecosystems to coastal hazards associated with climate change, the Coastal Storm Modeling System (CoSMoS) was applied to the study region (Barnard et al., 2014, 2019; Erikson et al., 2018a, 2018b; O'Neill et al., 2018). CoSMoS is a dynamic modeling approach that allows detailed predictions of coastal flooding due to projected SLR and future storms integrated with long-term coastal evolution (i.e., beach changes and cliff/bluff retreat) over large geographic areas (100s of kilometers). The prototype system of CoSMoS was developed for the California coast using the global WAVEWATCH III wave model, the TOPEX/Poseidon satellite altimetry-based global tide model, and atmospheric forcing data from Global Climate Models to determine regional wave and water-level boundary conditions. These regional conditions are then dynamically downscaled using a set of nested Delft3D wave (SWAN) and tide (FLOW) models, and are then linked at the coast to river discharge projections, fine-scale estuary models, and along the open coast to closely spaced XBeach (eXtreme Beach) cross-shore profile models.

Projections of multiple storm scenarios (daily conditions, annual storm, 20-year- and 100-year-return intervals) were developed under a suite of sea-level rise scenarios ranging from 0 to 2 m, along with an extreme 5-m scenario. All the relevant physics of coastal storms (e.g.,

Table 1
Summary of methods for each of the five components of the study.

Component	Method	Data Timeframes	Scale/resolution	Output	Geographic range
Climate	Localized Climate Analogue (LOCA) 10 GCMS (8 GCMs for hourly sea level) RCP 4.5 and 8.5	Historical: 1985–2014, Future: 2020–2039, 2040–2059, 2060–2099	6 km grid	# Extreme hot days/yr, # wet days/yr, daily max T, difference in daily min and max, difference in median annual precip, length of wet season, hourly sea level	Santa Barbara County @ 6 km resolution, entire CA coast?
Watershed	Hillslope River Routing (HRR) Simulated surface and groundwater runoff from hill slope to channels	Historical: 1961–2000 Future: 2021–2060; 2061-2100	~1 km^2 sub-basins	Daily discharge, annual maximum daily discharge, 100-year flood discharge, hydrological seasonality (timing and length)	Watersheds draining into Santa Barbara Channel from west of the Ventura River to east of Point Conception, in southern Santa Barbara County.
Coastal Hazards	Coastal Storm Modeling System 3.0 (CoSMoS)		2 m digital elevation model (DEM)	Water level (m NAVD88), flood extent, wave conditions, shoreline evolution, average beach loss (m), cliff retreat	California Coast
Wetlands	Habitat evolution model based on elevation (LIDAR DEMs and in situ measurements), inundation (NOAA tide data), and habitat (multispectral aerial images)			Habitat categories (upland, transition, high marsh, mid marsh, low marsh, high mudflat, low mudflat and subtidal) For SLR of +0–254 cm sea	Carpinteria Salt Marsh,
Beaches	Predictive framework for ecological features based on relationships between ecological measurements of the daily beach high tide strand line level (HTS) and projections of physical measurements of total water level (TWL) and beach profiles from measured by CoSMoS 3.0USGS)			Projections of Profiles of and widths of beach zone widths above TWL (dry sand) for ambient conditions, annual storm conditions, and above mean high water for SLR of 0 cm, 50 cm, 100 cm, 150 cm, 200 cm, 500 cm (MHW)	Seven beaches in southern Santa Barbara County including: Sands/Elwood, West Isla Vista, East Campus, Arroyo Burro, East Beach, Santa Claus Lane, and Carpinteria City/State Beach

tides, waves, and storm surge) were modeled then scaled down to local, 2 m-scale flood projections for use in community-level coastal planning and decision-making. Rather than relying on historic storm records, wind and pressure from global climate models were used to simulate coastal storms under changing climatic conditions during the 21st century (Erikson et al., 2015, 2018a; O'Neill et al., 2017). For locally-generated seas and surge within the Santa Barbara Channel, downscaled wind and pressure fields were utilized (Pierce et al., 2014, 2018). Further, the hydrodynamic modeling resolution, which is typically on the order of ~50–100 m, was enhanced to ~10 m to feed directly into the detailed ecosystem vulnerability assessments for the beaches and tidal wetlands at Carpinteria, and Goleta (e.g. Goleta Slough and Devereux Slough).

Long-term shoreline change and cliff retreat projections also are provided, including uncertainty, using state-of-the-art approaches for each of the 10 SLR scenarios. Predictions of sandy shoreline change were produced by CoSMoS-COAST (Coastal One-line Assimilated Simulation Tool; Vitousek et al., 2017). The model accounts for the dynamical processes of wave-driven alongshore and cross-shore transport, shoreline retreat due to scenarios of sea-level rise, and natural and anthropogenic sources of sediment estimated via data assimilation of historical shoreline data. The model is "trained" with historical wave and shoreline data through 2010, and the calibrated model is used to produce a prediction of shoreline evolution by 2100. Historical shoreline data used to tune the model parameters in Santa Barbara comes from 3 aerial LIDAR surveys (Fall 1997; Spring 1998; and Fall 2009) (NOAA, 2012) as well as semi-annual USGS GPS surveys conducted in Goleta and Carpinteria from 2005 to 2010.

Up to 7 numerical models were used to predict future cliff position at each transect (Limber et al., 2018). All models related breaking wave height and period to rock or substrate erosion, based on the idea that as sea level rises, waves will break closer to the cliff and accelerate sea cliff retreat relative to existing or historic rates of change. The models varied in complexity and each made slightly different assumptions about how waves and SLR drive future cliff retreat. However, using the models as an ensemble provides improved predictive capacity over any single model. The main sources of uncertainty in the cliff projections arise from the base error of the historic retreat rates (measured between 1933 and 2010) that the predictions are based on, how well the individual models agree with one another, and difficulties estimating unknown model coefficients.

For each of the 40 SLR and storm scenarios, products include: flood extent, depth, duration, elevation, and uncertainty based on sustained flooding projections; maximum wave run-up locations; maximum wave height and current speed; and detailed population demographic and economic exposure (Jones et al., 2017). All the model results can be downloaded in native GIS formats (Barnard et al., 2016) or viewed interactively in publicly available web tools to analyze the coastal hazards (Ballard et al., 2019) and associated socioeconomic impacts (Jones et al., 2017).

2.4. Coastal wetland ecosystem methods

This study focused on Carpinteria Salt Marsh, a fully tidal wetland of 93 ha located ~12 km east of Santa Barbara, California, USA. The regularly flooded middle tidal marsh is vegetated primarily by a salt tolerant succulent, pickleweed *Sarcocornia pacifica (=Salicornia virginica)*. Other species, including the succulents *Arthrocnemum subterminale* and *Jaumea carnosa*, saltgrass *Distichlis spicata*, and alkali heath *Frankenia salina*, are found along with *Sarcocornia* at higher tidal elevations. Regionally rare and endangered plant species that include *Cordylandthus maritimus* (=*Chloropyron maritimum*), *Lasthenia glabrata*, *Sueada calceoliformis,* and *Astragalus pycnostachyus* var. *lanosissimus* are also found in the high marsh and upland transition habitats. The wetland is surrounded by urban and residential development that includes railroad tracks, roads, housing, and business development. The amount

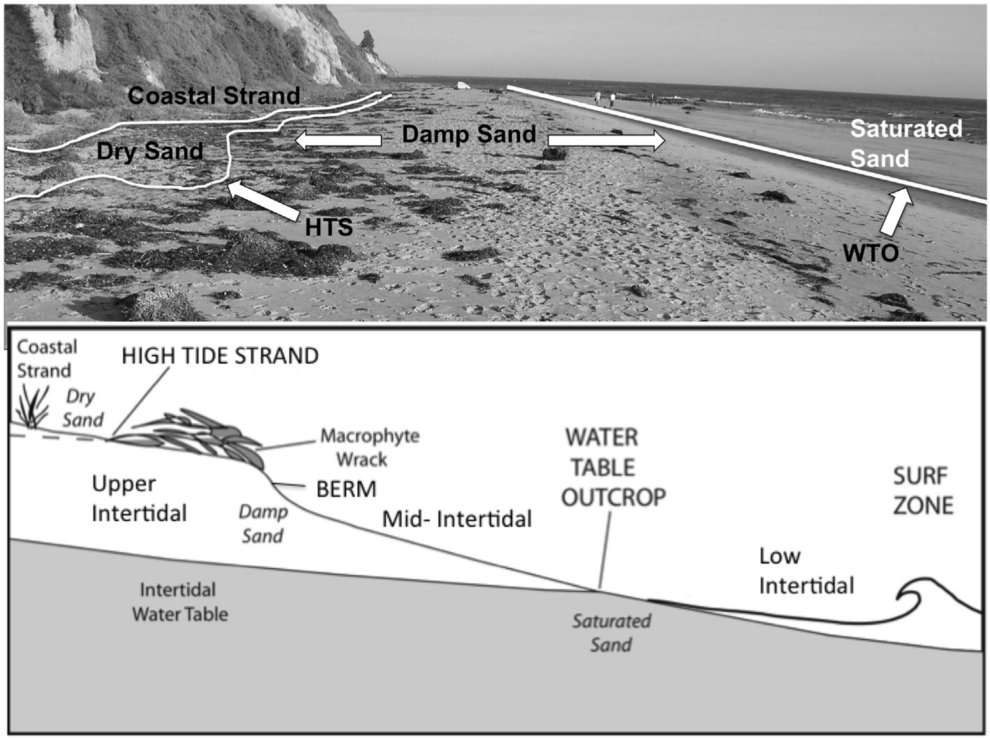

Fig. 4. Illustration of the major zones and ecological features for a bluff-backed sandy beach in Santa Barbara, CA (HTS = High tide strand, WTO = Water table outcrop).

of freshwater runoff entering the wetland is highly variable both within and among years and coincides with seasonal storm events that are generally restricted to December through March (Beighley et al., 2003). Tidal waters from the Santa Barbara Channel enter the wetland through an inlet at the southern border maintained open through a rock revetment.

The distribution and area of existing habitats in Carpinteria Salt Marsh were identified using a multispectral aerial image. Vegetation classification algorithms were run on the georeferenced image to produce a simplified vegetation/habitat classification. The habitats and grouping criteria consisted of: 1) open water subtidal, 2) mudflat - divided into high mudflat (frequently exposed, inundated < 50% of the time) and low mudflat (frequently flooded, inundated ≥ 50% of the time, 3) coastal salt marsh - vegetated by halophytic plants, further divided into middle and high/mixed marsh on the basis of general plant species composition, with *S. pacifica* dominant in the middle marsh at lower elevations, and a mixture of species at the higher elevations, 4) salt marsh – upland transition habitat that encompasses a gradient from salt marsh to terrestrial vegetation infrequently hit by the tides, and 5) undeveloped upland.

A digital elevation model (DEM) constructed from data acquired by the California Coastal Conservancy Coastal Light Detection and Ranging (LiDAR) was used to link elevation and habitat distributions (based on vegetation). LiDAR elevations are influenced by plant canopy cover and were adjusted downward for each habitat using average Real Time Kinematic Global Positioning System (RTK GPS) elevation survey data from each habitat. Five complete years of tide data (2006, 2009, 2011, 2013 and 2014) acquired from the NOAA tide station at Santa Barbara, California (http://tidesandcurrents.noaa.gov/), were used together with the DEM and habitat classification to link elevation, inundation frequency and habitat (average deviation of tide data from long-term MSL = −2 cm). Habitat evolution scenarios were derived for SLR ranging from 0 (no SLR) to 2.5 m relative to the marsh surface by raising the elevation reached by tidal waters and computing habitat change based on the habitat – inundation frequency relationship.

Outcomes pertaining to the possible timing of habitat evolution were derived for the high and low SLR National Research Council (2012) scenarios. The scenario affects the timing of habitat evolution, but not the changes *per se* predicted to occur to habitats eventually with SLR. Reynolds et al. (2018) estimated accretion rates of 3.7 mm year in the top 30 cm of sediment using ^{210}Pb. Therefore, we explored how an average annual accretion rate of 4 mm yr^{-1} would influence the timing of evolution of marsh habitats.

The highest positive sea level anomalies associated with the El Niño of 2015 occurred within Carpinteria Salt Marsh July–October 2015 (Myers et al., 2017). On October 23, 2015, marsh elevation was measured using a RTK GPS at 1 m intervals along transects crossing mudflat and salt marsh habitat recording the condition of vegetation at each measurement point. We then compared the observed changes in vegetation condition associated with the short-term sea level anomaly associated with the El Niño of 2015 to the habitat conversion predicted to occur with longer-term SLR.

2.5. Sandy beach ecosystem methods

A critical impediment to assessing the vulnerability of sandy beach ecosystems to climate change has been a lack of information that can be used to integrate standard elevational metrics (MSL, MHW) with key ecological components and habitat zones of beach ecosystems (Dugan et al., 2013). To address this issue, standard elevational metrics were related with key ecological components and habitat zones of beaches to generate predictions of the ecological responses and resulting vulnerability of sandy beach ecosystems to pressures from climate change, with a focus on SLR. Seven study beaches including beaches with different landward backings: three bluff-backed beaches, one dune-backed beach, one armored beach, one groomed and filled beach and one beach with a mixture of dunes, armoring and grooming (Fig 1). We measured and modeled an ecologically important feature of beach ecosystems, the upper intertidal zone for our analyses (Fig. 4). Located closest to the landward boundaries of the beach, upper intertidal zones are edge habitats that are highly vulnerable to SLR.

Total Water Level (TWL) datum (Moore et al., 2006; Ruggiero and List, 2009) was used as a proxy for defining the dynamic seaward boundary, the daily High Tide Strand line (HTS), of the upper intertidal zone of the study beaches (see Fig. 4) (see Dugan et al., 2013). Total Water Level (TWL) on a beach is the sum of the tide level, plus the elevation above the tide level reached by wave runup, including wave setup (Ruggiero and List, 2009). The TWL datum, where available, can provide a closer approximation of the 24-h High Tide Strand line (HTS) feature that bounds the upper beach zone and is followed by key beach biota (see Dugan et al., 2013 for rationale), than the Mean High Water (MHW) datum. Assuming a moderate beach slope (est. 4–8 ^{O}), the mean elevations of typical upper beach species (Clark, 1969) for the study region yielded an estimated TWL of 11–22 m above MHW datum, bracketing the proxy data bias estimates between MHW and TWL (average 18 m with a bias uncertainty of 9 m) for California beaches from Ruggiero and List (2009). Results of Dugan et al. (2013) for a Santa Barbara beach indicated that the tidal datums of mean sea level (MSL) and mean high water (MHW), were located well below the ecological envelope of upper intertidal talitrid amphipods that burrow at the HTS. These comparisons suggest that TWL can be applied to mapping of ecologically relevant upper intertidal zone features in the study region. The use of TWL was validated as a proxy for the elevation and location of the 24-h High Tide Strand line (HTS) for use in modeling projected responses of beach ecosystems to climate change using data on beach profiles, elevations, widths and coastal processes (Barnard et al., 2009b; Griggs and Russell, 2012). This modeled datum combined with data on study area beaches (Dugan et al., 2003, 2008; 2011, 2013; Hubbard and Dugan, 2003) was then used to develop a predictive framework of potential changes in the widths of upper beach zones at selected beaches that represented the range of conditions present in the study area.

Projections of changes in upper beach zone widths under different SLR levels (50 cm, 100 cm, 150 cm, 200 cm, 500 cm) were generated using projections from CoSMoS (O'Neill et al., 2018). The CoSMoS runup (TWL) outputs for ambient and one-year/annual storm conditions were used as a proxy for the location of the High Tide Strand (HTS) under future sea level conditions allowing for an estimate of the upper beach zone widths. The distance from the back beach location, defined by the CoSMoS non-erodible shoreline, to the runup point along each cross-shore transect (CST) was measured using ArcMap 10.2 and Matlab R2015b. The same method was used to measure the distance from the back beach to the location of the CoSMoS projected shoreline, represented by the mean high water (MHW) elevation (Vitousek et al., 2017). In some bluff-backed areas, the upper beach zone width was estimated using the location of the CoSMoS projected mean high water shoreline when its location was landward of the runup projection. In certain locations where the CoSMoS model did not produce a runup position, the upper beach zone width was interpolated based on adjacent CSTs as well as the preceding and successive sea level conditions.

3. Results

Results, lessons learned and implications for local government ecosystem-based adaptation are summarized in Tables 2 and 3.

3.1. Projected climate and sea level changes in the Santa Barbara region

All climate models examined are consistent in projecting increasing temperatures across Santa Barbara County throughout the 21st Century. The average magnitude of the projected temperature increases using the RCP8.5 emission scenario is about 1.5 °F by 2030, 3 °F by 2050, and 6–7 °F by 2090. The temperature increases are more pronounced in the inland and mountain areas of the county and less along the coast and offshore islands.

The number of extremely hot days (as measured by current historical values) in the Santa Barbara region is projected to increase significantly with more than a doubling by 2050 and a nearly 10-fold increase by 2090 (Fig. 5), consistent with previous findings over a broader domain (Gershunov and Guirguis, 2012).

The median of the ten model ensemble of projections suggests that annual precipitation amounts in Santa Barbara County will not change significantly during the 21st Century. However, the individual model projections were inconsistent with some showing reduced multi-decade average annual precipitation and others increased annual precipitation relative to current historical average values. As a result, there is considerable uncertainty in this result. The model projections are in greater agreement indicating fewer but more intense storms, a reduction in the number of rainy days (also see Polade et al., 2017) (Fig. 6) Additionally, the models indicate a decrease in the length of the wet season (also see Pierce et al., 2018) that would heighten the risk of wildfire during the longer dry season. A majority of the models project an increase in the year-to-year variability of annual precipitation by the second half of the 21st Century that would increase the likelihood of extended periods of drought.

Sea level heights are projected to increase substantially, under different scenarios of SLR during the 21st Century (Fig. 7). Even the most optimistic SLR scenario examined produced non-linear increases in both the frequency and duration of high water levels, which are accentuated during storm events that mostly occur during winter months. During the historical period, extreme water level events are primarily limited to months June–August and November–February. This is due to the highest astronomical tides that occur in these months as well as strong winter storms that impact water level that occur during the winter months. By mid-century, the number of extreme water level events increases and occur more broadly throughout the year. With the high-range SLR scenario, extreme water level events occur in all months. By the end of the century, the number of hours with extreme water levels increases dramatically in all months.

3.2. Watershed projections

Under future climate conditions, watershed runoff and the resulting river discharges in the Santa Barbara area are likely to increase in both volume and extreme magnitude (Feng et al., 2019) (Fig. 8). From averages of the hydrologic model simulations driven by the 10 downscaled GCM projections, in the second half of the 21st Century (2061–2100), mean annual discharge will increase by 19% under RCP 4.5 and by 37% under RCP 8.5, as compared to the historical period (1960–2000). The increases in discharge extremes are even higher: 28% and 65% for annual peak discharge during 2061–2100 under RCP 4.5 and 8.5, respectively. These changes mainly result from nonlinear hydrologic response to precipitation alterations. Although the changes in annual precipitation are minimal (within ± 2%), the rainfall events under future climate tend to transform from low to moderate (< 36 mm/day) to high (> 36 mm/day) intensities. Under RCP 8.5, rainfall events with high intensities during 2061–2100 will increase by 28% compared to historical period, in contrast, the small rainfall events (< 16 mm/day) will decrease by 18%. In addition to changes in precipitation events, the seasonality of precipitation will also be impacted. During 2061–2100, the wet season length will shrink by 11 and 18 days, respectively, under RCP 4.5 and 8.5, mainly due to a late onset. This alteration in precipitation (i.e., more intensified rainfall events concentrated in a shorter period) leads to the more pronounced changes in watershed runoff and river discharges. More frequent intense rainfall events lead to wetter soil conditions during the rainy season which leads to more efficient runoff generated contributing to increase in streamflow, especially the extremes (e.g., annual peak flow).

3.3. Coastal hazards projections

CoSMoS flooding projections indicate considerable changes in

Table 2
Results and implications for local government.

Results	Implications for local government
Temperature will increase through the 21st century. RCP 8.5 projections: 1.5 °C by 2030 3 °C by 2050 6–7 °C by 2090 Number of extremely hot days will double by 2050 and 10x by 2090.	Warmer temperatures would increase demand for water and energy related to air conditioning, and increase the exposure to certain health issues (e.g. mosquito-borne diseases). More frequent, more intense and longer lasting heat waves would cause detrimental impacts on health and ecosystems.
Precipitation amount may not change. Storms would be fewer but more intense with decreased length of the wet season and fewer wet days. Increased likelihood of extended droughts.	Longer dry spells and more frequent drought would impact ecosystems along with municipal, industrial and agricultural water supplies. In particular, longer dry seasons would increase vulnerability to wildfires. Heavy precipitation events would cause floods and erosion.
Sea level will increase significantly over the 21st century. Extreme water level events will occur in more months, eventually year-round.	SLR and more frequent and higher extreme sea levels would cause increased coastal and estuarine flooding and inundation, and increase coastal erosion.
Under future climate, more intense rainfall events during a shorter and delayed wet season, would lead to changes in seasonality of streamflow (i.e., increase in wet season streamflow and decrease in dry season streamflow) and pronounced increase in the magnitudes of low-frequency flows (e.g., 100-yr flood).	Informs flood hazard planning. Changes in streamflow seasonality may increase the risk of severe droughts and wildfire events, and also impact the nutrients/sediment export to the Santa Barbara coastal ecosystems.
Storms and the higher-end SLR scenarios (i.e., 0.5 m +) expected in the latter half of the century pose the greatest risk to ecosystems.	Plan for SLR and storm-related impacts to intensify
Dramatic changes in beaches and wetlands are projected for mid century with severe impacts to structure and function occurring earlier	Immediate need to incorporate model projections in both short and long-term planning
Vegetated salt marsh would turn to predominantly mudflat with 30 cm slr (accretion rates affect rate of change). Loss of habitat impacts animals who live in the marsh and those that forage and nest in the marsh (e.g. loss of upland habitat impacts endangered Beldings Savanah Sparrow in Carpinteria Salt Marsh).	Wetland ecosystems will change and habitat for endangered/sensitive species will be reduced unless opportunities are provided for habitat to transgress inland.
The timing of marsh changes are affected by multiple factors- rate of SLR, accretion of sediment on the marsh surface, estuarine tidal dynamics, - making it uncertain when in the future changes to habitat will occur.	It is difficult to plan/implement adaptation strategies for the future without adversely affecting existing estuary function. Need to work with ecologists to monitor changes to the marsh and identify trigger points and create an adaptive management plan that is implemented when triggers are reached.
Many already narrow beaches (backed by infrastructure or cliffs) would narrow considerably; eroding on average by more than 25m by 2100. Without interventions, 50–75% may experience complete erosion by 2100.	Plan for a future with less dry sand space on beaches and carefully balance human and ecosystem needs. A first step is to identify beaches that can transgress inland and/or are wide enough to support ecosystems and recreation in the future.

coastal hazards across the Santa Barbara region over the coming decades, including areas comprising sensitive coastal ecosystems, such as the region's coastal estuaries and creeks, narrow, often bluff-backed beaches, and dune fields. Several of these locations, such as Goleta Slough and Carpinteria, are vulnerable to coastal flooding from a major storm at present, while the vulnerability of other locations is more acute later in the century (Fig. 9). The East Beach area adjacent to Santa Barbara Harbor, for example, does not reach a critical threshold for extreme storm impacts until between 0.5 and 1 m of SLR, expected between the middle and the end of the century (Sweet et al., 2017); exposure to flooding then increases progressively through the higher SLR scenarios. Conversely, the projected flooding for Carpinteria during an extreme storm, including the salt marsh, already is high today, but does not begin to increase appreciably until higher SLR scenarios are reached (e.g., 1.5 m). Goleta Slough and Carpinteria Salt Marsh, in addition to the region's many narrow beaches and small creek mouths, would be vulnerable to everyday flooding independent of storm conditions for SLR scenarios expected later this century (i.e., 0.5–1 m), indicating a complete displacement of existing ecosystems.

The proportion of coastal flooding affecting developed vs. undeveloped land is roughly equivalent across scenarios, with wetlands and open space generally being most vulnerable to present-day and future coastal flooding among the undeveloped land cover types. However, the undeveloped flooded areas that are designated as shrubs/grassland and barren/open space increase the most as SLR increases. While the area of wetland flooding does not change significantly, wetland habitat is projected to change by mid-century. Overall, there is little change in flooding exposure when transitioning from the 0–0.5 m SLR scenarios, but there is a significant change from 0.5 to 1 m, particularly for the no-storm scenarios, and another significant change from 1 to 2 m SLR for the 100-year storm scenarios. In almost all cases extreme storms significantly increase the areas exposed to flooding, especially for the 0.5 and 2 m SLR scenarios, where land area exposed to flooding can more than double during storms compared to SLR alone. Up to ~10 km^2 of undeveloped land in the study area could be exposed to flooding over the next century, with wetlands, shrubs/grassland and open space being the most extensively flooded land cover types.

The CoSMoS-COAST model predicts that the sandy beaches in the study area will narrow considerably; eroding on average by more than 25 m by 2100, and 50–75% may experience complete erosion (up to infrastructure or cliffs) by 2100 without interventions. The further narrowing and/or loss of future beaches (and the ecosystems supported by those beaches) will primarily result from accelerating SLR combined with a lack of ample sediment in the system, which together will continue to drive the landward erosion of beaches, effectively drowning them between the rising ocean and the backing cliffs and/or urban hardscape. Many sandy beaches are already narrow and some are almost completely devoid of dry sand at high tide, which was particularly notable following the El Niño of 2015-16 that stripped significant volumes of sand off beaches due to elevated sea level and wave energy. The marginal sand supply both stresses existing sandy beach ecosystems and leaves the cliffs more vulnerable to wave attack, further placing cliff top ecosystems and structures at risk. Mean historical cliff retreat rates across Santa Barbara average ~0.2 m/yr. Model results suggest that a 1 m rise in sea level will accelerate retreat rates to 0.31 m/yr during the 21st Century, an increase of 55%.

3.4. Coastal wetland ecosystem impacts

Carpinteria Salt Marsh is currently comprised primarily of mid (35%) and high (38%) vegetated marsh habitat with smaller amounts of high mudflat (9%) and subtidal (8%), mostly confined to the deeper portions of tidal creeks and channels (Fig. 10). There is also a narrow upland transition zone bordering the intertidal portions of the wetland, which is restricted in landward extent by surrounding residential and urban development.

Table 3
Lessons learned and implications for local government.

Lessons learned	Implications for local government
Temperature and precipitation projections, from an ensemble of global climate models run under moderate and high emissions scenarios, downscaled to a 6 km grid are useful for local decision makers	Informs city and county long range planning and flood hazard mapping at a scale useful to local-level planning
For local government planning purposes, climate projections can be translated from native climate grid output into GIS.	GIS is a format commonly used by local governments in city and county planning documents.
Downscaled climate, coastal hazards and shoreline change, and watershed runoff model projections are useful for both natural and built environments	During climate adaptation planning the same models used for anticipating impacts to the built environment can be used to anticipate ecosystem impacts
Extreme events, superimposed on changing climate and rising sea levels, are a critically important component of regional climate changes. Extreme high sea level events combined with terrestrial flooding are projected to double the land area exposed to flooding.	Extreme events are important to consider for long-range planning because they deliver high impacts to both natural and built environments.
Regional changes projected for Santa Barbara County were similar to other southern California and Mediterranean regions, with substantial warming, shorter wet seasons, longer dry spells and, occasionally larger rainfall events.	Many of the results exhibited by climate simulations downscaled to the Santa Barbara region may apply to municipalities and ecosystems elsewhere in Southern California and other Mediterranean regions. Furthermore, southern California temperature projections are close to global averages
El Niño events provide a window to future conditions. For example, during the 2015–2016 El Niño a 10 cm above normal sea level and 50% wave energy increase resulted in all except the widest Santa Barbara area beaches to be devoid of dry sand. These sea level conditions are projected to occur on a regular basis before mid-century.	El Niños are an opportunity for local governments to get firsthand experience of projected climate change impacts (and consequences of management actions).
Large-scale wildfire and debris flow events suggest there are synergies between climate-related impacts that may result in larger events than anticipated.	Plan for large-scale disasters in the future
The most landward (upper) part of both beach and wetland ecosystems are the most vulnerable to climate change. Upper beach and wetland habitat, areas with the greatest biodiversity and most rare/endangered species, are lost first with SLR. Coastal ecosystems, including beaches and wetlands, have already “lost ground” and the remaining habitats are severely threatened by SLR from climate change. Adaptive management and conservation of these irreplaceable ecosystems is urgently needed to restore and enhance their resilience and preserve their biodiversity and ecosystem function.	Conservation of beaches, dune systems and estuaries can occur by discouraging development adjacent to these dynamic ecosystems and encouraging open space buffers and restoring native vegetation and landforms on public and private land. Incorporation of SLR into restoration activities provides opportunities for ecosystems to transgress inland.
Extent of wetland flooding does not indicate amount of habitat change	Expert knowledge of ecosystems is needed to project future impacts. Physical data (e.g. SLR maps) alone are not sufficient
Surrounding infrastructure is an impediment to marsh transgression	Focus development away from the coast. Remove old structures
Beach ecosystem response to projected SLR is strongly affected by beach landward boundary (e.g. armored, developed, bluff-backed, dune-backed), with dune backed beaches having the greatest resilience to slr. As sea level rises, armored beaches will disappear first, bluff-backed beaches with no room to retreat will disappear next; dune backed beaches are the most resilient but dune area will shrink as beaches retreat landward.	Prevent the installation of new armoring and identify opportunities to remove armoring on beaches and wetlands. City parks and open space can provide buffers for beaches. Require setbacks for beachfront and beach-adjacent properties. Restore and protect dunes.
Wide beaches that are intensively managed are an unrealized opportunity for providing refuge for beach biodiversity (conserving beach ecosystems) and rare species (Dugan et al., in progress).	Stopping or strategically changing beach grooming practices can conserve/enhance beach ecosystem biodiversity and allow formation of dunes that contribute to storm protection.
SLR impacts to upper beach ecosystems can be approximated using total water level (TWL) projections.	Local governments and others can use total water level projections on USGS maps to anticipate future impacts to the ecologically sensitive, biodiverse upper beach ecosystem

High marsh and the upland transition are initially the most vulnerable to SLR, continuously declining in area and evolving into mid marsh with rising sea level. Mid-marsh would initially increase in area, but begin converting to high and eventually low elevation mudflat as SLR exceeds ∼+25 cm, relative to the marsh surface (Myers et al., 2017). Approximately one-half of the existing high mudflat experiences an inundation regime that supports cordgrass, *Spartina foliosa,* characteristic of low marsh in other southern California wetlands (Myers et al., 2017). Thus, a caveat to the sequence of habitat evolution proposed above is the possible creation of vegetated low marsh if the high mudflat becomes colonized by cordgrass.

Less certain is the actual timing of habitat evolution, which is dependent on the interaction between future rates of SLR and accretion of the marsh surface. For example, an average net accretion rate of 4 mm yr^{-1} keeps pace with SLR under the minimum year 2050 SLR scenario (Fig. 10). However, an accretion rate of 4 mm yr^{-1} only slows habitat conversion under the maximum 2050 SLR scenario. In this case, mudflat habitat would comprise 56% of habitat with accretion compared with 70% without accretion. However, under the longer term maximum 2100 SLR scenario, accretion rates of up to 4 mm yr^{-1} do not appreciably slow the rate of evolution of vegetated marsh to mudflat; the wetland could consist of > 80% mudflat by the end of the 21st Century with or without 4 mm yr^{-1} accretion (Fig. 10). Little change in area of mudflat is expected by the end of the century under the minimum SLR scenario if the marsh surface accretes at 4 mm yr^{-1}.

Higher water levels associated with the El Niño of 2015 increased inundation frequencies (as proportion of tides hitting a particular elevation) in the marsh relative to pre-El Niño values, providing a possible preview of the effects of increased inundation on marsh habitats. For example, inundation frequency estimated for mid marsh habitat, at a tidal elevation of 1.4 m NAVD88 for the months July–December 2015, was double that (0.29) of the five year average pre- El Niño value (0.14) (Myers et al., 2017). This increase in inundation frequency corresponded to a pre-El Niño frequency typical of a tidal elevation of 1.1 m NAVD88 and mudflat habitat. *Sarcocornia* at this elevation appeared stressed or dying. Consequently, one might expect habitat conversion over time from *Sarcocornia* dominated mid marsh to high mudflat over time if the higher inundation regime was prolonged.

3.5. Sandy beach ecosystem impacts

Results from CoSMoS modeling indicated that the majority of sandy beaches in the study area are projected to decline in overall width with increasing SLR. However, the loss of beach width will not be evenly distributed across intertidal zones. Upper beach zones were projected to experience the greatest declines in width and losses with SLR. Model

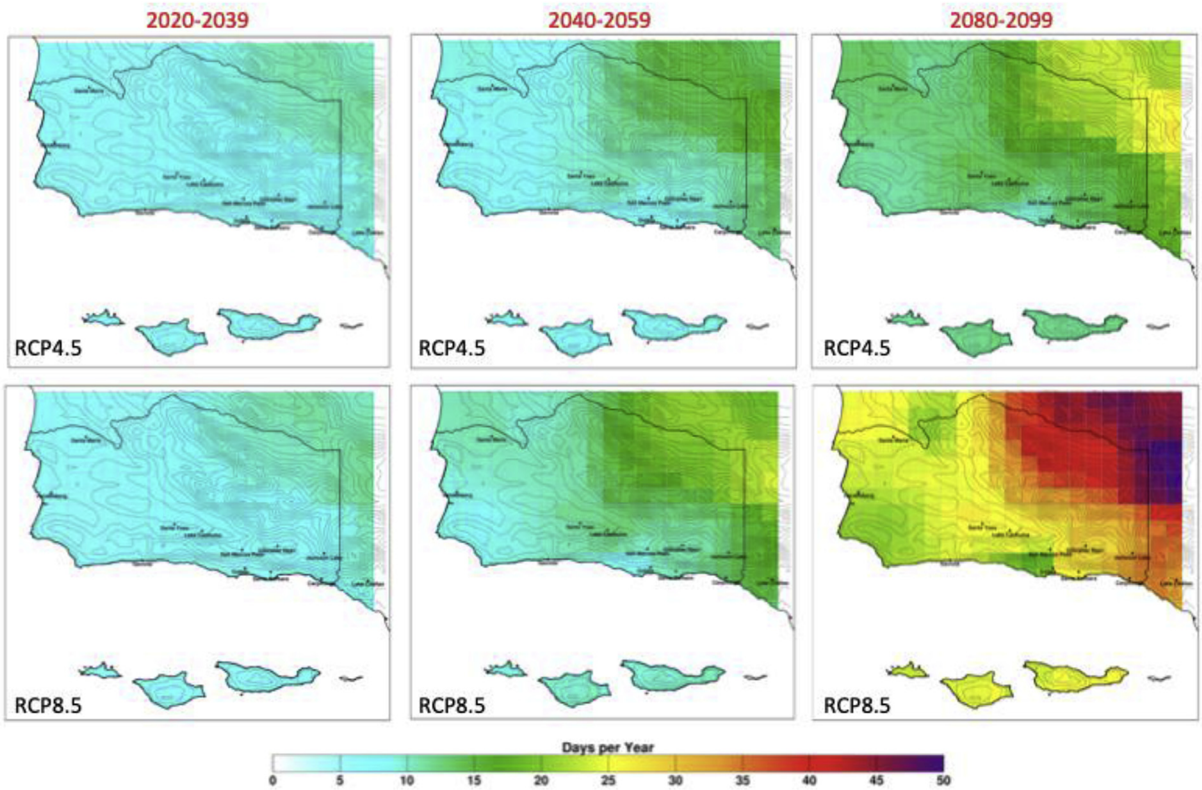

Fig. 5. Ensemble mean number (days/year), from ten downscaled GCMs, of extremely hot days per year during 2020–2039 (left column), 2040–2059 (middle column), 2080–2099 (right column) for emission scenarios RCP4.5 (top row) and RCP8.5 (bottom row). An extremely hot day is defined as day with daily temperature maximum meeting or exceeding the 99%-percentile value of daily temperature maximums during the 1985–2014 historical period.

results projected significant declines (average > 70%, range: 51%–98%) in the widths of upper intertidal zones with 50 cm of SLR for the study beaches (Fig. 11). The projected responses of sandy beach ecosystems to SLR were strongly affected by the potential for the shoreline to retreat. This means the type of landward boundary and the degree of human alterations in the form of coastal armoring and development are important factors in the vulnerability of beach ecosystems to climate change.

For bluff-backed beaches a rapid loss of upper beach and mid beach zones with increasing SLR was projected with < 15% of this critical upper beach zone estimated to remain with 50 cm SLR at the study beaches (West Isla Vista, East Campus, Arroyo Burro) (Fig. 11). The limited accommodation space for retreat of bluff-backed beaches restricts their ability to adjust and makes them extremely vulnerable to SLR. The majority of sandy beaches are bluff-backed in the study area (Habel and Armstrong, 1977) with limited scope for retreat. With projected climate change and SLR, our projections suggest that upper beach zones will become increasingly rare and vanish from much of the bluff-backed beaches, resulting in major declines in biodiversity and ecosystem function for the majority of the Santa Barbara coast.

Dune-backed beaches, such as the study beach at Sands/Ellwood, were projected to have the greatest resilience to increasing SLR for upper and mid intertidal zones, maintaining narrow zones of upper (9%) and mid-intertidal habitats even with 200 cm SLR (Fig. 11). However even this dune-backed beach lost > 60% of the width of the upper beach zone with 50 cm of SLR. Dune-backed beaches although more resilient, are now rare in the study area making up less than 3% of the sandy beaches.

Beaches with shoreline armoring that occupies upper beach zones and limits potential migration of the shoreline were projected to have the most rapid loss of upper and mid beach zones with SLR (~99% for upper zone at Santa Claus Lane with 50 cm SLR) (Fig. 11). Beaches with a mix of armored and unarmored shorelines and management, such as the adjacent Carpinteria beaches, showed some variation in projected responses to SLR in the different sections. The dune-backed section of Carpinteria State Beach was projected to maintain more upper beach zone width at 50 cm SLR (Fig. 11) compared to the armored and groomed section. However, with 100 cm of SLR, upper beach zones were not detectable on this study beach.

The groomed and filled study beach which has an artificially wide upper intertidal zone was also projected to have some resilience to SLR but still lost > 50% of the upper beach zone width with 50 cm SLR (Fig. 11). Regular mechanized grooming and sand contouring with heavy equipment inhibits the development of coastal strand and dune vegetation above the reach of tides and the beach fills from harbor dredging periodically increase the width of the beach. The behavior of this beach under SLR reflects the retreat of the intertidal beach into the wide unvegetated and degraded dune zone created by the combination of grooming, flattening and filling activities. This beach was projected to maintain some width in the upper beach zone for much of the shoreline segment for both 50 and 100 cm SLR, but with 150 cm SLR the upper beach zone was projected to shrink to < 5 m in width.

4. Discussion

4.1. Watershed impacts

Increased runoff and peak event streamflows in a shortened wet season, which starts later, and decreased runoff in a lengthened dry season is expected. Under a warmer future climate, less precipitation and watershed runoff and higher potential evapotranspiration during an elongated dry season would lead to a drier soil condition, which increases the probability of droughts and wildfires. The majority of nutrients and sediment fluxes occur at the beginning of wet season (Homyak et al., 2014), and the fluxes of nutrients and sediment are significantly and positively associated with hydrologic variability

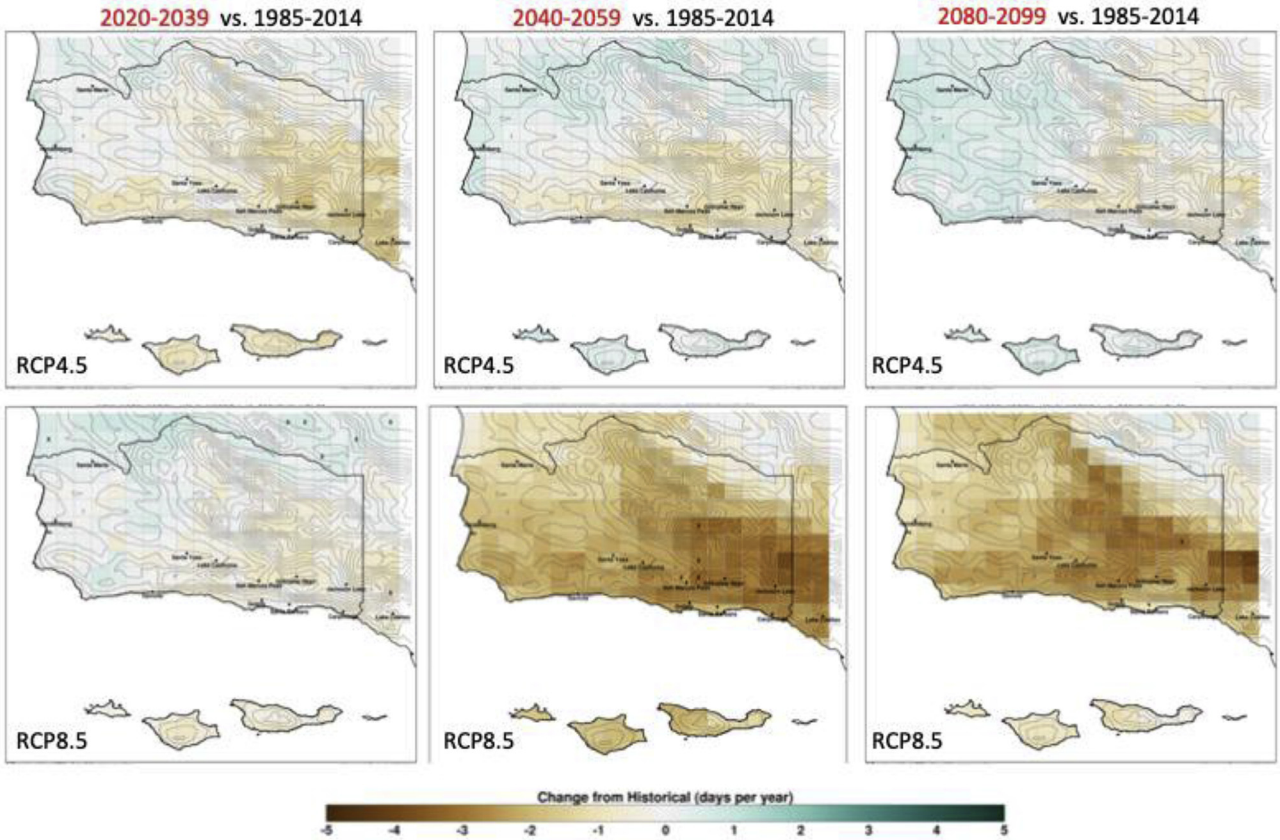

Fig. 6. Change in the number of wet days per year, averaged over the 10 downscaled GCMs. Change values are differences of 2020–2039 (left column), 2040–2059 (middle column), 2080–2099 (right column) vs. the 1985–2014 historical period for emission scenarios RCP4.5 (top row) and RCP8.5 (bottom row).

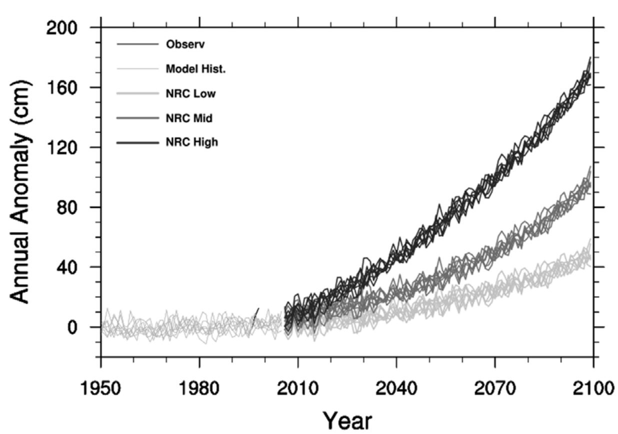

Fig. 7. Annual sea level anomalies modeled for Santa Barbara. Model produced values during the 1950–2005 historical period (grey lines) and modeled projections during the 2005–2100 period (colored lines) are derived from output of eight GCMs for each of three NRC SLR scenarios, shown as green, blue and red. The black curve fragments between 1990 and 2014 are based on a limited set of observations at Santa Barbara Harbor.

(Aguilera and Melack, 2018). Therefore, increased runoff in a delayed wet season will result in changes in the timing and quantity of nutrients and sediment export to the coastal ecosystems.

Drier and longer dry seasons increase wildfire occurrence and more intense rainfall events stacked closer together increase runoff and erosion. The combination of these can lead to massive debris flows. For example in January 2018 a debris flow was caused by intense rainfall (Oakley et al., 2018) following the massive Thomas wildfire.

4.2. Coastal wetland ecosystems

Biological resources supported by small, urbanized Pacific coast estuaries will change as rising water levels due to SLR alter key physical and biological properties known to structure marsh plant communities and habitats. The distribution of marsh plant species typically varies with tidal inundation along an elevational gradient, although considerable overlap of species can occur (Zedler et al., 1999). Because these estuaries, are surrounded by buildings and infrastructure, and are unable to transgress inland, the habitat "zones", occupied by characteristic vegetation that extend from low to high elevations in most southern California estuaries (Ferren,1985; Page et al., 2003; Sadro et al., 2007), without intervention, will evolve towards more subtidal habitat as sea level rises.

Although little net change in the overall area of vegetated marsh is predicted up to about 20 cm of relative SLR (Myers et al., 2017), the most landward - high/mixed salt marsh and transition habitats-are the most immediately vulnerable. As water levels rise, these habitats will continuously decrease area and evolve into mid marsh habitat. Loss of transition/high marsh has dramatic consequences for native salt marsh plant diversity, typically highest in these habitats that include the most rare, threatened and endangered species (Zedler et al., 1992). Fourteen of sixteen plant species of conservation concern reported from Carpinteria Salt Marsh are found in the high marsh and transition habitat and initially the most vulnerable to SLR (Myers et al., 2017). Of particular interest is the Federally listed endangered Salt Marsh Birds-beak, restricted to higher elevations with sandier soils, and Coulter's Goldfields, a species of Federal Management Concern also found in areas with sandier soils and alluvial deposits (Ferren, 1985). In addition, the Federal and California listed endangered Ventura Marsh Milkvetch has been planted in the wetland as part of a recovery plan for the species

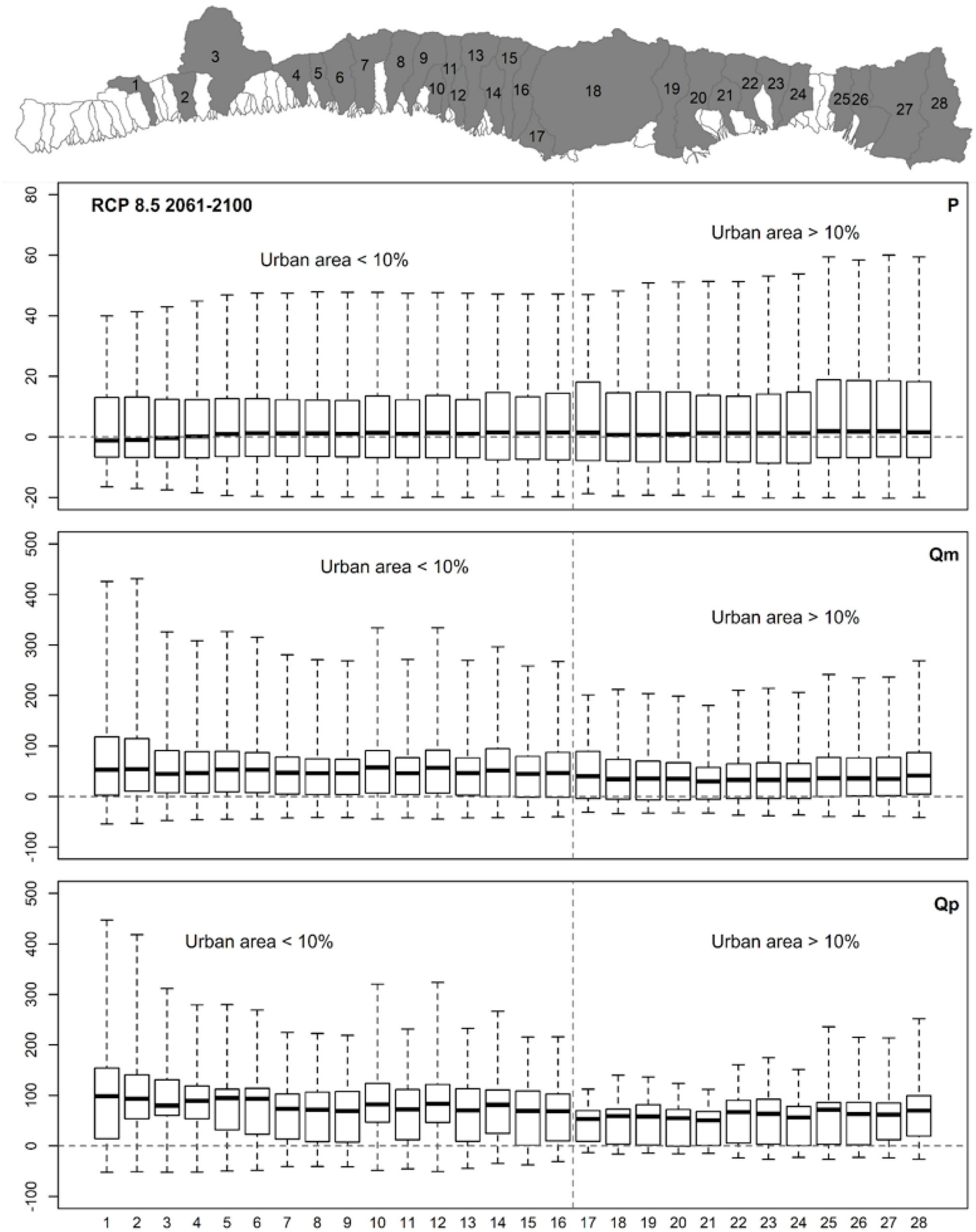

Fig. 8. Relative changes (upper and lower bounds of boxes are 25% and 75% respectively; whiskers are max and min, and heavy line as median) of annual precipitation, annual streamflow and anual peak flow in the major Santa Barbara watersheds (indicated by the grey watersheds in the map) during 2061–2100 based on 10 GCM output simulations for scenario RCP 8.5; only watersheds with drainage areas larger than 7 km^2, which account for roughly 83% of the study area, are shown. The figure is adapted from Feng et al. (2019).

(caption on next page)

Fig. 9. Example of future flood hazards in Goleta (top), Santa Barbara Harbor/East Beach (middle) and Carpinteria (bottom), showing the 1 m SLR scenario coupled with the 100-year coastal storm. (Basemap: 2012 NAIP Imagery).

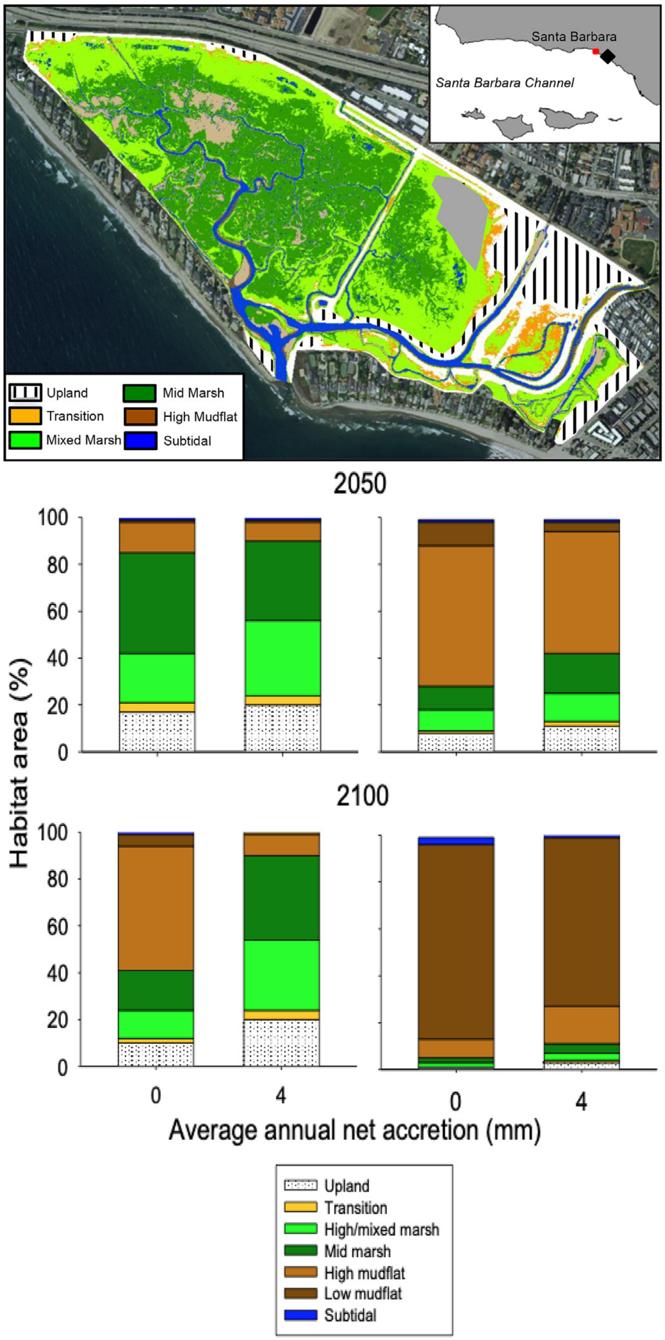

Fig. 10. A) Location of Carpinteria Salt Marsh and present distribution and areas of modeled habitats and B) scenarios of change in habitat areas by years 2050 and 2100 assuming no accretion of the marsh surface and an average annual accretion rate of 4 mm yr^{-1}.

and is vulnerable to increased inundation with SLR.

Middle marsh, vegetated primarily by *Sarcocornia pacifica*, including foraging and perching habitat for the endangered Belding's Savannah Sparrow *(Passerculus sandwichensis beldingi)* is less immediately vulnerable to relative SLR and is expected to initially increase in area as it shifts landward. Eventually middle marsh converts to mudflat, which along with subtidal habitats are the least vulnerable to the adverse impacts of SLR. Shorebirds and wading and water birds could benefit from the expansion in mudflat, as it would increase loafing and foraging area.

Currently, sedimentation and the conversion of mudflat to vegetated marsh is a priority management concern because of the importance of mudflat as feeding and loafing habitat for shorebirds (Ferren et al., 1997). Over the short term, an increase in the rate of SLR may stabilize existing habitats, offsetting sediment accretion, currently a management concern in Carpinteria Salt Marsh that is leading to a loss of mudflat habitat (Myers et al., 2017). Over the longer term, if accretion is unable to keep pace with accelerating SLR, marshes will evolve to be more mudflat-dominated then, eventually, subtidal systems, decreasing both habitat and the potential for attenuation of storm events.

The development of policy-making and long-term climate change adaptation planning based on projections, modeling and monitoring (Filho et al., 2018) is challenging given the uncertainty in rates and thus timing of SLR, the effects of other climatic factors on the evolution of marsh habitats, and surrounding urban and agricultural development that limits adaptation options. Ecological monitoring of rates of SLR and sediment accretion of the marsh surface will be required to inform the timing of adaptation measures, which may involve alterations of surrounding infrastructure to allow wetland habitats to transgress into upland, and/or manipulation of sediment delivery to elevate the marsh surface.

4.3. Sandy beach ecosystems

Sandy beach ecosystems and the biodiversity and ecosystem functions and services they provide are extremely vulnerable to projected SLR in southern Santa Barbara County and elsewhere in the world (Schlacher et al., 2007). The upper intertidal zones of beaches are already limited along the study coastline and are projected to be most immediately vulnerable to SLR. Loss of these zones will strongly reduce intertidal biodiversity (losses of 40–50% of endemic upper beach species), decrease the prey available for birds and fish and eliminate nesting habitat for species of concern (California Grunion and Western Snowy Plover) (Dugan et al., 2003; Hubbard et al., 2014; Martin, 2015; Dugan and Hubbard, 2016; Schooler et al., 2017).

Although often narrow in width, upper intertidal zones are ecologically vital and critically important to biodiversity and ecosystem function. Upper intertidal zones have already been lost to erosion or altered by management practices and armoring on many beaches in the study area. Loss of upper beach zones will affect the resilience of both beach ecosystems and coastal communities by impacting the existence of sand-trapping coastal strand vegetation and dynamic topography that accumulates sand. In the absence of upper beach zones, sand accumulation (Dugan and Hubbard, 2010), wrack retention (Revell et al., 2011) and nutrient cycling (Dugan et al., 2011) are impacted, and the buffer areas that both protect coastal communities and are required by the mobile intertidal animals of lower intertidal zones to survive high waves and storm conditions (Dugan et al., 2013) are greatly diminished.

Projected responses of sandy beach ecosystems to SLR were strongly affected by the potential for the existing shoreline to retreat or migrate landward. Thus the type of landward boundary, (e.g. armored, developed, bluff-backed, dune-backed), significantly affects the vulnerability of beaches to SLR, with dune-backed beaches having the greatest resilience. As sea level rises, armored beaches are projected to disappear first, bluff-backed beaches with no room to retreat will disappear next and dune-backed beaches will be the most resilient but dune area will shrink as beaches retreat landward.

The majority of beaches in the study area are backed by resistant sea

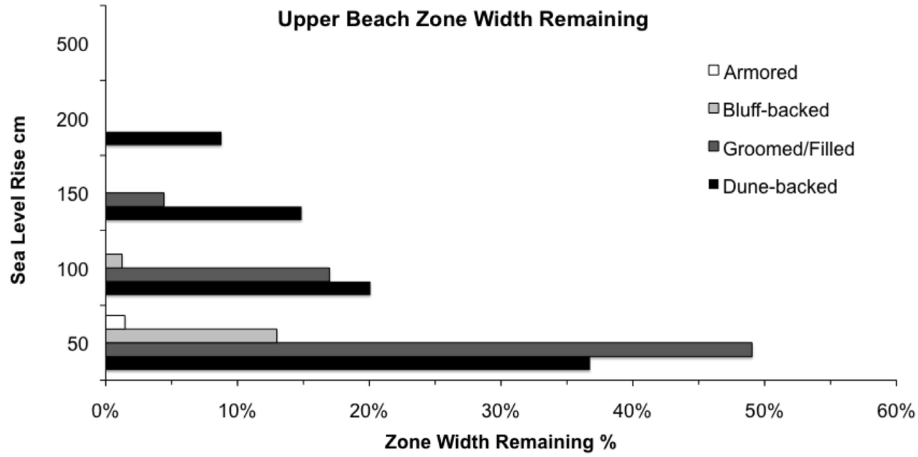

Fig. 11. Projected values of the proportion of upper beach zone widths (above HTS) remaining for armored, bluff-backed, groomed/filled, and dune-backed beaches in southern Santa Barbara County based on the CoSMoS 3.0 model results under different levels of SLR (50 cm, 100 cm, 150 cm, 200 cm and 500 cm).

bluffs that provide limited scope for migration of the shoreline to adjust to SLR. These bluff-backed beaches were projected to have a rapid loss of upper beach and mid beach zones with increasing SLR with < 15% of the critical upper beach zone estimated to remain with 50 cm SLR. The limited scope for retreat and habitat migration of bluff-backed beaches and their associated ecosystems restricts their ability to adjust and makes them extremely vulnerable to SLR. Thus with projected climate change and SLR, upper beach zones are projected to become increasingly rare and vanish from the majority of the Santa Barbara coast, resulting in major declines in biodiversity and ecosystem function.

Shoreline armoring is already widespread and its use is expected to increase with erosion and threats to infrastructure caused by rising sea levels in the study area and elsewhere (Dugan et al., 2018). Beaches with shoreline armoring that occupies upper beach zones have already lost ecologically important upper beach habitat (Dugan and Hubbard, 2006; Dugan et al., 2008). Armoring structures, such as seawalls and revetments, greatly limit the potential migration of the shoreline. For this reason, armored beaches were projected to have the most rapid loss of upper and mid beach zones with SLR.

Dune-backed beaches were projected to be more resilient to SLR but have an extremely limited distribution in southern Santa Barbara County. The dune-backed beach we studied maintained a narrow zone of upper beach even with 200 cm SLR. However even the dune-backed beach lost > 60% of the width of the upper beach zone with 50 cm of SLR.

Our projections indicated that some of the relatively wide beaches in the study region, currently managed for recreation and tourism, have the potential to maintain some upper and mid beach habitats with increasing SLR. These zones were projected to persist for much longer on these altered beaches than on the bluff-backed or armored beaches in the study area. These beaches are currently subject to frequent mechanized maintenance activities, such as beach grooming, that have reduced or eliminated dune habitat, significantly reduced biodiversity and degraded ecosystem functioning. Changing management of these beaches to restore dunes, biodiversity and function of these degraded beaches could provide an opportunity to enhance their resilience to SLR and to conserve more area of intact beach ecosystems as sea levels rise.

4.4. Future management

The threat of frequent flooding, permanent inundation, beach loss and wetland conversion to predominantly un-vegetated mudflats increases significantly around 0.5 m of SLR (~2050). Applying effective sediment management practices will be a key factor in conserving the region's coastal ecosystems and mitigating future coastal hazards. Sand is a valuable resource, especially for a sediment-starved stretch of coastline like southern Santa Barbara County (Patsch and Griggs, 2008). Maintaining the existing supply of sand to beaches in the littoral cell, allowing more sand to flow from watersheds to beaches and wetlands and providing accommodation space for coastal ecosystems to accumulate sand wherever possible will be key components of future coastal management efforts to maintain the dynamics of sandy beach widths and ecosystems, and to protect adjacent communities from flooding. However, in some highly vulnerable areas of the coast, the most effective action may be to focus development away from the coastline and allow space for coastal ecosystems and cliffs to retreat.

In southern Santa Barbara County, opportunities to maintain sandy beaches and remnant estuaries into the future are few. Efforts to design and implement suitable coastal management actions to mitigate projected impacts should be prioritized, as post-tipping point responses are more costly and less effective (Selkoe et al., 2015). An adaptation approach not prioritizing ecosystems, which may involve the installation of barriers or walls along the shoreline to protect urban development, will result in estuary habitat evolution running its course and beaches drowning with rising sea levels, with consequent loss of biodiversity and important ecosystem services vital to wildlife and coastal communities. An EbA approach would enable the shoreline and habitats to transgress, which may involve the establishment of landward migration corridors through removing or elevating some infrastructure and providing land to permit wetland and beach transgression (King et al., 2018); increasing sediment supply, either directly or indirectly to ameliorate SLR; and reducing shoreline armoring and mechanized beach grooming.

5. Conclusions

Shorelines and coastal ecosystems in southern Santa Barbara County are highly vulnerable to climate change impacts from multiple drivers, both landward - changes in both dry and wet extremes of precipitation and watershed runoff- and seaward – heightened water levels that result from SLR. Effects upon coastal ecosystems are projected to grow increasingly severe, with impacts to biodiversity and storm buffering capacity becoming significant around 2050, and reaching more dramatic levels of severity (e.g. area flooded) by 2100. Extreme short period events, including heat waves, high coastal ocean levels and storm rainfall-driven floods, will occur with increasing frequency and severity. These impacts are projected to be significant even under moderate scenarios of greenhouse gas emission and attendant climate changes. Although little can be done to maintain some coastal ecosystems, such as bluff-backed beaches, there are opportunities to attenuate climate change related impacts on wide beaches and wetlands. Local governments can manage these ecosystems and the surrounding area so they more effectively sustain ecosystem services and the beneficial services they provide into the future (e.g. stopping beach grooming and restoring wide beaches so dunes can form; allowing both wetlands and beaches to transgress inland; removal of shoreline armoring and effective sediment management), contributing to an ecosystem-based adaptation approach.

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References

Priestley, C.H.B., Taylor, R.J., 1972. On the assessment of surface heat flux and evaporation using large-scale parameters. Mon. Weather Rev. 100 (2), 81–92. https://doi.org/10.1175/1520-0493(1972)100<0081:OTAOSH>2.3.CO;2.

Aguilera, R., Melack, J.M., 2018. Relationships among nutrient and sediment fluxes, hydrological variability, fire, and land cover in coastal California catchments. J. Geophys. Res. Biogeosciences 123 (8), 2568–2589. https://doi.org/10.1029/2017JG004119.

Baker, I., Peterson, A., Brown, G., McAlpine, C., 2012. Local government response to the impacts of climate change: an evaluation of local climate adaptation plans. Landsc. Urban Plan. 107 (2), 127–136. https://doi.org/10.1016/j.landurbplan.2012.05.009.

Ballard, G., Barnard, P.L., Erikson, L., Fitzgibbon, M., Higgason, K., Psaros, M., Veloz, S., Wood, J., 2019. Our Coast Our Future (OCOF). Petaluma, California. www.pointblue.org/ocof.

Barnard, P.L., O'Reilly, B., van Ormondt, M., Elias, E., Ruggiero, P., Erikson, L.H., Hapke, C., Collins, B.D., Guza, R.T., Adams, P.N., Thomas, J.T., 2009a. The Framework of a Coastal Hazards Model: A Tool for Predicting the Impact of Severe Storms. U.S. Geological Survey Open-File Report 2009-1073. pp. 21. http://pubs.usgs.gov/of/2009/1073/.

Barnard, P.L., Revell, D.L., Hoover, D.J., Warrick, J., Brocatus, J., Draut, A.E., Dartnell, P., Elias, E., Mustain, N., Hart, P.E., Ryan, H.F., 2009b. Coastal Processes Study of Santa Barbara and Ventura County, California. U.S. Geological Survey Open-File Report 2009–1029. http://pubs.usgs.gov/of/2009/1029/.

Barnard, P.L., Allan, J., Hansen, J.E., Kaminsky, G.M., Ruggiero, P., Doria, A., 2011. The impact of the 2009-10 El Niño Modoki on U.S. West coast beaches. Geophys. Res. Lett. 38 (13). https://doi.org/10.1029/2011GL047707.

Barnard, P.L., Hubbard, D.M., Dugan, J.E., 2012. Beach response dynamics of a littoral cell using a 17-year single-point time series of sand thickness. Geomorphology 139–140, 588–598. https://doi.org/10.1016/j.geomorph.2011.12.023.

Barnard, P.L., van Ormondt, M., Erikson, L.H., Eshleman, J., Hapke, C., Ruggiero, P., Adams, P.N., Foxgrover, A.C., 2014. Development of the Coastal Storm Modeling System (CoSMoS) for predicting the impact of storms on high-energy, active-margin coasts. Nat. Hazards 74 (2), 1095–1125. https://doi.org/10.1007/s11069-014-1236-y.

Barnard, P.L., Short, A.D., Harley, M.D., Splinter, K.D., Vitousek, S., Turner, I.L., Allan, J., Banno, M., Bryan, K.R., Doria, A., Hansen, J.E., Kato, S., Kuriyama, Y., Randall-Goodwin, E., Ruggiero, P., Walker, I.J., Heathfield, D.K., 2015. Coastal vulnerability across the pacific dominated by El Niño/southern oscillation. Nat. Geosci. 8 (10), 801–807. https://doi.org/10.1038/ngeo2539.

Barnard, P.L., Erikson, L.H., Foxgrover, A.C., O'Neill, A.C., Herdman, L.M., 2016. CoSMoS (Coastal Storm Modeling System) Southern California v3.0 Phase 2 Storm-Hazard Projections. U.S. Geological Survey Data Release. https://doi.org/10.5066/F7T151Q4.

Barnard, P.L., Hoover, D., Hubbard, D.M., Snyder, A., Ludka, B.C., Allan, J., Kaminsky, G.M., Ruggiero, P., Gallien, T.W., Gabel, L., McCandless, D., Weiner, H.M., Cohn, N., Anderson, D.L., Serafin, K.A., 2017. Extreme oceanographic forcing and coastal response due to the 2015-2016 El Niño. Nat. Commun. 8, 14365. https://doi.org/10.1038/ncomms14365.

Barnard, P.L., Erikson, L.H., Foxgrover, A.C., Hart, J.A.F., Limber, P., O'Neill, A.C., van Ormondt, M., Vitousek, S., Wood, N., Hayden, M.K., Jones, J.M., 2019. Dynamic flood modeling essential to assess the coastal impacts of climate change. Sci. Rep. 9 (1), 4309. https://doi.org/10.1038/s41598-019-40742-z.

Beighley, R.E., Melack, J.M., Dunne, T., 2003. Impacts of California's climatic regimes and coastal land use change on streamflow characteristics. J. Am. Water Resour. Assoc. 39 (6), 1419–1433. https://doi.org/10.1111/j.1752-1688.2003.tb04428.x.

Beighley, R.E., Eggert, K.G., Dunne, T., He, Y., Gummadi, V., Verdin, K.L., 2009. Simulating hydrologic and hydraulic processes throughout the Amazon river basin. Hydrol. Process. 23 (8), 1221–1235. https://doi.org/10.1002/hyp.7252.

Bourne, A., Holness, S., Holden, P., Scorgie, S., Donatti, C.I., Midgley, G., 2016. A socio-ecological approach for identifying and contextualising spatial ecosystem-based adaptation priorities at the sub-national level. PLoS One 11 (5). https://doi.org/10.1371/journal.pone.0155235.

California Department of Water Resources, 2015. Perspectives and Guidance for Climate Change Analysis. Climate Change Technical Advisory Group. California Department of Water Resources Technical Information Record. pp. 142.

Cayan, D.R., Bromirski, P.D., Hayhoe, K., Tyree, M., Dettinger, M.D., Flick, R.E., 2008. Climate change projections of sea level extremes along the California coast. Clim. Change 87 (1), 57–73. https://doi.org/10.1007/s10584-007-9376-7.

Clark, M.B., 1969. Distribution and seasonal dynamics of animal populations on San Diego beaches. Masters thesis, 177.

Convention of Biological Diversity, 2009. Connecting Biodiversity and Climate Change Mitigation and Adaptation: Report of the Second Ad Hoc Technical Expert Group on Biodiversity and Climate Change. CBD Technical Series, vol. 41.

Defeo, O., McLachlan, A., Schoeman, D.S., Schlacher, T.A., Dugan, J., Jones, A., Lastra, M., Scapini, F., 2009. Threats to sandy beach ecosystems: a review. Estuarine, Coastal and Shelf Science. https://doi.org/10.1016/j.ecss.2008.09.022.

Dugan, J.E., Hubbard, D.M., 2006. Ecological responses to coastal armoring on exposed sandy beaches. Shore Beach 74 (1), 10–16. https://doi.org/10.1111/j.1439-0485.2008.00231.x.

Dugan, J.E., Hubbard, D.M., 2010. Loss of coastal strand habitat in Southern California: the role of beach grooming. Estuar. Coasts 33 (1), 67–77. https://doi.org/10.1007/s12237-009-9239-8.

Dugan, J.E., Hubbard, D.M., 2016. Sandy beach ecosystems. Ecosyst. Calif. 20, 389–408.

Dugan, J.E., Hubbard, D.M., McCrary, M.D., Pierson, M.O., 2003. The Response of Macrofauna Communities and Shorebirds to Macrophyte Wrack Subsidies on Exposed Sandy Beaches of Southern California. Estuarine, Coastal and Shelf Science, vol. 58. Academic Press, pp. 25–40. https://doi.org/10.1016/S0272-7714(03)00045-3.

Dugan, J.E., Hubbard, D.M., Rodil, I.F., Revell, D.L., Schroeter, S., 2008. Ecological effects of coastal armoring on sandy beaches. Mar. Ecol. 29 (1), 160–170. https://doi.org/10.1111/j.1439-0485.2008.00231.x.

Dugan, J.E., Hubbard, D.M., Page, H.M., Schimel, J.P., 2011. Marine macrophyte wrack inputs and dissolved nutrients in beach sands. Estuar. Coasts 34 (4), 839–850. https://doi.org/10.1007/s12237-011-9375-9.

Dugan, J.E., Hubbard, D.M., Quigley, B.J., 2013. Beyond beach width: steps toward identifying and integrating ecological envelopes with geomorphic features and datums for sandy beach ecosystems. Geomorphology 199, 95–105. https://doi.org/10.1016/j.geomorph.2013.04.043.

Dugan, J.E., Emery, K.A., Alber, M., Alexander, C.R., Byers, J.E., Gehman, A.M., McLenaghan, N., Sojka, S.E., 2018. Generalizing ecological effects of shoreline armoring across soft sediment environments. Estuar. Coasts 41, 180–196. https://doi.org/10.1007/s12237-017-0254-x.

Erikson, L.H., Hegermiller, C.A., Barnard, P.L., Ruggiero, P., van Ormondt, M., 2015. Projected wave conditions in the Eastern North Pacific under the influence of two CMIP5 climate scenarios. Ocean Model. 96, 171–185. https://doi.org/10.1016/j.ocemod.2015.07.004.

Erikson, L.H., Barnard, P.L., O'Neill, A.C., Wood, N., Jones, J., Finzi-Hart, J., Vitousek, S., Limber, P.W., Fitzgibbon, M., Hayden, M., Lovering, J., Foxgrover, A.C., 2018a. Projected 21st Century coastal flooding in the Southern California Bight. Part 2: tools for assessing climate change driven coastal hazards and socio-economic impacts. J. Mar. Sci. Eng. 6 (3), 76. http://dx.doi.org/10.3390/jmse6030076.

Erikson, L.H., Espejo, A., Barnard, P.L., Serafin, K.A., Hegermiller, C.A., O'Neill, A., Ruggiero, P., Limber, P.W., Mendez, F.J., 2018b. Identification of storm events and contiguous coastal sections for deterministic modeling of extreme coastal flood events in response to climate change. Coast. Eng. 140, 316–330. https://doi.org/10.1016/j.coastaleng.2018.08.003.

Feng, D., Beighley, E., Raoufi, R., Melack, J., Zhao, Y., Iacobellis, S., Cayan, D., 2019. Propagation of future climate conditions into hydrologic response from coastal southern California watersheds. climatic change. https://doi.org/10.1007/s10584-019-02371-3.

Ferren, W.R., 1985. Carpinteria Salt Marsh: Environment, History, and Botanical Resources of a Southern California Estuary. Herbarium. Dept. of Biological Sciences, University of California, Santa Barbara. https://doi.org/10.5962/bhl.title.63944.

Ferren, W.R., Page, H.M., Saley, P., 1997. Management Plan for Carpinteria Salt Marsh Reserve- A Southern California Estuary. Prepared for the University of California Natural Reserve System. Museum of Systematics and Ecology, Department of Ecology, Evolution, and Marine Biology, Oakland, Californa Environmental Report No. 5.
Filho, W.L., Modesto, F., Nagy, G.J., Saroar, M., YannickToamukum, N., Ha'apio, M., 2018. Fostering coastal resilience to climate change vulnerability in Bangladesh, Brazil, Cameroon and Uruguay: a cross-country comparison. Mitig. Adapt. Strategies Glob. Change. https://doi.org/10.1007/s11027-017-9750-3.
Gershunov, A., Guirguis, K., 2012. California heat waves in the present and future. Geophys. Res. Lett. 39 (17). https://doi.org/10.1029/2012GL052979.
Gitay, H., Suárez, R.T., Watson, R.T., Dokken, D.J., 2002. Climate Change and Biodiverisity. IPCC Technical Paper V. https://doi.org/10.2307/1551672.
Griggs, G.B., Russell, N.L., 2012. City of Santa Barbara: Sea-Level Rise Vulnerability Study. California Energy Commission Public Interest Energy Research Program.
Guyadeen, D., Thistlethwaite, J., Henstra, D., 2019. Evaluating the quality of municipal climate change plans in Canada. Clim. Change 152 (1), 121–143. https://doi.org/10.1007/s10584-018-2312-1.
Habel, J.S., Armstrong, G.A., 1977. Assessment and Atlas of Shoreline Erosion along the California Coast. State of California. Department of Navigation and Ocean Development.
Halpern, B.S., Walbridge, S., Selkoe, K.A., Kappel, C.V., Micheli, F., D'Agrosa, C., Bruno, J., Casey, K., Ebert, C., Fox, H., Fujita, R., Heinemann, D., Lenihan, H., Madin, E., Perry, M., Selig, E., Spalding, M., Steneck, R., Watson, R., 2008. A global map of human impact on marine ecosystems. Science 319 (5865), 948–952. https://doi.org/10.1126/science.1149345.
Heidrich, O., Dawson, R.J., Reckien, D., Walsh, C.L., 2013. Assessment of the climate preparedness of 30 urban areas in the UK. Clim. Change 120 (4), 771–784. https://doi.org/10.1007/s10584-013-0846-9.
Homyak, P.M., Sickman, J.O., Miller, A.E., Melack, J.M., Meixner, T., Schimel, J.P., 2014. Assessing nitrogen-saturation in a seasonally dry chaparral watershed: limitations of traditional indicators of N-saturation. Ecosystems 17 (7). https://doi.org/10.1007/s10021-014-9792-2.
Hubbard, D.M., Dugan, J.E., 2003. Shorebird use of an exposed sandy beach in southern California. Estuar. Coast Shelf Sci. 58, 41–54. https://doi.org/10.1016/S0272-7714(03)00048-9.
Hubbard, D.M., Dugan, J.E., Schooler, N.K., Viola, S.M., 2014. Local extirpations and regional declines of endemic upper beach invertebrates in southern California. Estuar. Coast Shelf Sci. 150, 67–75. https://doi.org/10.1016/j.ecss.2013.06.017.
IPCC, 2013. Climate Change 2013: the Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.
IPCC, 2018. Global Warming of 1.5°C. Intergovernmental Panel on Climate Change.
Jones, H.P., Hole, D.G., Zavaleta, E.S., 2012. Harnessing nature to help people adapt to climate change. Nat. Clim. Chang. https://doi.org/10.1038/nclimate1463.
Jones, J.M., Henry, K., Wood, N., Ng, P., Jamieson, M., 2017. HERA: a dynamic web application for visualizing community exposure to flood hazards based on storm and sea level rise scenarios. Comput. Geosci. 109, 124–133. https://doi.org/10.1016/j.cageo.2017.08.012.
Kantamaneni, K., Phillips, M., Thomas, T., Jenkins, R., 2018. Assessing coastal vulnerability: development of a combined physical and economic index. Ocean Coast Manag. 158, 164–175. https://doi.org/10.1016/j.ocecoaman.2018.03.039.
Kantamaneni, K., Sudha Rani, N., Rice, L., Sur, K., Thayaparan, M., Kulatunga, U., Rege, R., Yenneti, K., Campos, L.C., 2019. A systematic review of coastal vulnerability assessment studies along Andhra Pradesh, India: a critical evaluation of data gathering, risk levels and mitigation strategies. Water 11, 393. https://doi.org/10.3390/w11020393.
Keenan, J.M., 2018. Types and forms of resilience in local planning in the U.S.: who does what? Environ. Sci. Policy 88, 116–123. https://doi.org/10.1016/j.envsci.2018.06.015.
King, P.G., Nelsen, C., Dugan, J.E., Hubbard, D.M., Martin, K.L., 2018. Valuing beach ecosystems in an age of retreat. Shore Beach 86 (4), 45–59.
Limber, P., Barnard, P.L., Vitousek, S., Erikson, L.H., 2018. A model ensemble for projecting multi-decadal coastal cliff retreat during the 21st century. J. Geophys. Res. Earth Surf. 123 (7), 1566–1589. https://doi.org/10.1029/2017JF004401.
Lindseth, G., 2004. The Cities for Climate Protection Campaign (CCPC) and the framing of local climate policy. Local Environ. 9 (4), 325–336. https://doi.org/10.1080/1354983042000246252.
Livneh, B., Bohn, T.J., Pierce, D.W., Munoz-Arriola, F., Nijssen, B., Vose, R., Cayan, D.R., Brekke, L., 2015. A Spatially Comprehensive, Hydrometeorological Data Set for Mexico, the U.S., and Southern Canada 1950-2013. Scientific Data, vol. 2. https://doi.org/10.1038/sdata.2015.42.
Lovejoy, T.E., Hannah, L., 2005. Climate Change and Biodiveristy. TERI Press.
Martin, K., 2015. Beach-spawning Fishes: Reproduction in an Endangered Ecosystem. CRC Press. https://doi.org/10.1201/b17410.
Mawdsley, J.R., O'Malley, R., Ojima, D.S., 2009. A review of climate-change adaptation strategies for wildlife management and biodiversity conservation. Conserv. Biol. 23 (5), 1080–1089. https://doi.org/10.1111/j.1523-1739.2009.01264.x. https://doi.org/10.1111/j.1523-1739.2009.01264.x.
McLachlan, A., Defeo, O., 2018. In: The Ecology of Sandy Shores, second ed. Academic Press.
Measham, T.G., Preston, B.L., Smith, T.F., Brooke, C., Gorddard, R., Withycombe, G., Morrison, C., 2011. Adapting to climate change through local municipal planning: barriers and challenges. Mitig. Adapt. Strategies Glob. Change 16 (8), 889–909. https://doi.org/10.1007/s11027-011-9301-2.
Moeslund, J.E., Arge, L., Bøcher, P.K., Nygaard, B., Svenning, J.C., 2011. Geographically comprehensive assessment of salt-meadow vegetation-elevation relations using LiDAR. Wetlands 31 (3), 471–482. https://doi.org/10.1007/s13157-011-0179-2.
Mooney, H., Larigauderie, A., Cesario, M., Elmquist, T., Hoegh-Guldberg, O., Lavorel, S., Mace, G.M., Palmer, M., Scholes, R., Yahara, T., 2009. Biodiversity, climate change, and ecosystem services. Curr. Opin. Environ. Sustain. https://doi.org/10.1016/j.cosust.2009.07.006.
Moore, L.J., Ruggiero, P., List, J.H., 2006. Comparing mean high water and high water line shorelines: should proxy-datum offsets be incorporated into shoreline change analysis? J. Coast. Res. 224, 894–905. https://doi.org/10.2112/04-0401.1.
Moser, S.C., Luers, A.L., 2007. Managing climate risks in California: the need to engage resource managers for successful adaptation to change. Clim. Change 87 (1). https://doi.org/10.1007/s10584-007-9384-7.
Munang, R., Thiaw, I., Alverson, K., Liu, J., Han, Z., 2013. The role of ecosystem services in climate change adaptation and disaster risk reduction. Curr. Opin. Environ. Sustain. https://doi.org/10.1016/j.cosust.2013.02.002.
Munroe, R., Roe, D., Doswald, N., Spencer, T., Möller, I., Vira, B., Reid, H., Kontoleon, A., Giuliani, A., Castelli, I., Stephens, J., 2012. Review of the Evidence Base for Ecosystem-Based Approaches for Adaptation to Climate Change. Environmental Evidence. BioMed Central Ltd. https://doi.org/10.1186/2047-2382-1-13.
Myers, M.R., Cayan, D.R., Iacobellis, S.F., Melack, J.M., Beighley, R.E., Barnard, P.L., Dugan, J.E., Page, H.M., 2017. Santa Barbara Area Coastal Ecosystem Vulnerability Assessment. CASG-17-009. Available from. https://caseagrant.ucsd.edu/project/santa-barbara-area-coastal-ecosystem-vulnerability-assessment-sba-ceva.
National Research Council, 2012. Sea Level Rise for the Coasts of California, Oregon and Washington: Past, Present and Future. National Academies Press, Washington, DC.
NOAA, 2012. 2009-2011 California Coastal Conservancy Coastal Lidar Project. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Office for Coastal Management. http://www.coast.noaa.gov/dataviewer/index.html?action=advsearch&qType=in&qFld=ID&qVal=1124#.
Oakley, N.S., Cannon, F., Munroe, R., Lancaster, J.T., Gomberg, D., Martin Ralph, F., 2018. Brief communication: meteorological and climatological conditions associated with the 9 January 2018 post-fire debris flows in Montecito and Carpinteria, California, USA. Nat. Hazards Earth Syst. Sci. 18 (11), 3037–3043. https://doi.org/10.5194/nhess-18-3037-2018.
Ojea, E., 2015. Challenges for mainstreaming ecosystem-based adaptation into the international climate agenda. Curr. Opin. Environ. Sustain. 14, 41–48. https://doi.org/10.1016/j.cosust.2015.03.006.
Onuf, C.P., Quammen, M.L., Shaffer, G.P., Peterson, C.H., Chapman, J.W., Cermak, J., Holmes, R.W., 1979. An analysis of the values of central and southern California coastal wetlands. In: Greeson, P. E., Clark, J. R.. Clark. J. E. (Ed.), Wetland functions and values: the state of our understanding. American Water Resources Association, Minneapolis. Minnesota, pp. 186–199.
O'Neill, A.C., Erikson, L.H., Barnard, P.L., 2017. Downscaling wind and wavefields for 21st century coastal flood hazard projections in a region of complex terrain. Earth Space Sci. 4 (5), 314–334. https://doi.org/10.1002/2016EA000193.
O'Neill, A.C., Erikson, L.H., Barnard, P.L., Limber, P.W., Vitousek, S., Warrick, J.A., Foxgrover, A.C., Lovering, J., 2018. Projected 21st century coastal flooding in the Southern California Bight. Part 1: development of the third generation CoSMoS model. J. Mar. Sci. Eng. 6 (2), 59. https://doi.org/10.3390/jmse6020059.
Page, H.M., Schroeter, S.C., Reed, D., Ambrose, R.F., Callaway, J., Dixon, J., 2003. An inexpensive method to identify the elevation of tidally inundated habitat in coastal wetlands. Bull. South Calif. Acad. Sci. 102, 130–142.
Pasquini, L., Cowling, R.M., 2015. Opportunities and challenges for mainstreaming ecosystem-based adaptation in local government: evidence from the Western Cape, South Africa. Environ. Dev. Sustain. 17 (5), 1121–1140. https://doi.org/10.1007/s10668-014-9594-x.
Pasquini, L., Cowling, R.M., Ziervogel, G., 2013. Facing the heat: barriers to mainstreaming climate change adaptation in local government in the Western Cape Province, South Africa. Habitat Int. 40, 225–232. https://doi.org/10.1016/j.habitatint.2013.05.003.
Patsch, K., Griggs, G., 2008. A sand budget for the Santa Barbara littoral cell, California. Mar. Geol. 252 (1–2), 50–61. https://doi.org/10.1016/j.margeo.2008.01.013.
Pierce, D.W., Cayan, D.R., Thrasher, B.L., 2014. Statistical downscaling using localized constructed analogs (LOCA). J. Hydrometeorol. 15 (6), 2558–2585. https://doi.org/10.1175/jhm-d-14-0082.1.
Pierce, D.W., Cayan, D.R., Kalansky, J.F., Scripps Institution of Oceanography, 2018. Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. California's Fourth Climate Change Assessment, California Energy Commission. Publication number: CCCA4-CEC-2018-006.
Polade, S.D., Gershunov, A., Cayan, D.R., Dettinger, M.D., Pierce, D.W., 2017. Precipitation in a warming world: assessing projected hydro-climate changes in California and other Mediterranean climate regions. Sci. Rep. 7 (1). https://doi.org/10.1038/s41598-017-11285-y.
Raoufi, R., Beighley, E., 2017. Estimating daily global evapotranspiration using penman-monteith equation and remotely sensed land surface temperature. Remote Sens. 9 (11). https://doi.org/10.3390/rs9111138.
Rauken, T., Mydske, P.K., Winsvold, M., 2015. Mainstreaming climate change adaptation at the local level. Local Environ. 20 (4), 408–423. https://doi.org/10.1080/13549839.2014.880412.
Reckien, D., Salvia, M., Heidrich, O., Church, J.M., Pietrapertosa, F., De Gregorio-Hurtado, S., D'Alonzo, V., Foley, A., Simoes, S., Krkoška Lorencová, E., Orru, H., Orru, K., Wejs, A., Flacke, J., Olazabal, M., Geneletti, D., Feliu, E., Vasilie, S., Nador, C., Krook-Riekkola, A., Matosović, M., Fokaides, P., Ioannou, B., Flamos, A., Spyridaki, N., Balzan, M., Fülöp, O., Paspaldzhiev, I., Grafakos, S., Dawson, R., 2018. How are cities planning to respond to climate change? Assessment of local climate plans from

885 cities in the EU-28. J. Clean. Prod. 191, 207–219. https://doi.org/10.1016/j.jclepro.2018.03.22.

Reid, H., 2016. Ecosystem- and community-based adaptation: learning from community-based natural resource management. Clim. Dev. 8 (1), 4–9. https://doi.org/10.1080/17565529.2015.1034233.

Revell, D.L., Griggs, G.B., 2006. Beach width and climate oscillations in Isla Vista, Santa Barbara, California. Shore Beach 74, 8–16.

Revell, D.L., Dugan, J.E., Hubbard, D.M., 2011. Physical and ecological responses of sandy beaches to the 1997–98 El Niño. J. Coast. Res. 27 (4), 718. https://doi.org/10.2112/jcoastres-d-09-00179.1.

Reynolds, L.C., Simms, A.R., Ejarque, A., King, B., Anderson, R.S., Carlin, J.A., Bentz, J.M., Rockwell, T.K., Peters, R., 2018. Coastal flooding and the 1861-2 California storm season. Mar. Geol. 400, 49–59. https://doi.org/10.1016/j.margeo.2018.02.005.

Roberts, D., 2008. Thinking globally, acting locally - institutionalizing climate change at the local government level in Durban, South Africa. Environ. Urbanization 20 (2), 521–537. https://doi.org/10.1177/0956247808096126.

Roberts, D., Boon, R., Diederichs, N., Douwes, E., Govender, N., Mcinnes, A., Mclean, C., O'Donoghue, S., Spires, M., 2012. Exploring ecosystem-based adaptation in Durban, South Africa: "Learning-by-doing" at the local government coal face. Environ. Urbanization 24 (1), 167–195. https://doi.org/10.1177/0956247811431412.

Ruggiero, P., List, J.H., 2009. Improving accuracy and statistical reliability of shoreline position and change rate estimates. J. Coast. Res. 255, 1069–1081. https://doi.org/10.2112/08-1051.1.

Runting, R.K., Bryan, B.A., Dee, L.E., Maseyk, F.J.F., Mandle, L., Hamel, P., Wilson, K.A., Yetka, K., Possingham, H.P., Rhodes, J.R., 2017. Incorporating climate change into ecosystem service assessments and decisions: a review. Glob. Chang. Biol. 23 (1), 28–41. https://doi.org/10.1111/gcb.13457.

Ryan, G., 1994. Climate of Santa Barbara, California. NOAA Technical Memorandum. U.S. Department of Commerce NWS WR-225.

Sadro, S., Gastil-Buhl, M., Melack, J.M., 2007. Characterizing patterns of plant distribution in a southern California salt marsh using remotely sensed topographic and hyperspectral data and local tidal fluctuations. Remote Sens. Environ. 110 (2), 226–239. https://doi.org/10.1016/j.rse.2007.02.024.

Santana-Cordero, A.M., Monteiro-Quintana, M.L., Hernandez-Calveto, L., 2016. Reconstruction of the Termination of an Arid Coastal Dune System: the Case of the Guantarteme Dune System (Canary Islands, Spain), vol. 55. pp. 1834–2012. 73-85. https://doi.org/10.1016/j.landusepol.2016.02.021.

Scarano, F.R., 2017. Ecosystem-based adaptation to climate change: concept, scalability and a role for conservation science. Perspectives in Ecology and Conservation. Associacao Brasileira de Ciencia Ecologica e Conservacao. https://doi.org/10.1016/j.pecon.2017.05.003.

Schlacher, T.A., Dugan, J., Schoeman, D.S., Lastra, M., Jones, A., Scapini, F., McLachlan, A., Defeo, O., 2007. Sandy beaches at the brink. Divers. Distrib. 13 (5), 556–560. https://doi.org/10.1111/j.1472-4642.2007.00363.x.

Schooler, N.K., Dugan, J.E., Hubbard, D.M., Straughan, D., 2017. Local scale processes drive long-term change in biodiversity of sandy beach ecosystems. Ecol. Evol. 7 (13), 4822–4834. https://doi.org/10.1002/ece3.3064.

Selkoe, K.A., Blenckner, T., Caldwell, M.R., Crowder, L.B., Erickson, A.L., Essington, T.E., Estes, J.A., Fujita, R.M., Halpern, B.S., Hunsicker, M.E., Kappel, C.V., Kelly, R.P., Kittinger, J.N., Levin, P.S., Lynham, J.M., Mach, M.E., Martone, R.G., Mease, L.A., Salomon, A.K., Samhouri, J.F., Scarborough, C., Stier, A.C., White, C., Zedler, J., 2015. Principles for managing marine ecosystems prone to tipping points. Ecosyst. Health Sustain. 1 (5), 1–18. https://doi.org/10.1890/ehs14-0024.1.

Serafim, M.B., Siegle, E., Corsi, A.C., Bonetti, J., 2019. Coastal vulnerability to wave impacts using a multi-criteria index: Santa Catarina (Brazil). J. Environ. Manag. 230, 21–32.

Shi, L., 2019. Promise and paradox of metropolitan regional climate adaptation. Environ. Sci. Policy 92, 262–274. https://doi.org/10.1016/j.envsci.2018.11.002.

Stein, E.D., Cayce, K., Salomon, M., Bram, D.L., Grossinger, R., Dark, S., 2014. Wetlands of the Southern California Coast: Historical Extent and Change Over Time. 826. pp. 1–50 Southern California Coastal Water Research Project Technical Report.

Storlazzi, C.D., Willis, C.M., Griggs, G.B., 2000. Comparative impacts of the 1982-83 1997-98 El Niño winters on the central California coast. J. Coast. Res. 16 (4), 1022–1036.

Sweet, W.V., Kopp, R.E., Weaver, C.P., Obeysekera, J., Horton, R.M., Thieler, R.E., Zervas, C., 2017. Global and Regional Sea Level Rise Scenarios for the United States. NOAA Technical Report NOS CO-OPS 083. NOAA/NOS Center for Operational Oceanographic Products and Services.

Temmerman, S., Meire, P., Bouma, T.J., Herman, P.M.J., Ysebaert, T., De Vriend, H.J., 2013. Ecosystem-based coastal defence in the face of global change. Nature 504 (7478), 79–83. https://doi.org/10.1038/nature12859.

Tribbia, J., Moser, S.C., 2008. More than information: what coastal managers need to plan for climate change. Environ. Sci. Policy 11 (4), 315–328. https://doi.org/10.1016/j.envsci.2008.01.003.

US Census Bureau, 2017. Retrieved from. https://www.census.gov, Accessed date: 7 April 2019.

Valiela, I., Lloret, J., Bowyer, T., Miner, S., Remsen, D., Elmstrom, E., Cogswell, C., Robert Thieler, E., 2018. Transient coastal landscapes: rising sea level threatens salt marshes. Sci. Total Environ. 640–641, 1148–1156. https://doi.org/10.1016/j.scitotenv.2018.05.235.

Vitousek, S., Barnard, P.L., Limber, P., Erikson, L., Cole, B., 2017. A model integrating longshore and cross-shore processes for predicting long-term shoreline response to climate change. J. Geophys. Res.: Earth Surf. 122 (4), 782–806. https://doi.org/10.1002/2016JF004065.

Wamsler, C., Luederitz, C., Brink, E., 2014. Local levers for change: mainstreaming ecosystem-based adaptation into municipal planning to foster sustainability transitions. Glob. Environ. Chang. 29, 189–201. https://doi.org/10.1016/j.gloenvcha.2014.09.008.

Warrick, J.A., Melack, J.M., Goodridge, B.M., 2015. Sediment yields from small, steep coastal watersheds of California. J. Hydrol. Reg. Stud. 4, 516–534. https://doi.org/10.1016/j.ejrh.2015.08.004.

Wilson, E., 2006. December. Adapting to climate change at the local level: the spatial planning response. Local Environ. 11 (6), 609–625. https://doi.org/10.1080/13549830600853635.

Wolter, K., 1987. The Southern Oscillation in surface circulation and climate over the tropical Atlantic, Eastern Pacific, and Indian Oceans as captured by cluster analysis. J. Appl. Meteorol. Climatol. 26, 540–558.

Worm, B., Barbier, E.B., Beaumont, N., Duffy, J.E., Folke, C., Halpern, B.S., Jackson, J.B.C., Lotze, H.K., Micheli, F., Palumbi, S.R., Sala, E., Selkoe, K.A., Stachowicz, J.J., Watson, R., 2006. Impacts of biodiversity loss on ocean ecosystem services. Science 314 (5800), 787–790. https://doi.org/10.1126/science.1132294.

Zedler, J., Nordby, C., Kus, B., 1992. The ecology of Tijuana Estuary, California: a national estuarine research reserve. Ecosystems 164. http://ceic.resources.ca.gov/catalog/SouthernCAWetlandPublications/TheEcologyOfTijuanaEstuaryCAANationalEstuarineResearchReserve.html.

Zedler, J.B., Callaway, J.C., Desmond, J.S., Vivian-Smith, G., Williams, G.D., Sullivan, G., Brewster, A.E., Bradshaw, B.K., 1999. Californian salt-marsh vegetation: an improved model of spatial pattern. Ecosystems 2 (1), 19–35. https://doi.org/10.1007/s100219900055.

Zölch, T., Wamsler, C., Pauleit, S., 2018. Integrating the ecosystem-based approach into municipal climate adaptation strategies: the case of Germany. J. Clean. Prod. 170, 966–977. https://doi.org/10.1016/j.jclepro.2017.09.146.