Title

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Synthesis of Local Climate-Altering Criteria and the Potential Impacts of Climate Change on Organisms, Ecosystem Function, and Positive Feedback Loops in California's Channel Islands National Park

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Abstract

Microclimates can behave differently from the larger regional climate, and it is essential to consider various spatiotemporal scales when studying how climate change affects local ecosystems. This research identifies small-scale climate variations within Channel Islands National Park (CINP), particularly in areas where species might find refuge to adapt to climate change. The study identifies different climate characteristics in this region by creating a microclimate framework and analyzing historical data accordingly. It also explains the need for scaling down climate information to the ecosystem level and provides a literature review of all known criteria necessary. The goal is to help inform park managers of local conditions and potential threats to prioritize areas for conservation and restoring biodiversity and natural resources. While global and regional climate models help understand broad trends, they often need more detail to grasp ecological changes at the community or individual species level. Scaling down climate information can enhance the accuracy of predictive models used in environmental assessments and impact studies, and identifying existing microclimates can help assess the overall health of an ecosystem. The research categorizes the scaling process into four levels: macro, meso, topo, and micro. It outlines the procedure for identifying microclimates, analyzes model predictions, illustrates future climate scenarios, and highlights correlations between various physical factors using recent climatological observations. The study starts with a review of existing literature to provide context for each climate variable's impact on the overall ecosystem, explains the research methods, presents the results, and concludes with a discussion of the findings and suggestions for future research beyond the scope of this study. The research was conducted in collaboration with The Nature Conservancy and the National Park Service to address the specific needs of the park.

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1 Introduction & Background

1.1 Introduction

Due to a rapid increase in global warming from greenhouse gas emissions, anthropogenic climate change has impacted global ecosystem function, threatening all life on Earth. These changes inhibit biodiversity by increasing the amount of threatened and endangered species, thus expediting the world's current mass extinction event. Reducing biodiversity hastens the issues that cause it, creating positive feedback loops that contribute to more rapid ecosystem malfunction. Island ecosystems are especially vulnerable to climate change and are expected to become even more vulnerable in the coming decades (Arias et al., 2021). Although island ecosystems only cover 6 percent of the Earth's surface, they host 20 percent of the world's biodiversity—an existential necessity to sustaining life on Earth (Fernández-Palacios et al., 2021). Climate change causes various disturbances, further exacerbated by unsustainable land-use practices and ineffective conservation management. Because of its location, Channel Islands National Park is an ideal site for studying the effects of sustainable land use and management on the complex interactions between land, ocean, and the atmosphere.

The Channel Islands are one of California's most biodiverse regions (CNRA, 2021). This study attempts to develop a framework for fine-scale climate modeling in this region to support conservation management planning and protect biodiversity under anthropogenic climate change. The research identifies known climate-altering criteria, establishes parameters for ecosystem downscaling, assesses climate feedback loops, and discusses regional trends to understand how climate characteristics manifest differently at different spatiotemporal scales for each of the five islands. Considering the strong coupling of land, ocean, and atmospheric relationships, the research assesses historical changes in SST, air temperature, and precipitation and identifies correlations between these physical processes. Although the research context is conservation ecology, the frameworks can influence mitigation efforts involving human health and wellbeing, natural resource management, food security, and sustainable development. Ongoing and future research is necessary to create predictive models on a scale that is helpful for climate-smart management in this region. The model can help discern correlations between large-scale climate change, climate variability, and land use practices. It can also more accurately assess land-sea-atmosphere interactions and highlight the effects of vegetation die-offs, species' thermal thresholds, and the water and carbon cycles.

1.2 Background

The current extinction rate is estimated between 1,000 and 10,000 times higher than natural extinction rates, or the rate of extinction that would occur without human interference (Rafferty, 2023). Unlike previous extinction events, the sixth mass extinction has been caused and exacerbated by human-induced activity, including the unsustainable use of land, excessive water and energy consumption, toxic waste, and climate change. The earth's land is experiencing changes rapidly—many areas are facing deforestation and desertification, more frequent and extreme weather events, drought, flooding, and the extensive loss of life-sustaining organisms. Every process in the ecosystem is interconnected—sustainable ecosystem function requires a diverse biosphere, and measuring these changes requires an understanding of multiple processes with varying levels of complexity. The research aims to understand how and to what extent these interconnected processes affect climate locally and globally. Without functioning ecosystems, the planet is under immense pressure, propelling the positive feedback loops that exacerbate climate change.

Historical Impacts and Future Risks to the Terrestrial Ecosystem

Island habitats account for 20 percent of the world's biodiversity, 50 percent of the world's threatened species, and 75 percent of the known extinctions (Fernández-Palacios et al., 2021). California's Channel Islands are home to nearly 145 plants and animals found nowhere else (NASA, 2023). Sheep and cattle ranching on Santa Cruz, Santa Rosa, and San Miguel islands has depleted topsoil and led to erosion, and fish and marine mammals were consistently overharvested. Land use on the islands has changed substantially for this reason (Braje et al., 2015). Because of its isolated geography, many endemic species have evolved to the unique climate of the islands, but that isolation has now become a threat because of climate change. With every degree of warming, the risk of species extinction increases. However, the extent of that risk and the responses of current island ecosystems to environmental changes predicted for the coming decades are unclear.

The demise of functioning ecosystems affects all life on earth. Due to rising temperatures from global warming, species are reaching thermal thresholds, forcing them to migrate and evolve as food and water sources diminish. Historical nesting sites are impacted or become uninhabitable, thus decreasing chances of reproduction, ultimately reducing the chance of survival. Simultaneously, modern anthropogenic land-use practices like overgrazing, groundwater extraction, and deforestation reduce natural resources like water and vegetation and multiply positive feedback loops, reducing biodiversity and ecosystem function (Olsson et al., 2022). Focusing conservation management efforts on hyper-local areas with predicted stable climate relative to background climate change is increasingly recognized as a viable conservation strategy.

Climate variability manifests differently in different regions, creating microclimates that could provide natural refuges from large-scale climate effects for marine and terrestrial life. These refugia sites have the potential to mitigate biodiversity impacts if conservation efforts are focused appropriately on species migration and ecosystem adaptation. Local management and conservation efforts are futile in the face of larger-scale climate change; however, local ecological restoration can provide appropriate habitat mitigation for endangered species, reduce biodiversity loss, and improve overall ecosystem health. It is also increasingly apparent that land processes affect micro, meso, and macroclimatic conditions (FAO, 2020). By analyzing local climate change projections, determining the characteristics of microclimates, and identifying potential refugia sites in California's Channel Islands, the report will provide context to climate-smart planning and decision-making. In this context, the term climate-smart refers to incorporating climate change considerations into the work. The study will give greater context to conservation management needs based on the projected patterns of change when compared to local habitat changes, the abundance and type of current vegetation, species present compared to historical records, and areas vulnerable to extreme heat days, drought, wildfires, flooding, sea-level rise, coastal erosion, storm surge, and other extreme weather events. The study aims to create a framework for climate-smart restoration and natural resource management by considering the interdependent relationships and climate feedback loops between the ocean, atmosphere, and land.

Channel Islands Archaeological Background

Evidence indicates that the Channel Islands National Park archipelago has undergone substantial structural changes since human inhabitation of the islands began. One of the most dramatic changes to the landscape occurred between 19,000 and 10,000 years ago when the Pleistocene-aged Island of Santarosae (the island's name when it was one single, undivided territory) divided into the four northern Channel Islands of today because of glacial melting that caused rapid sea level rise (Braje et al., 2015). As a result, the total land mass of the islands diminished by more than 75 percent. Seacliff erosion has caused further land area loss, but the amount of decline since that time has not yet been studied (Braje et al., 2015).

Unique Geographic Features of California's Channel Islands

The Channel Islands are in Santa Barbara County, approximately 20 miles from Ventura in the Pacific Ocean off the west coast of California in North America. The isolated geography of the Channel Islands, along with their varying low-lying or steep coastal topographies, are especially vulnerable to climate change (Oppenheimer et al., 2019). Between twenty million and five million years ago, the islands were formed by shifts in the San Andreas Fault system, when a block of land that currently forms the Western transverse ranges broke loose and pivoted along the edge of the North American Plate—folding, faulting, and uplifting. This transformation created the islands as they are today. The islands are separated from each other and mainland California by the Pacific Ocean. The Channel Islands lie in the Santa Barbara Channel, an elongated basin stretching nearly 100km by 40km between the California coastline from Los Angeles to Point Conception. Sills between Anacapa Island and Port Hueneme and between San Miguel Island and Point Conception separate the channel from the Southern California Bight to the east and the open ocean to the west. The Channel Islands have distinct warm and cool currents to the east and west, giving them unique and varied climate characteristics (Hendershott & Winant, 1996).

2 Literature Review

The literature review in the following sections describes criteria that, in combination, determine specific climate types at various spatiotemporal scales. Several sections divide the information for greater understanding: (2.1) defining climate on varying spatial and temporal scales, (2.2) climatology, (2.3) global and continental climate trends, (2.4-2.6) climate-affecting criteria: topography, physical climate conditions, and biogeographic features, and (2.7) land-atmosphere-ocean interactions and feedback loops. The literature review outlines the conditions for each variable's influence on the climate system; all definitions and criteria in this section apply to the Channel Islands National Park study area. A broad, independent climate analysis is documented in the methods and results section. The criteria for determining various climate types can change based on the geographic region of interest, goals of conservation management, and specific climate analyses. Therefore, all necessary and known criteria for Channel Islands National Park are described in detail to synthesize the information in one document and to determine the level of influence or usefulness for inclusion in future studies.

2.1 Defining Climate at Various Spatial and Temporal Scales

Macroclimate

Macroclimate typically determines physical processes at a global scale and often at a regional scale. Macroclimates can be altered significantly by the sun's angle, latitude and longitude, and other large-scale meteorological phenomena. Throughout this study, macroclimate refers to both globally aggregated climate conditions and broader regional conditions that affect all the islands collectively. Global processes like atmospheric temperature and ocean currents alter macroclimate. However, many other macro and micro processes are involved in determining overall global climate conditions. Many existing findings that determine management decisions are founded on this region's assumed strong and smooth geographic climate gradients, which result from coarse-resolution climate data from historical observations and statistical models. While macroclimate quantifications are helpful in many aspects of climate science, downscaling techniques are often required to understand the influence of topography, soil, vegetation, and other fine-scale influences on local climate (Maclean & Early, 2023).

Microclimate

Microclimate refers to climate processes and conditions on each island at a scale that organisms experience. Thus, there are various microclimates within each island's boundary. For this study, microclimate describes any climatic condition within ~800m above and below the Earth's surface (vertically) and between <1m and 270m horizontally. These parameters are determined because current high-resolution data from downscaled climate models have a spatial resolution between ~270m (0.17 mile) and ~800m (0.5 mile), respectively. These ranges serve as a general guideline, rather than a strict rule, for understanding how localized variations of the considered variables can influence microclimates. Higher-resolution data is preferred when available. The specific microclimatic range may vary depending on the context and the consideration factors.

Sometimes, a smaller or larger range is more appropriate for studying a specific climate. Local conditions like vegetation, geology, topography, and land use can significantly alter microclimates. Variations in topography, geography, and land characteristics can affect microclimatic conditions across short distances, and hyper-local differences in temperature, water availability, wind, and sun exposure predict where unique species survive. The most substantial temperature and humidity gradients occur just above and below the terrestrial surface. Microclimates occur within and without tree canopies or vegetation, and the type and density of vegetation cover strongly influence the microclimate of a specified region. Rich biodiversity relies on the abundance of complex microclimates; strongly contrasting microclimates in proximity provide a diverse environment for many species to interact (Rita et al., 2021; Smith & Bookhagen, 2020; McNichol et al., 2022).

Microclimate conditions produce positive and negative feedback loops, where a change in one process accelerates or stalls a change in another process, and those feedback loops amplify the direction of overall change, and so on. These micro-processes are connected to the global climate system but can also decouple from it, often differing significantly by location. Microclimates can have a range of temperature values that differ from the broader climate; these fluctuations are 9 °C on average and can be up to 26°C (Pincebourde et al., 2016). The effective degree to which these local processes impact global atmospheric conditions depends on the magnitude of characteristic change and the extent of the geographic region. The following sections list biotic and abiotic variations and their degree of influence.

Within the Channel Islands National Park (CINP) boundary, dividing each island into a separate climate type is appropriate when looking at changing conditions due to the evident precipitation, SST, and air temperature gradients. Microclimates are hard to locate due to the complexity of making accurate, high-resolution calculations of multiple variables at multiple locations. Despite this complexity, it is necessary to do so. Understanding climate on a micro-scale is essential for maintaining ecosystem function in the face of climate change. A wide range of variables characterize microclimates, including temperature, precipitation, solar radiation, cloud cover, wind speed, wind direction, humidity, evaporation, evapotranspiration, and water availability. Fine-resolution biotic and abiotic variations, such as topography, soil type, land cover (especially vegetation), thermal mass, and proximity to the coast, among others, influence these processes.

Mesoclimate

Mesoclimate is the climate within a smaller region than a macroclimate but larger than a microclimate. This study defines mesoclimate as having climatic conditions at an intermediate geographic scale or, for simplicity, the aggregated climate conditions of each island. For example, Santa Barbara has a warm and dry climate at the mesoscale. In contrast, Santa Cruz has a hot and wet climate, and each island has many microclimates within those broader definitions. Mesoclimate is necessary to distinguish in this study because each island can be studied individually at this scale.

Topoclimate

'Topoclimate' is often used interchangeably with microclimate. However, topoclimates are variations in climate solely as a function of topographical features such as elevation, slope, and aspect, and they generally vary at a scale larger than microclimate (Barry & Blanken, 2016). Topoclimate is a function of topographical features and, therefore, a subcategory of the other climate scales. Therefore, its spatial and temporal ranges have broader vertical and horizontal parameters, which overlap the parameters of other climate scales in this study (section 4.2, table 2).

2.2 Climatology of Channel Islands National Park

Mediterranean Climate Type

Physical methods that classify climate types, like the Köppen Climate Classification system (Topiador et al., 2019), categorize the Channel Islands region as having a Hot-summer Mediterranean climate (Csa). This climate type has hot, dry summers and cool, wet winters. The Köppen Climate Classification system is a globally understood classification system used to model the distribution and growth of species and a tool for microclimate modeling and climate change predictions. The Mediterranean climate type is generally located between 30° and 45° latitude north and south of the equator and typically on the western sides of continents (Beck et al., 2018).

2.3 Global and Continental Climate Change Trends

The following global trends are significant for Channel Islands National Park due to the level of influence on the climate in this region.

Wet and Dry Climate Trends

Globally, some areas have experienced increased intensity and frequency of precipitation while others have experienced declines. This trend is projected to continue throughout the century. However, regarding water availability, climate change's effect on the water cycle is more complex than some areas getting drier or wetter (Nature Water, 2023). There are currently two frameworks for trends in water availability as climate changes. First, the overall conclusion from some models shows that globally, wet climates will become wetter while dry climates will become dryer (Feng & Zheng, 2016). This scenario is known as WWDD and holds that there will be widespread increased contrasts in available water (Zaitchik et al., 2023). The second hypothesized framework is that global aridification (GA) will occur (Nature Water, 2023). In the GA scenario, global evapotranspiration increases supersede precipitation changes in most terrestrial regions (Zaitchik et al., 2023).

Marine Heatwaves

Marine heatwaves—periods of anomalously high sea surface temperature (SST) at specific locations, lasting for a minimum of five consecutive days—are projected to increase further by mid and end-of-century (Barkhordarian et al., 2022). Globally, Marine heatwaves (MHWs) cause severe negative impacts on coastal and ocean ecosystems and can be attributed to rising levels of atmospheric greenhouse gases. They have occurred in all ocean basins worldwide, and the northeast Pacific 2013-2015 MHW event was a cause for significant concern. Replacing the typical strong east-west SST gradient was a more uniformly warm SST regime during the 2014-2016 marine heatwave around Channel Islands National Park and Marine Sanctuary. Acute events like this can alter the ecosystem structure and temporarily or permanently affect biodiversity (Freedman et al., 2020).

MHWs cause biologic and biogeographic disruptions that are at least four times more rapid and greater in magnitude than the effects of decadal-scale mean changes throughout the entire 21st century (Cheung & Frölicher, 2020). Climate projections show a doubling impact on essential fish species from MHW events by 2050 (Cheung & Frölicher, 2020). MHW events manifest positive climate feedback loops, which have been mentioned extensively in this study, and exacerbate the rate of change in this region. Projections also show that climate forcing has led to an outstanding warming pool in the northeast Pacific Ocean, indicating that this region is favorable for MHWs to become even more severe in the future (Barkhordarian et al., 2022). These projections will have devastating effects on Channel Islands National Park. For example, rising temperatures can cause mortality of intertidal species and deep-water corals, lead to more frequent and intense harmful algal blooms, change the food web by affecting nutrient levels and zooplankton, decrease oxygen levels, and force species movement to cooler waters (NOAA, 2020).

California Current System

Ocean currents create complex and highly dynamic water circulation around CINP, affecting the local climate. This results from the unique basin and ridge topography of the ocean bottom in the Southern California Bight (SCB). The islands are inundated by the southward-flowing California Current, which stays mainly to the west, directing cold water from the North Pacific Current down along the west coast of North America (Ugoretz, 2002). San Miguel Island is greatly affected by this cool, fresh current. To the east, the islands are immersed in the northward-flowing warm Inshore (Davidson) Countercurrent, which affects Santa Barbara and the inner islands more than the outer, westernmost islands (Muhs et al., 2014). The California Current System (CCS), including the California current and countercurrent, is associated with poleward and equatorward changes due to anthropogenic climate change (Brady, et al., 2017).

Model projections show ocean currents speeding up in some areas and slowing in others, affecting the upwelling of cold, nutrient-rich waters, and resulting in temperature and pressure changes, which will have climatological and ecologically significant impacts on the islands. Projections for the 1920 to 2100 period suggest that anthropogenic climate change will intensify upwelling in the California Current's northern region during the spring and weaken it in the central and northern regions throughout summer (Brady et al., 2017). The simulations also suggest that upwelling will decrease during part of the summer in the south, but that region does not have as clear of a seasonal shift. The human-induced changes in upwelling will emerge mainly in the second half of the century because of the system's internal climate variability. Overall, there is an agreed-upon intensification hypothesis in the poleward portion of the CCS during the "warm season," which spans May through August. The only other significant projected change is a trend of weakening Ekman transport in the Southern California Bight, with no significant change elsewhere in the CCS (Brady et al., 2017). Changes associated with the California Current system will cause disruptions to the normal state in the Northern Channel Islands region, potentially shifting the range or magnitude of the SST and air temperature spatial and temporal gradients around the Channel Islands (see results in section 4).

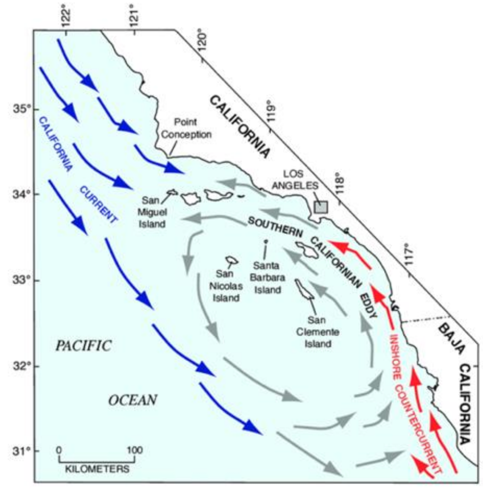


Figure 1. Southern region of the California Current System (CCS): Point Conception divides the central and southern "boundaries" of the CCS. This figure shows the location of warm and cool California Current and California Countercurrents surrounding the islands. The CCS is associated with poleward and equatorward changes resulting from climate change. There is a significant trend of weakening Ekman transport in the Southern California Bight and upwelling will decrease during part of the summer in this region, which will have ecologically significant effects on the islands (Brady et al., 2017). These changes will cause disruptions to the normal state, potentially changing the range or magnitude of the gradients seen in Figures 4A and 5A. (Muhs, 2018).

Changes in Global Wind Patterns (for Southern California)

A climate model cluster analysis published in Climate Dynamics in 2020 by UC Davis and UC Berkeley scientists predicts the frequency and magnitude of Northern and Southern California's projected near-surface wind speed (NSWS) changes by the end of the century. Results from this study show that NSWS decreases over the Northern Hemisphere (NH) mid-to-high latitudes and increases over the Southern Hemisphere (SH) as the global warming level (GWL) increases and that the characteristics become much more significant with higher GWLs.

Changes induced by global warming affect the temperature gradient, causing interhemispheric asymmetry of future NSWS changes. Global warming projections show a reduction in Hadley, Ferrell, and Polar cells over the NH and a strengthening of the Hadley cell over the SH, which could be another determinant of asymmetry changes in NSWS between the two hemispheres (Zha et al., 2021). In Southern California, projections show strong alongshore wind will become less frequent during the spring and fall seasons and more frequent in the winter. The wind change is attributed to a change in the geopotential height field pattern, which reduces the alongshore pressure gradient, leading to a weaker alongshore flow and decreased wind speed across the state of California (Wang et al., 2020). Winds in the Southern California Bight are generally weaker but highly variable compared to the remaining California coastal winds; thus, upwelling events in this region are limited to winter and early spring (Zha et al., 2021). Local upwelling during summer, while strong elsewhere along the California coast, is minimal in the SCB due to a significant reduction in wind stress. Small-scale eddies form from temporally and spatially variable local winds in this region, which introduces further complexity to modeling the future of wind change near the Channel Islands (Zha et al., 2021).

In the Southern region, marine air penetration peaks in frequency during the summer months and is projected to become more frequent with slightly increased onshore winds. The increase in geopotential height patterns cause these changes, which drives up wind speeds offshore, creating a better ventilation condition (Wang et al., 2020). Santa Ana winds, predominant in the winter months, are projected to decrease in frequency with weaker wind speeds associated with weakening of the onshore ridge during end-of-century (Wang et al., 2020). Weakened onshore flow, predominant in the summer months, is projected to increase in frequency by the end of the century due to the geopotential height anomaly, which strengthens the northerly wind offshore in NC, blocking the offshore flow in SC. Finally, the westerly wind is prominent during winter and spring, and projections show a decrease in frequency by end-of-century, along with weaker wind speeds due to suppressed onshore flow in Southern California (Wang et al., 2020).

Temperature Thresholds

All living organisms are affected by temperature, and the effect of temperature change varies across species and geographies. Living organisms develop and reproduce most effectively in their thermoneutral, or preferable, temperature zones where minimal physiological effort is necessary to maintain and sustain life. When organisms reach temperature thresholds or temperatures beyond their thermoneutral zones, it can lead to heat strain (Asseng et al., 2021). The estimated heat capacity of individual species depends on the environmental factors that determine the heat exchange rate, including ambient temperature, humidity, wind speed and direction, solar radiation, and precipitation (Asseng et al., 2021). In much of the current literature, temperature thresholds are distinguished using 1°C increments (Baccini et al., 2008; Crisci et al., 2017; Dixon et al., 2009; López-Bueno et al., 2021), and thresholds are determined relative to the native environments of individual species (Asseng et al., 2021; Dixon et al., 2009; Elsen et al., 2016; López-Bueno et al., 2021).

Humidity affects species' thermal thresholds as well. For example, a comfortable temperature range for humans is between 17°C and 24°C. However, with high humidity, the range could shift to some degrees lower; with low humidity, the range could extend to some degrees higher (Asseng et al., 2021). Standard thresholds also vary with geography due to species adaptation. For example, in one epidemiology study in 15 European cities, the meta-analytic estimate of the temperature threshold for humans was 29.4°C in Mediterranean cities and 23.3°C in north-continental cities (Baccini et al., 2008). In this study, the change in natural mortality for a 1°C increase in maximum temperature above the local threshold was 3.12% (95% credibility interval = 0.60% to 5.72%) in the Mediterranean region and 1.84% (0.06% to 3.64%) in the north-continental region (Baccini et al., 2008). Climatological temperature ranges in Channel Islands National Park vary within short distances, as described in section 4.17. Figure 15 shows hot and cool zones within each island, which helps illustrate zones where species might have more difficulty adapting to change. This study's maximum and minimum temperature values were divided into 0.5°C increments based on various supporting information sources. For example, one study in Spain showed that, on average, temperature thresholds have increased at a rate of 0.57°C/decade and maximum temperatures in the summer have increased at a rate of 0.41°C/decade (López-Bueno et al., 2021). The results section (4.17) also illustrates areas with more moderate temperature zones, which might serve as climate refugia. Determining refugia depends on various factors in the literature review and results section.

Poleward and Equatorward Species Distributions

Anthropogenic climate change is driving changes to species distributions, manifesting in new species arriving at Channel Islands National Park, particularly from the tropics. For example, in 2019, the Tropical Brown Booby began nesting and breeding on Santa Barbara Island (NPS, 2019). This phenomenon signifies a northward expansion of their known breeding range and highlights the potential for current island species to reach thermal thresholds. Overall, climate change is driving poleward increases and equatorward declines in marine species (Hastings et al., 2020).

2.4 Climate-Affecting Criterion: Topographic Features

Elevation

Topography drives microclimate conditions within Channel Islands National Park due to highly varied terrain. Elevation shapes microclimate through adiabatic processes and exposure to wind and solar radiation, further modified by slope, aspect, and hillshade (Dobrowski, 2011). At high altitudes, negating other factors, air and soil temperatures are lower than at low altitudes. Oxygen availability is also lower as altitude increases, affecting the species that can survive under these conditions (Spence & Tingley, 2020). The highest elevation in Channel Islands National Park is on Santa Cruz Island at Diablo Peak (Devil's Peak), which is 753 m (2,470 ft). On San Miguel Island, the highest peak is San Miguel Hill at 253 m (830 ft); the highest peak on Santa Rosa is Vail Peak, at 475 m (1,560 ft); Anacapa Island's highest peak is Vela Peak on West Anacapa at 283 m (930 ft), and Santa Barbara's highest peak is Signal Peak at 194 m (635 ft) (Davidson et al., 2019). Distributions of flora and fauna, down to the microbial level, are affected by the frequency of direct sunlight and the frequency of enveloping fog blankets. These vary with elevation, so measurements of fog and irradiance, among other factors, at different elevations are crucial for understanding microclimate conditions in this region (Redmond & McCurdy, 2005).

Slope

Slope shape is among the most influential factors affecting natural vegetation and species richness. It determines the amount of received solar radiation, erosion rate, and groundwater content and alters soluble plant nutrients (Zhang et al., 2022a). In the northern hemisphere, the sun is positioned in the southern sky. Because of this, south-facing slopes receive more direct sunlight and are typically drier than north-facing slopes. In Channel Islands National Park, on south-facing slopes, water evaporates more quickly, and plants must adapt to warmer, sunnier, and drier conditions. Plants on north-facing slopes must be suited to cooler, shadier, and wetter conditions. Concave slopes are likely at lower elevations than nearby convex slopes. Concave slopes are also more likely to accumulate soil and moisture and are closer to the water table. Groundwater seeps and springs contain dissolved minerals which can enrich the soil. These surface characteristics create deep, moist, fertile soils and a more productive environment for vegetation (Talebi & Uijlenhoet, 2007). Convex slopes increase runoff and erosion by gravity, carrying water and soil down. Water that cannot soak into the soil drains rapidly, carrying some of the soluble plant nutrients, leaving the soil dry, shallow, and infertile. These processes create a challenging environment for plants to survive. Convex slopes are typically higher in elevation than nearby concave slopes, exposing them to wind and other atmospheric elements (Bilir, 2021).

Aspect

Differences in incoming solar radiation (SR) create a range of microclimates across adjacent north-facing and south-facing slopes in the mid-latitudes. The differences in incoming SR between adjacent slopes lead to differences in temperature, humidity, transpiration, and the amount of energy available for photosynthesis. In one study, tree water use was covarying across hillslopes; the transpiration of a single tree species was higher on the drier, sunnier, south-facing slope, suggesting the strategies for water use differ in these microclimates. Trees on south-facing slopes transpired 20 percent more water during the dry Mediterranean summer, and water use by varying slope aspects supported different relationships to environmental conditions (Bilir, 2021).

Hillshade

Hillshade is a crucial topographical feature that influences microclimate and is a valuable tool in predicting dieback in semi-arid regions like Channel Islands National Park. In several studies, hillshade was the most deterministic factor of soil moisture and forest growth (Murphy et al., 2009). The primary factor of the hillshade map for Channel Islands National Park is the location of the sun in the sky relative to the point of location; this determination relies on azimuth, the angular direction of the sun (0° to 360°), and altitude (0—on the horizon—to 90—overhead). In one study (Najafifar et al., 2019), a linear trend was found in the percentage of tree mortality and hillshade value, with lower values of hillshade (areas with more shade) showing less decline and higher values (areas with less shade) showing more decline. Ultimately, the hillshade map is the most accurate and significant topographic variable to display soil moisture variation, and including hillshade criteria will increase the accuracy and scope of analyzing future changes in ecosystem capacity as temperatures increase and climate shifts occur (Najafifar et al., 2019).

2.5 Climate-Affecting Criterion: Biogeographic Features

The next step in quantifying the micro-scale climate characteristics of Channel Islands National Park requires field measurements of the following biogeographic features; quantified changes in each variable, compared to shifts in microclimate conditions, can show the extent of each criterion's influence on the overall system. It can also determine which criteria significantly affect change, giving managers a more robust idea of where to allocate their resources and efforts. Although the results section in this study does not include field measurements of these biogeographic features, laying out the framework for this case study is a vital first step in micro-scale modeling. This section determines all known variables contributing to changing climate conditions in Channel Islands National Park and explains why and how they do so.

Soil Composition

Soil composition affects the local microclimate by influencing the humidity and air temperature through water retention and evaporation. Clay soils, for example, retain more water than sandy soils (loam and silt). Sands with low nutritional content and larger particles retain the least water. CINP soils are mainly expandable clays that swell when wet, shrink when dry, and create deep cracks in the surface. They are chemically rich in salinity and sodium from airborne sea spray (Halvorson, 1988). The soils mainly consist of Vertisols, Alfisols, and Mollisols with vertic properties (Muhs et al., 2008).

Because of the high clay content and location on steep slopes, CINP soils are very prone to erosion. Vegetated areas have soils with lower salinity than those found in eroded areas of the islands. Once native vegetation has been disturbed, soil management is often more complex. These highly erosive soils have undergone substantial anthropogenic disturbance, leading to denudation and rapid runoff (Muhs et al., 2008). The soil's coverage and depth also affect above and below-ground temperature, water retention, and above-ground humidity. Bare and light-colored soils reflect more solar radiation than darker or mossy soils. Soil composition also affects the amount of carbon that can be stored in the soil, contributing to the amount of carbon dioxide in the atmosphere. Decreased soil carbon may raise greenhouse gas levels in the atmosphere, thus contributing to climate change (Xiao, 2010).

Soil Hydrologic Content

The amount of available soil moisture has consequences for sustainable ecosystem functions. At the micro-scale, soil moisture affects soil biodiversity and function, including plant-microbe interactions, plant productivity, soil biogeochemical cycles, and soil carbon sequestration (Zhang et al., 2023). Soil moisture content affects soil temperature, which can affect air temperature, transferring heat to the air via convection. Similarly, air temperature can affect soil temperature. Another vital relationship, soil respiration (soil-to-atmosphere CO2 flux), is a significant component of the global carbon cycle and is strongly influenced by local soil temperature and water content. Air and soil temperature are strongly correlated and explain similar variability in soil respiration (Jian et al., 2021; Tang, 2023).

Land Cover

Land cover has affected local changes in weather patterns globally, both from natural and anthropogenic changes. Local weather, temperature, and precipitation, among other factors aggregated over many areas, can influence Earth's climate by altering regional and global circulation patterns, disrupting the Earth's albedo, and altering the CO2 budget in the atmosphere. Land cover losses have accrued significantly from climate-related disruptions, habitat loss, and species migration (Sleeter, 2018). Soil and vegetation are typically studied together as they are interdependent. However, an increasingly important relationship—that between vegetation and the water cycle—is increasingly studied in climate change and microclimate research. One study found that increasing vegetation cover for 45 percent of the planet can increase rainfall and water availability by recycling water between vegetation and the atmosphere by evapotranspiration (Ciu et al., 2021). Therefore, reforestation and afforestation should be considered partial efforts to achieve sustainable development goals and improve water quality and security (Ciu et al., 2021).

Thermal Mass and Heat Capacity

Heat can be stored and delivered as sensible or latent heat, effectuated by phase changes. The heat capacity of a substance affects the temperature of its surrounding environment (Clauser, 2014). Thermal mass refers to a material's ability to absorb, store, and release radiant heat. Thermal mass typically refers to urban environments, mainly residential and commercial buildings or cities with major structures and excessive use of concrete and other humanmade materials (Kuczyński & Staszczuk, 2020; Reilly & Kinnane, 2017). However, thermal mass is also a consideration for climate conditions in natural landscapes. For example, water has a high capacity to absorb and store heat and is a 'high thermal mass' material. Varying temperatures relative to specific geological features can be measured to determine thermal mass. In recent scientific literature, thermal conditions vary tremendously within landscapes relative to specific wildlife species (Weiskopf et al., 2020).

Cold Air Drainage

Radiative cooling typically occurs at night and builds cold air near the surface, draining into valleys. This process creates cold air pools that collect at the valley bottom. A clear sky is the best indicator of cold pooling conditions on nights with low wind speed and cloud cover. Down-valley drainage flows dominate these cold pool valleys, creating significant temperature differences that can substantially affect the local climate. Valley size and geometry influence the daytime valley flow and affect whether it is coupled to the ambient flow or directed down the valley. This process is essential because night temperatures can impact vegetation growth and ecosystem function (Jemmett-Smith et al., 2018). At night, local temperature can become suppressed by several degrees and for several hours before and after sunset due to cold air drainage into valleys. This phenomenon can lead to an increase in growing season and annual net carbon uptake by >10% and >15%, respectively, from microclimate effects that regional-scale and global-scale terrestrial ecosystem models do not typically represent (Novick, 2016).

Proximity to Water

Proximity to large bodies of water like oceans, seas, lakes, and rivers greatly regulates local climate. The ocean's high heat capacity creates a more moderate climate around the coastal and island ecosystems, creating a smaller temperature range than inland regions (IPCC, 2021). In one case study in India, an analysis of the temporal and spatial variation of the water body cooling effect shows a statistically significant cooling effect in proximity to large bodies of water (Gupta et al., 2019). Subsequently, the cooling effect of water bodies in summer is stronger in the afternoon than in the morning, reaching the highest rate from 12:00 to 15:00 (Cheng et al., 2022). Other facts affect cooling as well. Cooling range and intensity decrease with the increase in distance, but on the other hand, wind speed also constitutes an essential factor influencing the overall cooling effect (Cheng et al., 2022). Relative to coastal California, air temperature has a high covariance with SST (Adkins, 2023). This relationship illustrates the coupled ocean-atmosphere interaction and provides CINP with a climate 'buffer' relative to inland and larger land mass geographies.

Water Availability

Due to its high heat capacity, water has a tremendous regulatory effect on the local climate. All life forms use water to carry nutrients, filter waste, and break down food. It also helps keep organisms cool, among other vital processes. Vegetation-atmosphere-water cycle interactions will evolve with future climate change, and quantifying these fluxes can provide insight into ecosystem vulnerability. Without proper water infiltration and storage, soil on the Channel Islands can become dryer, leading to further air and surface warming and increased ecological die-off (IPCC, 2021). Because CINP has a semi-arid landscape and climate, its groundwater is primarily recharged slowly by precipitation through the unsaturated zone (de Vries & Simmers, 2002; Stone & Edmunds, 2016; Cheng et al., 2021), and by atmospheric water from fog and clouds, particularly in the dry season from May through September (Fischer et al., 2009).

A rock-matrix permeability study on Santa Rosa Island showed trends between surface-water occurrence and different rock types and geologic structures (Schmidt & Minor, 2022). Lower and intermediate averaged permeabilities were found in volcanic rocks and intact, indurated sandstones and shale, correlating with a more continuous presence of surface water. Intermediate to higher averaged permeabilities were found in similar rock types. However, secondary fractures induced by tectonic and topographic stresses had little correlation with surface water, leading to generally dry valley floors. Faults with clay-rich, sheared, and comminuted cores exhibited low averaged permeability, whereas adjacent damage zones containing fractured rock exhibited intermediate to higher permeabilities. Beyond the damage zones, non-fractured rock protoliths generally express lower permeability (Schmidt & Minor, 2022). Observations throughout the island reveal that water presence correlates with the contacts between adjacent units, which forces groundwater to the surface, and the bedding orientation of bedrock (Schmidt & Minor, 2022). Along with a greater understanding of how the water cycle is affected by climate change, this knowledge could benefit vegetation restoration strategies. These water-limited ecosystems rely on surface water; thus, mapped geology can infer permeability and locate water-stressed and vulnerable or resilient areas within the CINP boundary.

2.6 Climate-Affecting Criterion: Physical Climate Conditions

There is variation in climate across the five islands within the CINP boundary (Adkins, 2023). Additionally, each island possesses microclimates throughout, varying with proximity to the sea, protection from the wind, vegetation, soil type, water content, and topographic features such as elevation, slope, hillshade, and aspect, among others (Redmond & McCurdy, 2005). As such, physical conditions manifest both global and local climate processes and feedback loops, and understanding each variable's relative influence on the overall climate system can provide a 'whole picture' approach. The various components of the climate system differ in composition; however, physical properties, chemical properties, structure, and behavior are all linked by mass fluxes, heat, and momentum, and all subsystems are interrelated (Baede et al., 2018). This section covers the physical conditions and influences on climate for this region: air temperature, precipitation, albedo, solar radiation and irradiance, wind speed, wind direction, Santa Ana winds, humidity, evaporation, evapotranspiration, atmospheric water vapor, cloud cover, and fog inundation.

Air Temperature

Temperature is the most deterministic feature of climatic conditions because it measures the overall energy flux at a specific location, which the inputs from all other variables have driven (Baede et al., 2018). The sea mainly controls air temperature in the Channel Islands region, leading to minor diurnal differences with cool days and relatively warm nights (Yoho et al., 1999). In the outer coastal regions, the lowest monthly mean climatological temperatures occur in February and the warmest in September. For the inner coastal waters, the coldest month is January, and the warmest is August. These differences are attributed to marine influences; there is a lag time from ocean water's slower cooling and warming compared to land areas. The average temperature difference over the ocean between the warmest and coldest months in this region is ~4°C (Yoho et al., 1999). The dominant annual climatic control is the Pacific Subtropical Anticyclone. In summer, this cell becomes stronger and migrates north, affecting the west coast with its eastern edge. At approximately 600m, the air is heated by compression due to subsidence, which creates a temperature inversion in this region. Another temperature inversion is created near the surface from cold water along the coast flowing southward. The coupling of these inversions creates a stable environment during the summer, preventing precipitation.

Precipitation

Precipitation is an important indicator of overall climatic conditions and ecosystem health. Rainfall affects the amount of surface water and groundwater available for drinking and irrigation and is essential for river flow; all these factors influence the type of flora and fauna in each area and determine their survival (Levine et al., 2008). In the Channel Islands region, most precipitation occurs in winter, with average climatological pre-industrial values between 150-360mm (Yoho et al., 1999). However, precipitation values vary for individual islands (Adkins, 2023). Summer precipitation occurs occasionally due to moist maritime subtropical air from the Gulf of California and from tropical storms straying from their usual path. November through April months receive 95 percent of the rainfall in this zone, and the distribution of average annual rainfall varies from north to south (Yoho et al., 1999). Spatial plots showing the location of precipitation in the northern Channel Islands can be found in section 4.8, Figure 7A, and temporal plots showing precipitation values on each island can be found in section 4.8, Figure 7B.

Monthly, yearly, and seasonal variations in precipitation influence the formation of different flora and fauna (Pathan et al., 2021). Additionally, deviations from normal precipitation values can disrupt many natural processes, mainly if changes occur more rapidly than species can adapt (NOAA, 2022). Coupled physical processes like precipitation and air temperature must be evaluated on the micro-scale to evaluate species' vulnerability to climate change in this region. Microclimates are listed in sections 4.15-4.16, using annual average precipitation and temperature variations to define the climatological differences within each island.

Sea Surface Temperature

Sea surface temperature (SST) can have a profound effect on global climate because the ocean interacts continuously with the atmosphere (IPCC, 2013), and because 71 percent of the planet's surface is covered by the ocean (Visbeck, 2018). Due to water's high heat capacity, it is estimated that over 91 percent of the excess heat energy affecting the earth's climate system is stored in the ocean (Lindsey & Dahlman, 2023; Levitus et al., 2012). In 2022, the year ended with the third consecutive anomalous La Niña winter in a row, but despite this influence, 2022 was still ranked the sixth-hottest SST year on record since 1854 (Johnson et al., 2023). Significant positive sea surface temperature anomalies can lead to a series of marine heatwaves in various parts of the world, like those that occurred in 2022 (Babcock et al., 2019; Huang et al., 2021; Oliver et al., 2021; Perkins-Kirkpatrick et al., 2019).

In addition to extreme heatwave events, increases in SST have led to increases in atmospheric water vapor over the world's oceans (IPCC, 2013). These water vapor increases produce heavy rain and snow, leading to changes in storm tracks, and contributing to drought in some areas (IPCC, 2013). In the western United States, large-scale changes in wind-driven vapor fluxes lead to changing precipitation patterns associated with atmospheric adjustments to strong ocean SST anomalies (Beaudin et al., 2023). SST increases can also lead to environmental and public health concerns, like longer growing seasons for seafood-contaminating bacteria, which can cause foodborne illness (Trtanj et al., 2016).

Relative Humidity and Atmospheric Water Vapor

Atmospheric water vapor is an essential climate variable because it directly affects the amount of available water for plant growth and photosynthesis (Chia & Lim, 2022). According to the Clausius–Clapeyron equation, air can hold ~7 percent more moisture for every 1°C temperature rise. So, moisture content must increase at the same rate for relative humidity to stay the same. In the real world, this perfect rate of increase is not occurring, and relative humidity in most areas is decreasing due to the lag between ocean warming and warming over land. The slower rate of evaporation over the ocean creates a saturation deficit. However, relative humidity is increasing in some areas—like India, and in some high-latitude regions (Willett, 2020). There are implications for these changes at both global and local scales. Increasing water vapor increases the positive feedback of warming, as increased water vapor plays a critical role in global warming as a greenhouse gas. Higher levels of water vapor in the atmosphere also lead to more rainfall—particularly during heavy rainfall events. Higher humidity can also raise the risk of heat stress on warmer days, exacerbating the thermal thresholds of already at-risk species. Decreased amounts of atmospheric water vapor can lead to other issues as well. Some plant species will need to adapt to changes to avoid moisture loss—for example, when plants close their stomata. In dryer conditions, there is also an increased risk of wildfire frequency and intensity (Willett, 2020).

Channel Islands terrestrial ecosystems have unique climate characteristics because of their proximity to the ocean. It is essential to compare global humidity trends to climatological values for the Channel Islands National Park to understand this region's risks more clearly. Diurnally, relative humidity in and around the Channel Islands varies. In the Channel Islands region, due to moist ocean air, the relative humidity at night and in the early morning is generally high—around 90 percent, often reaching 100 percent when temperatures are the lowest—and decreases slightly during the day because of solar radiation (Yoho et al., 1999). Afternoon relative humidity drops to about 60 percent, on average (Kimura, 1974), and lower readings occur during Santa Ana Wind episodes in the fall and winter months (Yoho et al., 1999).

Albedo

Surface albedo, the amount of incident short-wave solar energy reflected by the surface, varies by land cover and is also sensitive to factors like atmospheric and cloud conditions, soil, vegetation, topography, diurnal asymmetry, and spatial resolution. Lighter surfaces like sand, ocean-breaking waves, and ship wakes can increase albedo. Ocean water albedo is a function of sun glint, whitecaps, and water-leaving reflectance. Generally, the ocean surface presents a lower albedo than the surrounding terrestrial landscape due to its darker surface. Although higher surface albedo results from drier, lighter soils after vegetation damage from overgrazing, denuded surfaces show positive climate feedback loops at higher temperatures than vegetated surfaces because of the soil's thermal effect (Zhang et al., 2022b).

Solar Radiation and Irradiance

Solar radiation and wind speed are two main factors affecting thermal environments (Yanyan et al., 2022). The radiation output from the sun is constant at 1380 watts per square meter (W/m2). However, the value that is received by the earth depends on how much of that energy is reflected or intercepted by clouds, land cover, and the earth's surface. The amount of incoming solar radiation substantially affects local microclimate conditions. The solar insolation value, or the amount of energy absorbed by the earth's surface, also depends on the time of year and the time of day being measured due to the changing zenith angle of the sun. Channel Islands National Park (34.013787°N, -119.74982°W) with a fixed angle (horizontal, 0°) and fixed azimuth angle (south-facing, 180°), receives an average solar irradiance of 5.56 kWh/m2/day with monthly averages lowest in December (2.91 kWh/m2/day) and highest in June (June: 7.85 kWh/m2/day).

Wind Speed

Understanding future global terrestrial near-surface wind speed (NSWS) changes for specific global warming scenarios is essential for adaptation to climate change. Cold temperatures at the poles meet warm temperatures in the tropics and drive wind, and global climate trends show that these temperature differences are weakening in the northern hemisphere (McMonigal et al., 2023). The Arctic is warming faster than the tropics, therefore reducing the strength of the gradient between hot and cold air, thus reducing wind speed in this region (Rantanen et al., 2022).

Model projections show that NSWS will decrease over the northern hemisphere in mid-to-high latitudes and increase over the southern hemisphere as global warming increases by 1.5°C-4.0°C relative to preindustrial levels (Zha et al., 2021). NSWS changes are more significant as global warming levels increase. Compared to 1.5°C global warming, the NSWS is projected to decrease by -0.066 m s^{-1} over the northern hemisphere and increase by +0.065 m s^{-1} over the southern hemisphere with 4°C warming. These changes are especially significant in East Asia and South America, which reach -0.21 m s^{-1} and +0.093 m s^{-1}, respectively (Zha et al., 2021). Changes in temperature gradients induced by global warming could be the primary factor causing the NSWS changes. Intensified global warming induces the reduction in Hadley, Ferrell, and Polar cells over the northern hemisphere. The strengthening of the Hadley cell over the southern hemisphere could be another determinant of asymmetric changes in near-surface wind speed between the two hemispheres (Jinlin et al., 2021).

On the micro level, when the wind blows across bare soil or vegetation, friction with the surface always slows down the wind. The slowing down causes the air just above the soil to form a relatively still layer known as the boundary layer. The friction is severe enough that the air is almost static within a few millimeters of the soil surface. This process leads to manifestations of higher wind speeds with increased height from the surface (Burgess et al., 2016). These macro and micro changes in wind speed can drive temperature differences and vegetation patterns, and affect wildfire conditions within the CINP boundary. Nearby marine air reduces the temporal variation associated with local heat fluxes. Because the marine air is not typically calm in this region, the wind creates more movement of air that cannot build up as much heat over time. On sunny days when the wind calms, there are more local spatial and temporal temperature variations. The ocean's high heat capacity relatively insulates the islands, so this region's temperature does not span a sizeable absolute range. The presence of land causes the observed temperature range to be larger because land heats and cools more rapidly than ocean water (Redmond & McCurdy, 2005).

In the Santa Barbara Channel north of Del Norte between December 1999 and October 2004, 'calm' wind speeds, between 0 and 1 mph, were reported only 2.8 percent of the time, while wind speeds between 0 and 4 mph were recorded 62.3 percent of the time (Redmond & McCurdy, 2005). In the same period on the north side of Santa Cruz, 'calm' wind speeds were reported 7.6 percent of the time, while wind speeds between 0 and 4 mph were recorded 18.7 percent of the time. This data indicates a much higher incidence of 'calm' winds over land than winds over the ocean. The annual wind speed in the Santa Barbara Channel north of Del Norte is 9.8 mph, while at Del Norte, the average annual wind speed is only 4.1 mph (Redmond & McCurdy, 2005).

Wind Direction

Regional wind patterns are highly diverse, especially in this region, due to the bend in the coastline at Point Conception, where the Santa Barbara channel meets the Pacific Ocean, and the coast turns northward. In this region, there is a flow separation point and a large eddy in the airflow during the summer in the north wind regime (Redmond & McCurdy, 2005). These geographic differences often lead to substantially different wind conditions for Anacapa and San Miguel islands.

The typical wind regime along the coast of California is southerly in the winter and northerly in the summer (Redmond & McCurdy, 2005) because of the subtropical high-pressure system in the eastern Pacific to the west of San Francisco. Wind records on Santa Rosa Island show that the wind typically blows out of the northwest in the summer and southeast in winter (Redmond & McCurdy, 2005). In late spring and early summer, the Catalina Eddy, which brings May Gray and June Gloom, occurs when an area of low pressure, or a thermal low, develops over inland deserts because of surface heating and meets high-pressure systems from the eastern Pacific Ocean. The Catalina Eddy produces a north-northwesterly wind flow down the California coast and interacts with the islands (Mass & Albright, 1989).

Santa Ana Winds

A temperature difference between cooler air over inland California and warmer air over the Pacific Ocean creates a pressure gradient in autumn and winter. This gradient produces the hot and dry Santa Ana winds, which blow from the east and follow the coastal mountain ranges (Conil & Hall, 2006; Hughes & Hall, 2010). Occasionally, offshore Santa Ana winds can bring very warm temperatures from the land to the islands. Santa Barbara Island has recorded temperatures as high as 105°F (40.6°C), and the Main Ranch on Santa Cruz has recorded 109°F (42.8°C). The Sundowner is the Santa Ana wind analog in this area, located near Santa Barbara. An extremely anomalous warm Sundowner was recorded in 1859, with overnight temperatures so warm that fishermen burned their skin at night in the Santa Barbara Channel (Redmond & McCurdy, 2005).

Santa Ana Winds are the primary weather drivers of wildfires that frequently devastate Southern California and Channel Islands National Park (Guzman-Morales et al., 2018). For southern California, models project a decrease in the frequency, but not the intensity, of the hot Santa Ana winds (Hughes et al., 2011; Pierce et al., 2018; Guzman-Morales et al., 2019). The frequency is projected to decrease as much as one-fifth under medium emissions (IPCC, 2007) by 2050 (Hughes et al., 2011). This change is due to a potential weakening of the desert air and ocean air temperature gradient, resulting in a decrease in a southwestward pressure gradient force that drives these winds. The most pronounced projections are reductions in early fall and late spring and the shoulders of the SAW season (Guzman-Morales et al., 2019). Decreasing frequency of Santa Ana Winds could lead to further warming and increased wildfire risk over the Channel Islands.

Evapotranspiration

Terrestrial ecosystems face significant consequences due to the acceleration of the global water cycle with increased warming. Rising temperatures cause the rate and amount of ocean evaporation to increase, and precipitation increases over areas with more vegetation (ICM, 2022). Simultaneously, areas with little or no vegetation are becoming dryer. This phenomenon is linked to the biological relationship between land and atmosphere, where water recycling becomes cyclical. Vegetation encourages more precipitation by collecting moisture from the air and drawing it out of the ground, and then recycling it into the atmosphere again, where it can fall as rain (Yu et al., 2017). A study in the Sahel desert of Africa (Yu et al., 2017) showed amplified regional moisture recycling due to positive vegetation-rainfall processes. Heat and moisture fluxes significantly correlate with vegetation cover, including weakened lapse rate, higher surface pressure, and anomalous lower-tropospheric to mid-tropospheric subsidence, supporting an active stability mechanism between these climate drivers (Yu et al., 2017).

Evapotranspiration is an essential element of the water cycle and, therefore, pertinent to maintaining ecosystem function. The most significant amount of actual ET occurs on San Miguel Island; the lowest is on Anacapa Island. The SPEI 1-month totals show the number of months in a year with a Standardized Precipitation-Evaporation Index (SPEI) <= -1. The SPEI depicts the combined impacts of precipitation deficits and potential evapotranspiration on soil moisture. The observed baseline average between 1961-1990 shows the annual SPEI average of 0.4 months within the park's boundary. By mid-century (2035-2064) for the RCP 4.5 scenario, projections show a statistically significant increase in SPEI of +2.9 months on average, and for the RCP 8.5 scenario, an increase of +3.8 months on average. By the end of the century (2070-2099), projections show +4.1 months, on average, for the RCP 4.5 scenario and +7.0 months, on average, for the RCP 8.5 scenario (Pierce et al., 2018).

Cloud Cover and Fog Inundation

Cloud cover and fog inundation modulate radiation, temperature, water availability, carbon budgets, and forest and vegetation distributions on the Channel Islands (Still et al., 2015). Spatial variations in cloud cover and fog immersion have been shown to drive significant changes in modeled water budgets and correspond closely to patterns of tree growth and mortality on the Islands (Yu, et al., 2017). The source of fresh water evaporated from the ocean's surface can be delivered to the terrestrial ecosystem to provide water inputs and reduce drought severity. Frequent cloud cover near the coast also reduces evapotranspiration relative to inland sites by nearly 25 percent, which can delay the onset of, and moderate the severity of annual summer droughts (Fischer et al., 2006)

Fog is a vital ecosystem driver on the islands; the interaction between fog and vegetation is an important relationship here, mainly because more water is delivered via fog than via precipitation in the summer months (Fischer & Still, 2007; Fischer et al., 2016). Low cloud cover and fog are significant drivers of vegetation growth, phenology, species distribution, interspecific competition, nutrient cycling, and wildfires

(Manzoni et al., 2012; Carbone et al., 2013; Emery et al., 2018; Lawson et al., 2018). Fog affects entities in the system like trees and vegetation and processes like how water moves through the system. Low clouds and fog can mitigate water deficits during the regular dry season in Mediterranean climates. These factors can substantially impact ecosystem function even in areas with insignificant fog and low cloud coverage (Breshears et al., 2008; Vasey et al., 2012; Clemesha et al., 2021).

Vegetation on the islands is greatly affected by fog reduction. For example, bishop pine distribution is changing because of disappearing fog over the islands (Carbone et al., 2012), and Coyote brush is a nurse plant for oaks; it collects fog and waters the ground so the oaks can grow (Brennan et al., 2018). Pines grow more in years with more precipitation but even more in years with more fog. This phenomenon is a positive feedback loop: if there is no fog, the plants cannot grow, but there must be plants to achieve more fog (Torben et al., 2014).

2.7 Land-Atmosphere-Ocean Interactions and Feedback Loops

Microclimatic factors affect macroclimatic conditions, but it is still undetermined how large-scale restoration projects that alter land characteristics affect local land-atmosphere exchanges of energy and water, mainly because few projects of relevant scope and scale have been completed or reported in the literature in recent decades. In one case study over the Loess Plateau in the Northwestern region of China, scientists found that increasing vegetation and reducing erosion, among other large-scale restoration practices, led to a significant increase in rainfall in the local region. Quantitatively evaluating this feedback can provide further context for climate-smart adaptation planning (Zhang et al., 2021).

Macroclimatic conditions affect local ecosystems, and the aggregated microclimatic conditions of local ecosystems affect the conditions of the macroclimate (IPCC, 2021). This phenomenon provides context for understanding chemical, physical, and biological processes on different temporal and spatial scales. It highlights the need to analyze and understand specific climate-forcing feedback loops generated by isolated or group variables. These interdependent relationships manifest in unexpected ways. For example, changes in sea surface temperature can provide a basis for predicting changes in the greenness of terrestrial ecosystems at seasonal to intra-seasonal scales. The most substantial impacts of SSTs on the Enhanced Vegetation Index (EVI) were identified over arid or semi-arid tropical regions and regions covered mainly by sparse vegetation (Yan et al., 2019).

Feedback Loops Between Sea Surface Temperature and Cloud Cover

The relationship between convective cloud area percentage, or Cloud Cover (CLC), and SST is complex because multiple processes influence it. This relationship can be summarized in three parts: temperature inversion, cloud albedo effect, and cloud feedback. Low clouds form in regions with a stable temperature inversion by which air temperature increases, rather than decreases, with height (Klein et al., 2017). This inversion is often created by the difference in SST and air temperature, whereby SST convectively cools the air directly above it while the air aloft is warmer (Iacobellis & Cayan, 2013).

Cloud coverage affects air temperature and SST because clouds have a high albedo; they reflect incoming solar radiation into space rather than allowing the Earth's surface to absorb it. The amount of solar radiation reflected to space exceeds the amount of IR trapped by low clouds, causing a net cooling effect. Cloud feedbacks occur because changes in SST influence the properties of low clouds, and conversely, changes in low clouds can impact SST. Warmer SST can lead to increased ocean evaporation, increasing the lower atmosphere's moisture content. Increased air moisture can lead to enhanced low cloud formation if other conditions are favorable. Conversely, if low clouds become thicker or more extensive, they can reduce the amount of sunlight reaching the ocean surface, causing cooling and potentially impacting SST (Graham, 1999).

Several other processes, like atmospheric circulation patterns, wind speed, humidity, and aerosol concentrations, influence the relationship between low cloud formation and SST. These processes can modulate cloud formation and dynamics, increasing the complexity of the relationship between low clouds and SST. Quantifying interactions between low clouds and SST can play a crucial role in climate modeling, predicting climate change, and understanding the mechanisms of specific climate-driven and climate-altering feedback loops (Stephens, 2005).

Feedback Loops Between Sea Surface Temperature and Air Temperature

The relationship between SST and air temperature is paramount, especially in coastal and island regions where air masses interact with the ocean's surface (Mass et al., 2022). SST influences air temperature and vice versa due to the exchange of heat and moisture between the ocean and the atmosphere (Mass et al., 2022). SST can influence weather patterns like atmospheric circulation and other weather systems. Temperature differences between the ocean and adjacent land masses can contribute to forming sea breezes, which bring cooler air from the ocean toward the land during the day (Miller et al., 2003). These local wind patterns impact local air temperature, and understanding their relationship is crucial for studying climate and assessing the impacts of climate change in this region. For example, the westernmost point on San Miguel Island benefits from the cool California Current, leading to milder SST and milder air temperatures. At the same time, the warm Southern California countercurrent contributes to the warmer climate along the easternmost and southernmost islands of Anacapa and Santa Barbara (Muhs et al., 2014).

Feedback Loops Between the Terrestrial Biosphere and the Water Cycle

One important positive climate feedback loop involves interactions between ocean evaporation, atmospheric water vapor, and the water cycle of the terrestrial biosphere (Green et al., 2017). As the water cycle speeds up, areas with high water content are significantly affected. This can lead to more frequent and intense precipitation events over some CINP regions. Without implementing climate-smart land management, erosion and nutrient runoff risks remain high (NOAA, 2009).

Global warming increases the amount of water vapor in the air from increased evaporation, which leads to further warming. Water vapor acts as a greenhouse gas; it traps heat from escaping the atmosphere and continuously sends longwave radiation back to the Earth's surface, leading to further warming (Buis, 2022). Natural seasonal variability and terrestrial vegetation abundance can modulate water and energy fluctuations in the atmosphere, thus affecting the climatic conditions that consequently regulate vegetation dynamics (Green et al., 2017). Feedback loops between the biosphere and atmosphere are widespread and regionally intense, affecting up to 30 percent of regional precipitation and surface radiation variance. In moderately wet regions and the Mediterranean, substantial biosphere-radiation feedback loops are present, such that precipitation and radiation increase vegetation growth. This growth is accompanied by latent and sensible heat transfer from vegetation, which affects cloudiness and incident surface radiation due to increased boundary layer height and greater convection. In optimal conditions, increased evapotranspiration can increase moist convection, leading to increased precipitation (Green et al., 2017).

3 Methods and Materials

3.1 Study Area

The Northern region of California's Channel Islands, or Channel Islands National Park, was chosen based on current research gaps, data availability and access, stakeholder interest, and significance of the issue. The Nature Conservancy (TNC) Islands team and the National Park Service (NPS) are interested in assessing climate change vulnerabilities and thresholds of adaptive capacity to include in their conservation management plan for the islands. NPS owns most of the Channel Islands National Park; the rest is partially TNC-owned land.

3.2 Data Analysis Methods

The research uses fine-resolution global climate models (GCMs) and other historical climate data to analyze local climate conditions. The report relies on historical and projected climate analyses from various data sources—it combines statistical downscaling methods, spatial analysis, Empirical Orthogonal Function (EOF) analysis, and quantifying correlation coefficients between various datasets. The broad approach of the research synthesizes existing scientific literature. It incorporates case studies from successful global land-based projects aiming to manage landscapes and natural resources sustainably and maintain or reestablish biodiversity. The results section compares observed and downscaled time series variables from various model outputs and forcing scenarios. It finds correlations and variations between them, showing coherent and decoupled patterns among the island groups.

3.3 Statistical Methods Used in Mediterranean Climate Type Projections

The Hot-Summer Mediterranean Climate Type projection analysis focused on the end-of-century (2099) scenario for the most extreme climate scenario, RCP 8.5 (Representation Concentration Pathways = 8.5W/m2 of radiative forcing). Data was obtained from the CMIP5 multimodel ensemble (MME), a collection of 31 Global Circulation Models (GCMs) from the World Climate Research Programme. The criterion used to create the Mediterranean Climate zone projections was sourced from a Hydrology and Earth System Sciences publication, which identifies the Köppen-Geiger climate classifications for each climate zone (Peel et al., 2007). The parameters which define the climate type for Channel Islands National Park, a Hot-summer Mediterranean climate type, are as follows:

Csa = Hot-summer Mediterranean climate; the coldest month averaging above 0°C (32°F) (or -3°C (27°F)), at least one month's average temperature above 22°C (71.6°F), and at least four months temperature averaging above 10°C (50°F). At least three times as much precipitation exists in the wettest month of winter as in the driest month of summer, and the driest month of summer receives less than 40mm (1.6 in) of precipitation (Peel et al., 2007). Several spatial data layers were analyzed and summed in ArcGIS to define the hot-summer Mediterranean climate type. The process used temperature anomaly layers, added separately to the mean annual temperature baseline climatology layer to create the 2039 Mean Annual Temperature (RCP 8.5) and 2099 Mean Annual Temperature (RCP 8.5) layers. Twelve baseline monthly temperature layers were used (one for each month of the year), along with the Mediterranean baseline winter temperature, Mediterranean baseline summer temperature, driest summer precipitation anomalies, and wettest winter precipitation anomalies. Using GIS statistical analysis, the data layers were parsed to the Csa criterion provided above, and the following layers were created: Mediterranean summer precipitation, Baseline Köppen Mediterranean Climate type, and 2099 Köppen Mediterranean climate type (RCP 8.5). The Mediterranean summer precipitation layer was created by combining the wettest winter precipitation layer with the driest. The Baseline Köppen Mediterranean Climate type layer was created by combining the Mediterranean summer precipitation layer, Mediterranean winter temperature baseline layer, and Mediterranean summer baseline layers. The 2099 Köppen Mediterranean climate type (RCP 8.5) was created by repeating this process with the same criteria for its datasets with RCP 8.5 projections for 2099. The final layers are illustrated in a geospatial plot in section 4.4.

3.4 Data Sources, Data Resolution, Grid Size, and Statistical Downscaling Techniques Used

This study uses multimodel ensemble simulations and historical data from CMIP6 and CMIP5, where applicable. The CMIP5 ensemble is used for local CINP climate analyses via the Cal-Adapt climate tool and in some spatial analyses. GHRSST data was used to assess the historical and projected changes and correlations between sea surface temperature (SST), air temperature, cloud coverage (CLC), precipitation (PPT), and soil moisture (SM). Digital Elevation Models (DEMs) were sourced from USGS, and four topographic features were analyzed for Channel Islands National Park: slope, aspect, elevation, and hillshade. The CMIP6 ensemble includes an average of over 50 GCMs and was the most recent ensemble of universal GCMs at the time of the completion of this study. The CMIP5 ensemble incorporates 40 GCMs from 20 climate modeling research groups globally. Parameter-elevation Regressions on Independent Slopes Model (PRISM) temperature and precipitation data are used for spatial analyses and compared to the GHRSST SST time series to find local climate correlations among these variables. Localized Constructed Analogs (LOCA) statistical methods were applied to many datasets listed. In some instances, it is more beneficial to analyze high-resolution data than the most up-to-date data, but combining these spatial and temporal features is essential for accurately assessing high-resolution climate conditions while retaining high confidence and time relevance.

In some instances, statistically downscaled GCM data was used. This data was transformed from the relatively coarse-resolution original GCM grid to a finer resolution. The finer resolution (100 m-800 m) regional grid data used in this analysis incorporates information about topography and land surface (Pierce et al., 2018). in some instances, very high-resolution gridded data was unavailable, and more coarse resolutions were substituted. Often, the decision was made to use coarser, more up-to-date data, and in other instances, finer resolutions were substituted for coarser, newer datasets. The methodologies used depended on the goals of the individual analyses. Table 1 shows the data used in the study: each variable, its application, grid resolution, time span, sample period, and sources.

Table 1. Data sources, variables, grid resolution, time span, sample period, and applications within the various sections of the text.

Variable	Application(s)	Description	Grid Resolution	Time Span	Sample Period	Source
Baseline Air Temperature	Section 4.3 (Figure 2A)	Mean Annual Baseline Temperature to Compare to CMIP5 Projections	1.0-deg, annual	1986–2005	Baseline	https://climate-knowledge portal.worldbank.org/cmip5
2039 Air Temperature (RCP 8.5)	Section 4.3 (Figure 2B)	CMIP5 Multimodel Ensemble (MME) mid-century RCP 8.5 climate projection	1.0-deg, annual	2020-2039	2039	https://climate-knowledge portal.worldbank.org/cmip5
2099 Air Temperature (RCP 8.5)	Section 4.3 (Figure 2C)	CMIP5 Multimodel Ensemble (MME) end-of-century RCP 8.5 climate projection	1.0-deg, annual	2080-2099	2099	https://climate-knowledge portal.worldbank.org/cmip5
Baseline Mediterranean Climate Type	Section 4.4 (Figure 3A, 3B)	Layer created in GIS using historical precipitation and air temperature climate data	1.0-deg, annual	1986–2005	Baseline	https://climate-knowledge portal.worldbank.org/cmip5
2099 Mediterranean Climate Type (RCP 8.5)	Section 4.4 (Figure 3A, 3B)	Layer created in GIS using CMIP5 Multimodel Ensemble (MME) end-of-century RCP 8.5 precipitation and air temperature projections	1.0-deg, annual	2080-2099	2099	https://climate-knowledge portal.worldbank.org/cmip5
Sea Surface Temperature (SST)	Section 4.6 (Figure 5)	High resolution gridded spatial SST (NASA)	0.1-deg, weekly	2016-2023	2016-2023	https://podaac.jpl.nasa.gov/dataset/CMC0.1deg-CMC-L4-GLOB-v3.0
Sea Surface Temperature (SST)	Sections 4.5 (Figures 4A, 4B), 4.18 (Figures 16A-E, 18A-B)	Lower resolution gridded spatial SST (NASA)	0.25-deg, daily	1995-2020	2012-2016, 2002-2016, 2003-2020, 1995-2020	https://podaac.jpl.nasa.gov/dataset/MUR25-JPL-L4-GLOB-v04.2
Maximum Annual Air Temperature (tmax)	Section 4.17 (Figure 15)	Maximum Air Temperature Climatology (30-year normal)	800m, annual	1895-2023	1895-2023	https://prism.oregon state.edu
Minimum Annual Air Temperature (tmin)	Section 4.17 (Figure 15)	Minimum Air Temperature Climatology (30-year normal)	800m, annual	1895-2023	1895-2023	https://prism.oregon state.edu
Mean Annual Air Temperature (tmean)	Sections 4.7 (Figure 6A), 4.14 (Figure 13), 4.15 (Table 4), 4.16 (Figure 14), 4.18 (Figures 16A-E, 17A)	Mean Air Temperature Climatology (30-year normal)	800m, annual	1895-2023, 2003-2020	1991-2020	https://prism.oregon state.edu
Mean Monthly Air Temperature (tmean)	Section 4.7 (Figures 6B, 6C)	Monthly Mean Air Temp (30-year normal)	800m, monthly	1895-2023	1895-2023	https://prism.oregon state.edu
Mean Annual Precipitation (ppt)	Sections 4.8 (Figure 7A), 4.14 (Figure 13), 4.15 (Table 4), 4.16 (Figure 14)	Precipitation Climatology (30-year normal)	800m, annual	1895-2023	1991-2020	https://prism.oregon state.edu
Mean Monthly Precipitation (ppt)	Section 4.8 (Figure 7B)	Monthly Mean Precipitation (30-year normal)	800m, annual	1895-2023	1895-2023	https://prism.oregon state.edu
Coastal Low Cloudiness (CLC)	Section 4.18 (Figures 16A-E, 17A-B, 18A-B).	Geostationary Operational Environmental Satellite (GOES)	Half hourly, 4km	1996-2021	May-September, 1996-2021	Rachel Clemshaw. Scripps Institution of Oceanography, UCSD
Elevation	Section 4.9 (Figures 8-12)	USGS 3D Elevation Program (3DEP) Datasets from The National Map	1/9 arc-second (approximately 3m)	N/A	N/A	https://www.sciencebase.gov/catalog/folder/4f70a58ce4b058caae3f8ddb
Aspect	Section 4.9 (Figures 8-12)	Subgroup derived from Elevation (3DEP) Dataset, created in ArcGIS	1/9 arc-second (approximately 3m)	N/A	N/A	https://www.sciencebase.gov/catalog/folder/4f70a58ce4b058caae3f8ddb
Slope	Section 4.9 (Figures 8-12)	Subgroup derived from Elevation (3DEP) Dataset, created in ArcGIS	1/9 arc-second (approximately 3m)	N/A	N/A	https://www.sciencebase.gov/catalog/folder/4f70a58ce4b058caae3f8ddb
Hillshade	Section 4.9 (Figures 8-12)	Subgroup derived from Elevation (3DEP) Dataset, created in ArcGIS	1/9 arc-second (approximately 3m)	N/A	N/A	https://www.sciencebase.gov/catalog/folder/4f70a58ce4b058caae3f8ddb
Channel Islands National Marine Sanctuary (CINMS) Boundary	All Sections with Spatial Plots	Polygon for Channel Islands National Park and Marine Sanctuary Boundary and Surrounds	W° Bound: -120.64208 E° Bound: -118.90712 N° Bound: 34.20707 S° Bound: 33.36241	N/A	N/A (dataset Published in 2008)	https://www.fisheries.noaa.gov/inport/item/40040

4 Results: Overview

Overall, on various spatiotemporal scales, across different variables, there are variations in climate conditions across the Channel Island National Park region. Current climate models do not have the resolution to provide island-scale predictions. Thus, basic regional patterns are determined to comment on the probable effects when compared to large-scale, global shifts in climate. One of the most significant challenges of conservation and natural resource management is determining how large-scale changes will likely affect the spatial gradients in the following sections (4.6-4.8).

The Channel Islands' unique geography creates these spatial climate gradients, both oceanographically and meteorologically. The northern Channel Islands are located south of mainland California's Point Conception, about 50 km from the coast in the Santa Barbara Channel. Here, the southward-flowing California Current separates from the mainland and influences the two westernmost Islands: San Miguel and Santa Rosa. These two islands are in the path of the prevailing winds in summer, which favor upwelling. Alternatively, the eastern Islands of Santa Cruz and Anacapa are in the lee of Point Conception, thus shielding from the prevailing summer winds. Santa Cruz and Anacapa Islands are in the path of the Southern California Countercurrent, which brings warm water poleward along the coast (Fewings et al., 2015).

The macroscale gradients result from pressure and temperature differences converging with the Northern and Southern California currents. Warm air and ocean currents from the south (California Countercurrent) meet cooler air and currents from the north (California Current) in this region. As macroscale pressure and temperature gradients shift over time, mainly because of anthropogenic global warming, the frequency, intensity, and seasonality of equatorward coastal wind patterns are projected to shift, thus affecting the overall climate conditions of the Channel Islands (Wang et al., 2020).

Near-surface wind speed (NSWS) greatly influences atmospheric circulation and climate change (Shen et al., 2022). For this reason, it is crucial to compare the results in this section with the trends in equatorward coastal winds, which are expected to change at various global warming levels (GWL) in the Southern California Bight by the end of the century (Section 2.3: Global and Continental Climate Change Trends). While dissecting the results in the following sections, one should also consider changes to other global and regional patterns like the Santa Ana winds, the California Current system, and associated upwelling shifts which will affect local climate conditions (Section 2.3: Global and Continental Climate Change Trends, Section 2.6: Santa Ana Winds).

4.1 Analysis of Historical and Projected Physical Climate Conditions of Channel Islands National Park

The following air temperature and precipitation projections were assessed using 32 downscaled climate model projections from LOCA datasets generated to support California's Fourth Climate Change Assessment (Pierce et al., 2018). The data presented are aggregated over all LOCA grid cells that intersect with the Census Tract 6083980100 boundary for Channel Islands National Park. Historical data was derived from Gridded Observed Meteorological Data (Livneh et al., 2015) and previous climate assessments of Channel Islands National Park (Gonzalez, 2020; Easterling et al., 2017).

Historical Overview of Climate Change in Channel Islands National Park

Historically, the average yearly temperature within the park boundary has increased at a statistically significant rate of 1°C ± 0.2°C (1.8°F ± 0.4°F) per century between 1895 and 2017. For the same period, annual precipitation showed no statistically significant trend. Historical changes detected in the region include sea level rise of 10 ± 0.5 cm (4 ± 0.2 in) at Los Angeles from 1924 to 2019, sea surface temperature increase of 1.4°C ± 0.2°C (2.5°F ± 0.4°F) at Scripps Pier from 1916 to 2019, ocean acidity increase of 40 percent (-0.15 pH) off the Pacific coast since ca.1750, and dissolved oxygen reduction of 4% ± 1% in the northern Pacific Ocean from 1960 to 2010. Under the highest greenhouse gas emissions scenario from the Intergovernmental Panel on Climate Change, RCP 8.5, thirty-three climate models project an annual average temperature increase within the park boundary of 3.5°C ± 0.8°C (6.3°F ± 1.4°F) from 2000 to 2100 (Gonzalez, 2020).

Historical Air Temperature Values for Channel Islands National Park

For the period starting in 1895, temperatures increased on the islands at the highest rate in autumn, and for the period starting in 1950, temperatures increased at the highest rate in spring (Gonzalez, 2020). Since 1895, monthly temperatures have increased at statistically significant rates for six months, and since 1950, monthly temperatures have increased at statistically significant rates for five months of the year. Between 1895 and 2010, temperatures above 16ºC (61ºF) increased from zero to four months of the year. Temperature increases have been highest on Santa Barbara Island and the south shore of Santa Cruz Island. Temperature increases were lowest at high elevations, particularly on San Miguel Island and Santa Rosa Island (Gonzalez, 2020).

Projected Air Temperature Values for Channel Islands National Park

Temperature is the most deterministic feature of climatic conditions because it measures the overall energy flux at a specific location, driven by the inputs from all other variables. Historically, the observed average yearly temperature aggregated for Channel Islands National Park is 70.4°F (21.3°C) for the baseline from 1961 to 1990 (Pierce et al., 2018). By mid-century (2035-2064), for the RCP 4.5 scenario, temperature is projected to increase by +2.9°F, on average, with a mean range of 71.7°F to 74.6°F. For the RCP 8.5 scenario for the same period, temperature is projected to increase by +3.5°F, on average, with a mean range of 72.4°F to 75.1°F. By the end of the century (2070-2099), for the RCP 4.5 scenario, temperature is projected to increase by +3.8°F, on average, with a mean range of 72.7°F to 75.9°F. For the RCP 8.5 scenario for the same period, temperature is projected to increase by +6.3°F, on average, with a mean range of 74.7°F to 79.6°F. Extreme heat days are projected to increase under every scenario, ranging from an average of +6 days (RCP 4.5) and +7 days (RCP 8.5) by mid-century and an average of +9 days (RCP 4.5) and +19 days (RCP 8.5) by end-century (Pierce et al., 2018).

Historical Precipitation Values for Channel Islands National Park

The observed historical maximum 1-day precipitation for Channel Islands National Park boundary has been, on average, 1.321 inches from the 1961-1990 baseline. From the baseline (1961-1990) within the park's boundary, observed precipitation has recorded an average of 11.3 inches annually. The entire southwestern U.S. showed increases in extreme weather over the past century, with the amount of precipitation in 20-year events (a day with more precipitation than any other day in 20 years) increasing in all four seasons from 1948 to 2015 (Gonzalez, 2020; Easterling et al., 2017).

Projected Precipitation Values for Channel Islands National Park

By mid-century (2035-2064), the average increase in precipitation above baseline is projected to be +0.082" for the RCP 4.5 scenario and +0.090" for the RCP 8.5 scenario. By the end of the century (2070-2099), the average increases to +0.129" for the RCP 4.5 scenario and +0.202" for the RCP 8.5 scenario. On average, the observed historical maximum length of dry spell days is 165 days for the 1961-1990 baseline scenario. Projections within the park boundary show that by mid-century (2035-2064), the maximum length of dry spell days will increase, on average, by +9 days (RCP 4.5) and +8 days (RCP 8.5). By the end of the century, projections show +9 days (RCP 4.5) and +16 days (RCP 8.5). By mid-century, precipitation shows no significant changes, and by the end of the century (2077-2099), projections show an average increase of +0.2 inches (RCP 4.5) and +0.3 inches (RCP 8.5) (Pierce et al., 2018). Overall, Channel Islands National Park will receive a statistically insignificant increase in precipitation over the next several decades until 2100 under RCP 8.5 and 4.5 scenarios (Pierce et al., 2018). Within the park boundaries, the average annual precipitation will not change significantly in the next 50 to 75 years. However, precipitation will likely be delivered in more intense storms, and the wet season will have a shorter period (Pierce et al., 2018). There have already been impacts from a shift towards more extensive year-to-year fluctuations across California. For much of the state, wet years will become wetter, and dry years will become drier (Pierce et al., 2018).

4.2 Micro-, Topo-, Meso-, and Macroclimate Scales for CINP

Climatic observations and models are often grouped into spatial and temporal scales, typically based on the dimensions of the climate variations or processes they aim to represent. Generally, these groups are not precise; thus, there is much debate about their accuracy, resulting in widely varying definitions of what 'microclimate' is. For example, the World Meteorological Organization (WMO) identifies the microscale as <100 m spatial resolution, dependent on its application. Hence, the *microscale* definition is 'minutes for aviation, hours for agriculture, and days for climate description' (WMO, 2014). Microclimate is also described as 'the climate of an individual site or station characterized by rapid vertical and horizontal changes' (Geiger et al., 2009) and 'the layer of interface between the surface and atmosphere' (Barry & Blanken, 2016; Bramer et al., 2018). Here, the parameters defined for microclimate, mesoclimate, topoclimate, and macroclimate have been adopted from various scientific literature publications and distilled to incorporate the available data grid sizes. The table below defines climate scales to fit the criteria appropriate for the Channel Islands National Park study area. The value range includes horizontal, vertical, and time scales.

Table 2. A range of values classifying four different climatic groups: microclimate, topoclimate, mesoclimate, and macroclimate.

Climate Scale	Horizontal Scale	Vertical Scale	Time Scale
Microclimate	< 1 m to ~270 m	< 800 m	</> Minutes to Hours
Topoclimate	~10 m to ~10 km	<10 m to ~1.5 km	Minutes to Hours
Mesoclimate	~800 m to ~200 km	~500 m to ~4 km	Hours to Days
Macroclimate	> 200 km	~1 km to ~10 km	Days to Weeks

4.3 Macro- and Meso-scale Temperature Projections for CINP

This section uses CMIP5 multi-model ensemble (MME) data to show regional projections. Regional projections are mapped on three timelines: baseline (1986-2005), mid-century (2020-2039), and end-of-century (2080-2099) and global temperature distribution bar plots were included for each period, showing the global temperature distributions to compare to the Channel Islands region.

Section 4.3 illustrates a 1°C (1.8°F) increase in temperature from baseline, on the macro-scale by mid-century (2039) and a 3.5°C (6.3°F) increase in temperature, from baseline, on the macro-scale by end-of-century (2099) on a worst-case emissions scenario (RCP 8.5). The bar plots represent the distribution of global temperatures to compare, on each time scale, and highlight the warming "bracket" which the Channel Islands fall into relative to other areas globally. According to the IPCC, a world with 3°C warming would be catastrophic. This scenario leads to rising sea levels, desertification, more frequent and longer heatwaves, drought, increased intensity in natural disasters, wildfires, and a significant decline in natural resources, to name a few. As temperatures rise, climate feedback loops also intensify (IPCC, 2014). With this background information, the following plots highlight the necessary urgency for adaptation and mitigation in this region. These localized projections for Channel Islands National Park should be considered when analyzing the rest of the historical analyses in this study.

Figure 2. **(A)** Global and meso-scale (CINP) air temperature climatology, baseline greenhouse gas emissions scenario.

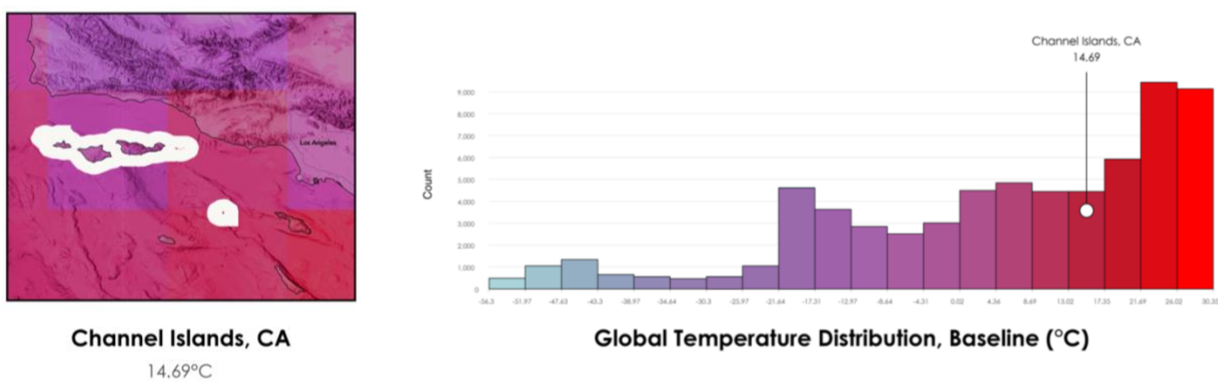


Figure 2. **(B)** Global and meso-scale (CINP) air temperature projections (2039), RCP 8.5 greenhouse gas emissions scenario.

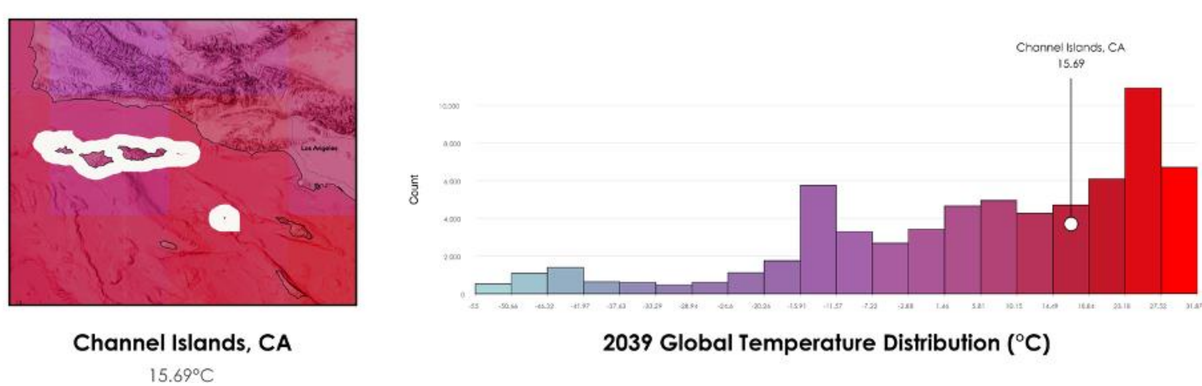
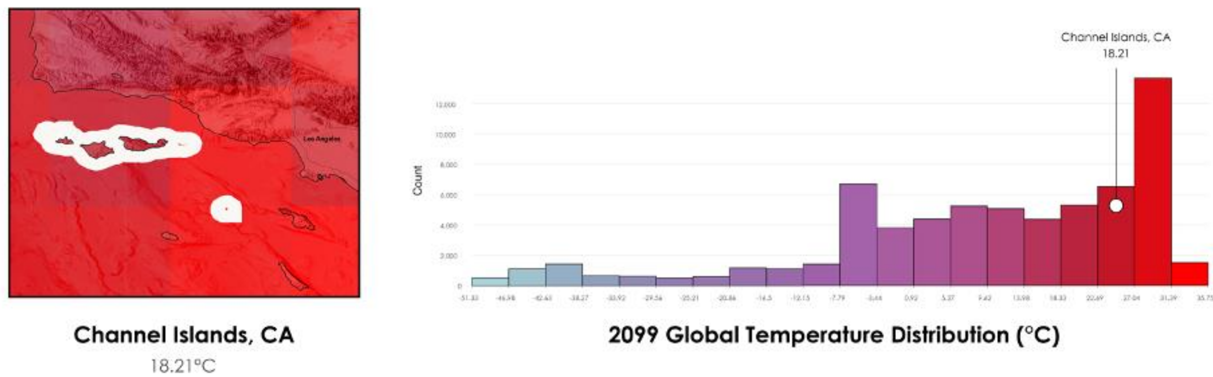


Figure 2. **(C)** Global and meso-scale (CINP) air temperature projections (2099), RCP 8.5 greenhouse gas emissions scenario.



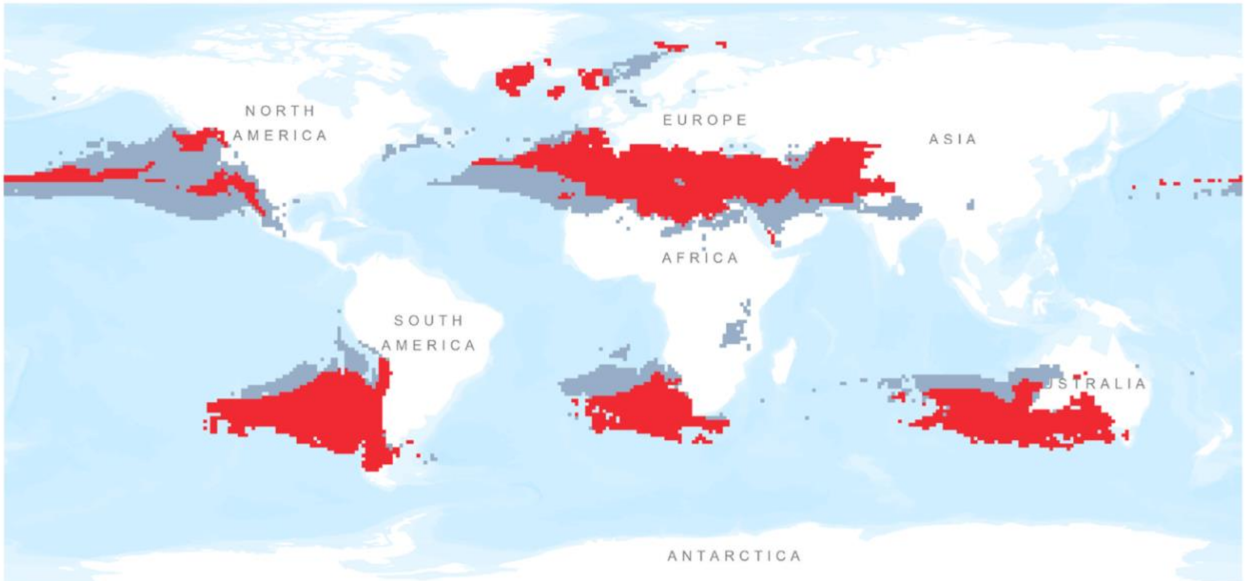
4.4 Macro- and Meso- Mediterranean Climate Type Projections

This section uses CMIP5 multi-model ensemble (MME) data to show the Mediterranean climate type projection over the region. Climate type was determined using the Köppen Mediterranean Climate Type criterion with baseline and projected air temperature anomalies and precipitation values. The full methodology for determining these climate zone shifts can be found in the Methods and Materials Section, 3.2. Regional and global projections are mapped on two timelines: baseline (1986-2005) and end-of-century (2080-2099). Under the RCP 8.5 climate forcing scenario, the arid climate zone is projected to increase by more than twice its present extent, leading to biodiversity threats within the Mediterranean climate zone (Barredo, 2018).

Section 4.4 illustrates the global and local projected changes over Channel Islands National Park by the end of the century (2099). Based on the Köppen Climate Classification System criterion, future projections indicate the Mediterranean Climate type will shift substantially by the end of the century on a worst-case emissions scenario (RCP 8.5). The changes in the spatial range of the Mediterranean climate type and the conversion of the current spatial range into an arid climate type could lead to substantial ecosystem impacts on the Channel Islands. The spatial data plots below show that the climate type not only shifts but also reduces in size, contracting by more than 50 percent in some areas, particularly in the western part of North America (Adkins, 2023).

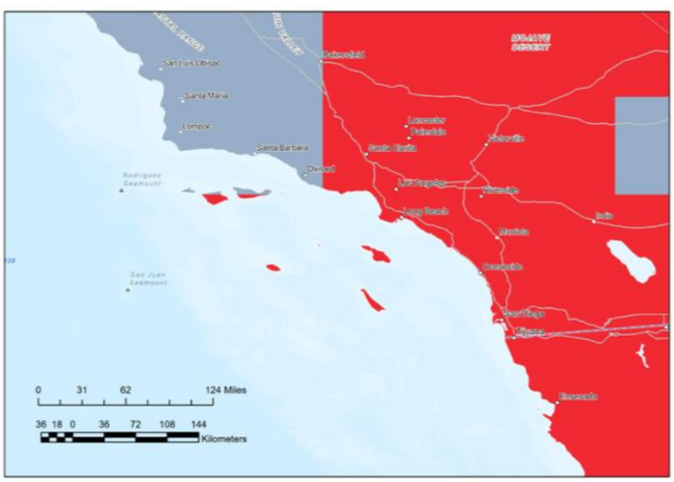
In the following maps, the grey color represents the baseline scenario for the location of the Mediterranean Climate type, and the red color represents the end-of-century projected Mediterranean Climate type location shift. The specific local changes, shown in Figure 3B, show that the northern half of the northernmost Islands that makeup Channel Islands National Park are affected more substantially by the climate type range shift than the southern islands.

Figure 3. **(A)** Side-by-side comparison of climatological Mediterranean Climate type and end-of-century (2099) projected global spatial shift in the Mediterranean Climate type on the macro-scale under the highest greenhouse gas emissions scenario (RCP 8.5).



- 2099 Mediterranean Climate Type Projection (RCP 8.5 scenario)
- Baseline Mediterranean Climate Type Scenario

Figure 3. **(B)** End-of-century (2099) projected spatial shift in the Mediterranean Climate type on the meso-scale for Channel Islands National Park under the highest greenhouse gas emissions scenario (RCP 8.5).



- 2099 Mediterranean Climate Type Projection (RCP 8.5 scenario)
- Baseline Mediterranean Climate Type Scenario

The projection indicates a need for assisted adaptation, new protected areas, buffer zones around protected areas, and ecological corridors connecting stable Mediterranean zones for Channel Islands National Park. It also indicates that managers need to focus the islands' habitat conservation management plan towards arid and other potential future climate types for migrating species from other climate zones to adapt.

4.5 Marine Heatwave Effects on Channel Islands National Park

Marine heatwaves are becoming more intense and frequent with climate change (Oliver et al., 2019). The graphs below show the intensity of the marine heatwave around Channel Islands National Park. There were significant increases in mean temperature during the 2014-2016 period. As stated in the literature review in section 2.3, Global and Continental Climate Change Trends, and illustrated below, during this period, the Channel Islands National Park and Marine Sanctuary normal SST gradient—illustrated in Figure 5, section 4.6—was replaced with a more uniformly warm SST regime. Looking at MHW events can show how the ecosystem may change.

Figure 4A illustrates the spatial average annual change in sea surface temperature (from baseline) surrounding Channel Islands National Park between 2012 and 2016, which captures the 2014-2016 marine heatwave. The westernmost islands received the most significant annual increase in SST during this time, illustrated in red below. The white area on the map indicates the lowest increase in SST; however, increases in SST were significant everywhere in the region for this period.

Figure 4. (A) Mean annual change in SST (°C) between 2012-2016 around the Channel Islands National Park and National Marine Reserve showing the spatial SST fluctuations during the 2014-2016 marine heatwave.

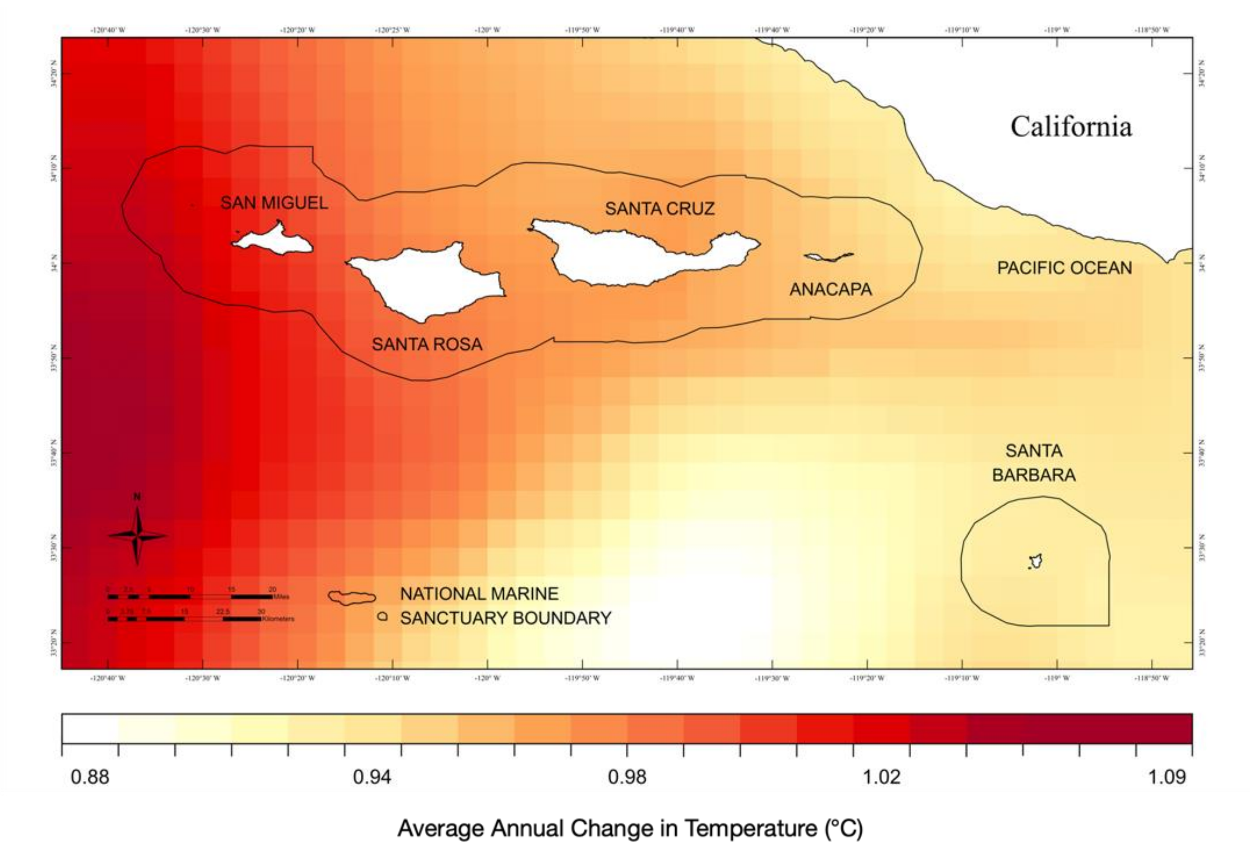
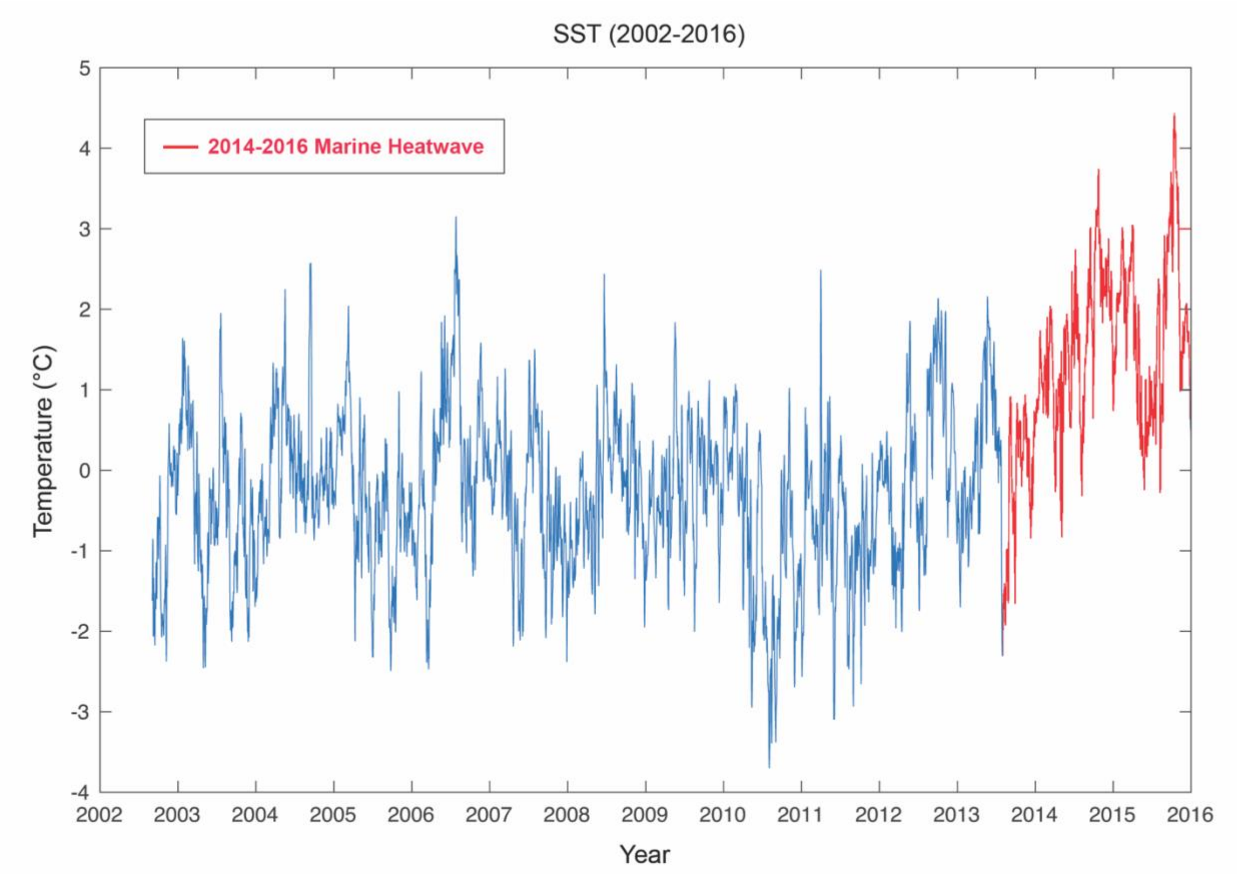


Figure 4B illustrates the average monthly change in sea surface temperature surrounding Channel Islands National Park between 2002 and 2016, capturing the 2014-2016 marine heatwave. The marine heatwave known as “the Blob” began in 2013 and peaked in 2015, illustrated in red below. The specific effects of the Blob are interpreted in section 2.3 of the literature review, Global and Continental Climate Change Trends.

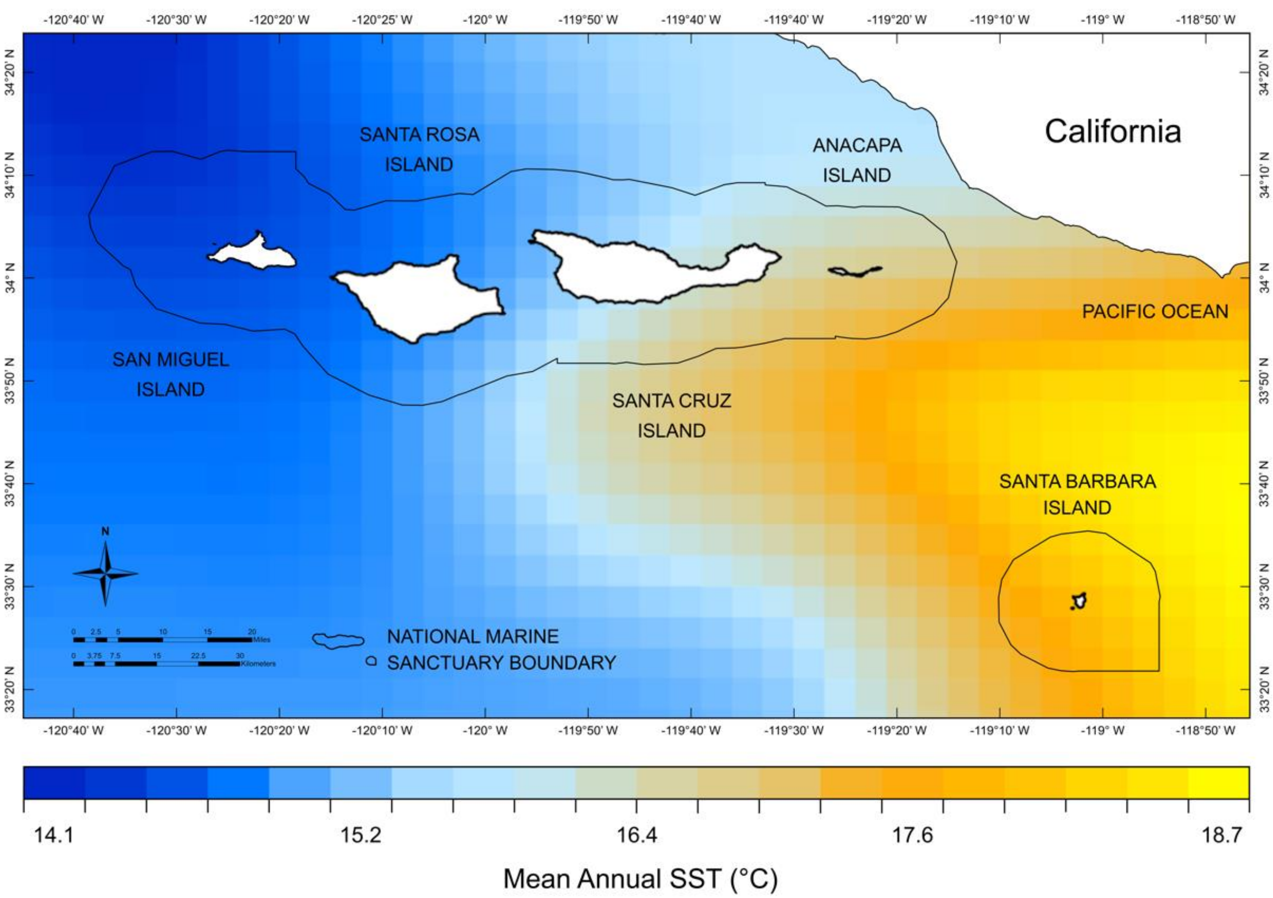
Figure 4. **(B)** Line graph showing monthly mean temporal SST (2002-2016) including normal (blue) temperatures for this region with natural variation and the rise and peak of the 2014-2016 marine heatwave (red).



4.6 Sea Surface Temperature (2016-2023)

The figure below shows spatial variations of SST (°C) across the islands. This SST gradient is affected by current global circulation patterns, which are projected to change by the end of the century, as stated in Section 2.3. Figure 5 shows the current mean SST variation over the islands. The following geospatial map illustrates many topics covered in the literature review, such as section 2.5: proximity to water, section 2.6: physical climate conditions, and section 2.7: land-atmosphere-ocean interactions and feedback loops.

Figure 5. Spatial analysis showing the east-west SST gradient around Channel Islands National Park (2016-2023).



4.7 Air Temperature Climatology (1991-2020)

There is a strong air temperature gradient among the island group (Figure 6A). Santa Barbara, Anacapa, and Santa Cruz Islands, annually, have higher temperatures than the more western islands of San Miguel and Santa Rosa. This indicates the region's geography, where Santa Barbara and Anacapa islands are in the lee of Point Conception, and San Miguel and Santa Rosa are in the direct path of the California Current. The data suggests that regions with cool ocean currents tend to have lower air temperatures, while areas with warmer ocean currents experience higher temperatures. Each island within the Channel Islands National Park boundary is affected differently due to the strong east/west and north/south temperature gradients. The westernmost islands are affected by cooler temperatures from the California Current and its respective wind patterns. In contrast, the easternmost islands are affected by the warmer air and waters from the California Countercurrent.

Figure 6. **(A)** Average climatological air temperature (1991-2020) within CHIS boundary.

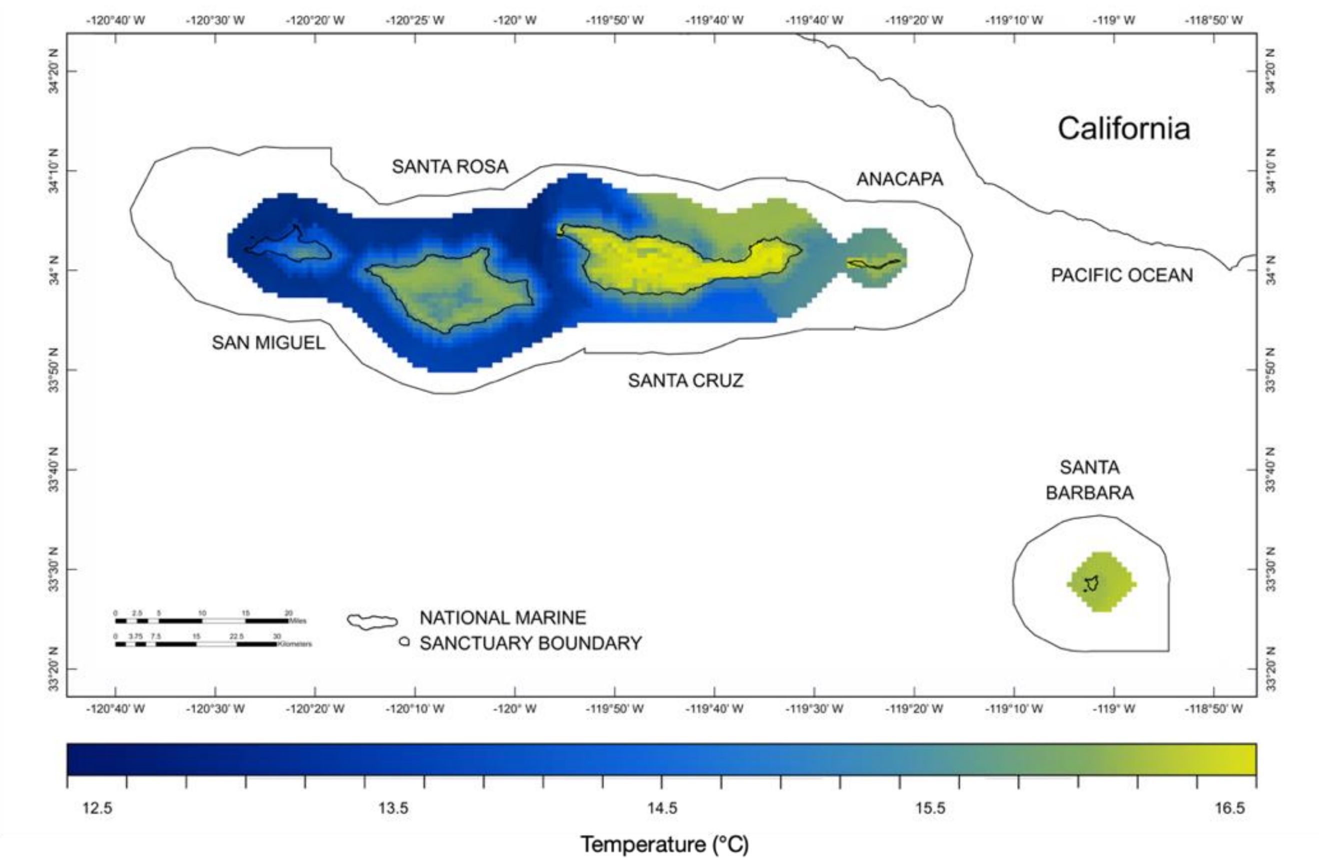


Figure 6. **(B)** Line graph showing the annual air temperature at individual Channel Islands National Park islands. The mean annual air temperature was aggregated from a 4 km grid cell in the center of each island (1895-2023). This time series indicates an overall increase in temperature among all five islands from 1895 to the present day. It also highlights the air temperature variation from east to west, showing cooler air temperatures over the westernmost islands and warmer temperatures over the easternmost islands. Average annual temperature difference between individual islands is ~0.5°C (~1°F), negating seasonal differences.

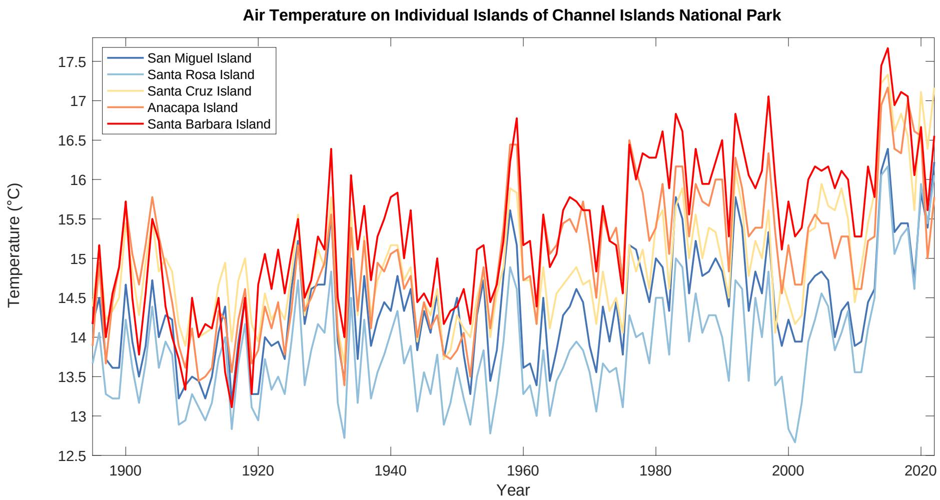
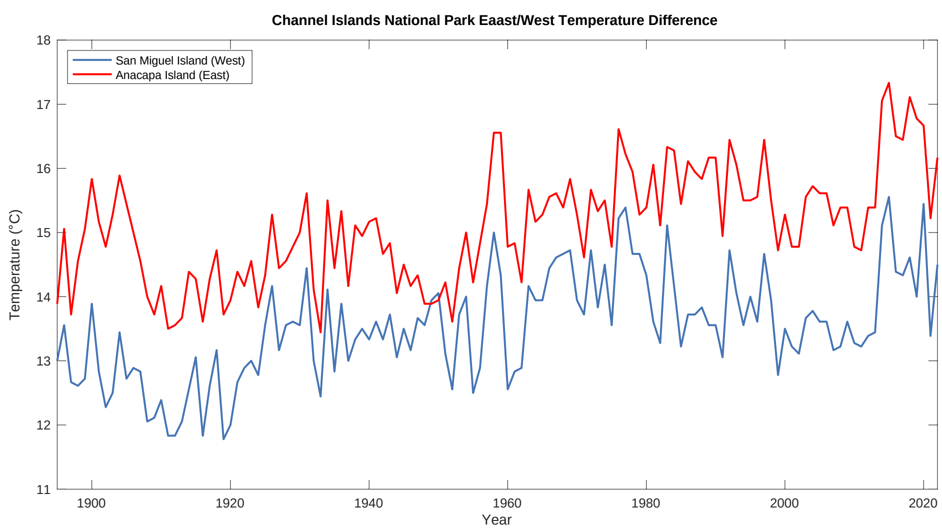


Figure 6. **(C)** Line graph of yearly temperature values for the furthest east point of Anacapa Island and the furthest west point of San Miguel Island. This illustrates a substantial difference in air temperature between the warmest island, Anacapa, and the coldest island, San Miguel. On average, annual air temperature differs ~2°C (~3.6°F) between these two islands.



4.8 Precipitation Climatology (1991-2020)

On the macro-scale, many climate change projections over the Channel Islands show that, on average, precipitation is projected to increase overall but at a statistically insignificant rate (Pierce et al., 2018; Gonzalez, 2020). Other projections for the entire state of California are uncertain—some models trending wetter, some drier (Polade et al., 2017). The figures below show historical precipitation trends obtained from the PRISM Climate Group at Oregon State University compared to these macro projections. Figure 7A shows a strong gradient, which indicates spatial variations of rainfall across all five islands. Santa Barbara Island showed a decrease in annual precipitation for the 1991-2020 period, though statistically insignificant, while San Miguel Island showed a statistically significant increase in annual precipitation. Because the amount of annual rainfall increase/decrease and projected changes are not consistent for each island, as illustrated below, the study provides a historical topo-to-meso-scale spatial precipitation analysis to compare to the projected future macro-values, which does not have the resolution to make accurate predictions on the micro- or topo- scales.

Figure 7. (A) Precipitation '30-year normal' showing average climatological precipitation (1991-2020) within CHIS boundary.

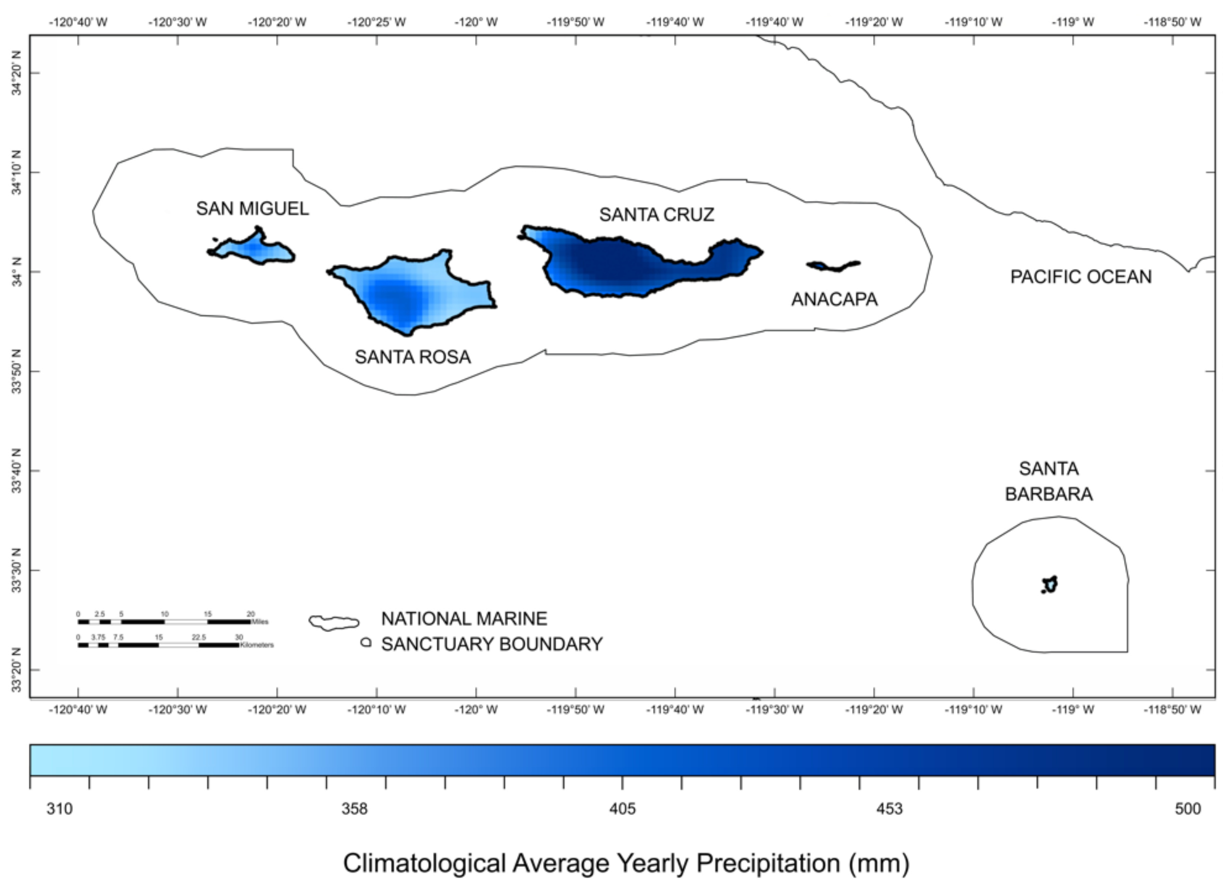
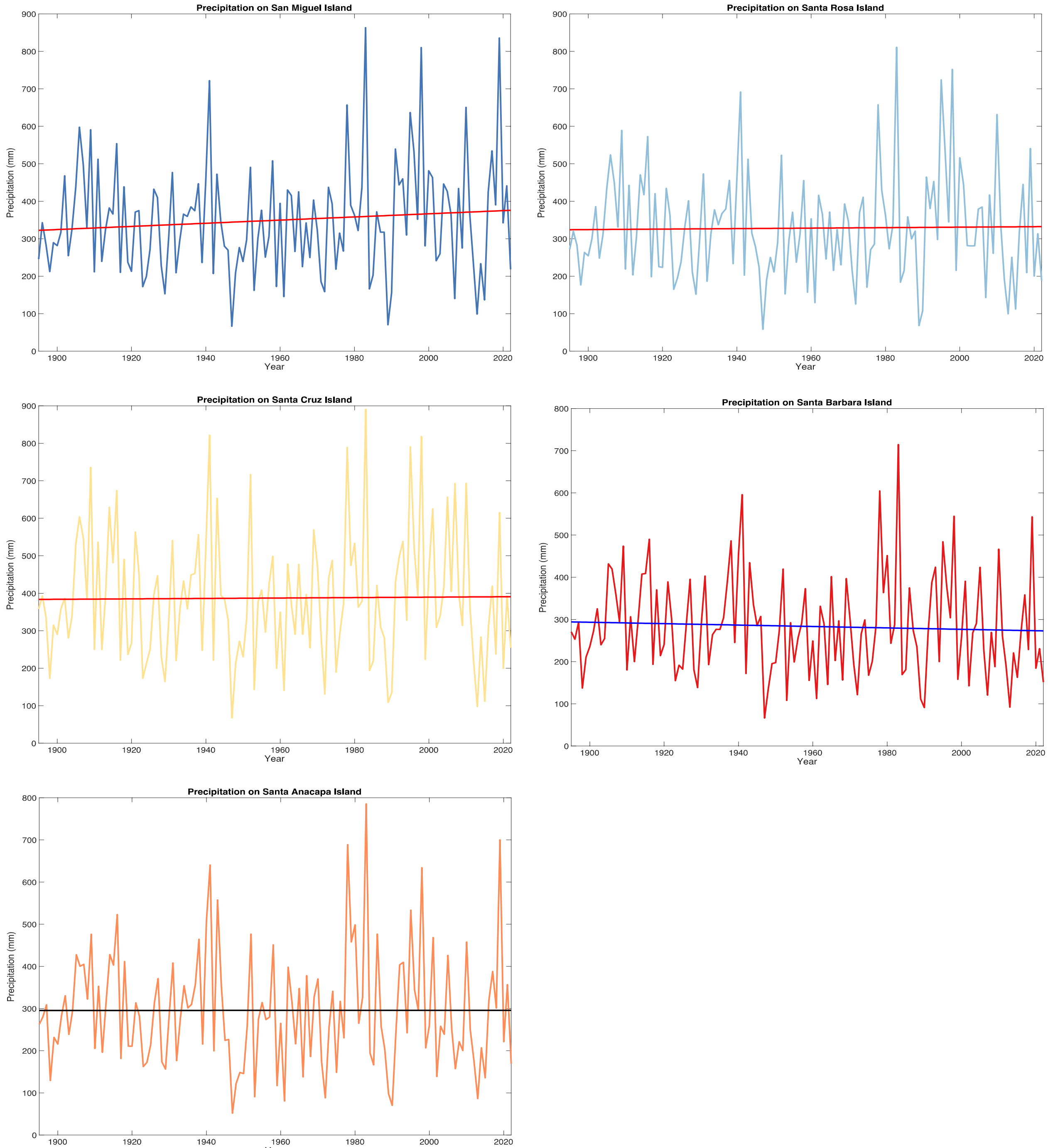


Figure 7. (B) Line graphs show each island's individual mean annual precipitation values (1895-2023). The mean annual temperature was aggregated from a 4 km grid cell in the center of each island. The spatiotemporal rainfall variability highlights the historical regional patterns in the Channel Islands National Park and identifies the changing trend over the most recent three full decades.



4.9 Topography of Channel Islands National Park

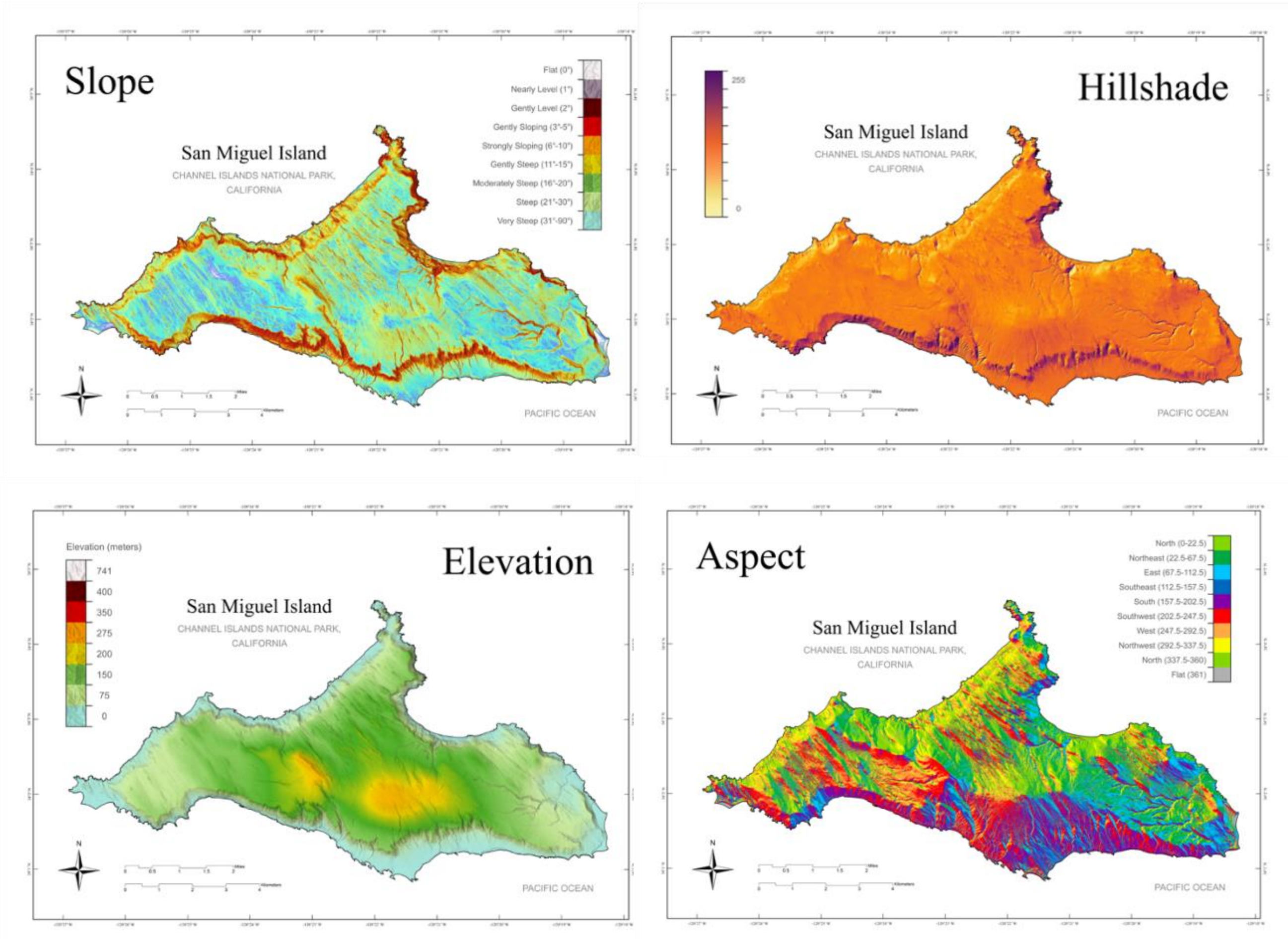
Topography is a critical driver of microclimate differences. The topographic maps in the following sections (4.9-4.13) illustrate sections 2.1 and 2.5 of the text, covering the spatial and temporal definitions of topoclimate and explaining how topography alters climate. As the literature review states, elevation shapes microclimate through adiabatic processes and exposure to wind and solar radiation, which are further modified by slope, aspect, and hillshade (Dobrowski, 2011).

The topographic maps below are compared to the other spatial plots in this study, including precipitation, air temperature, and heat maps with high and low-temperature anomalies. The comparison between these topographic features provides context to each variable's influence on physical climate manifestations. These maps have two primary purposes: first, to comment on the similarities between the geographic locations of each topographic variable and how they may affect local climatic conditions. Second, to comment on the complexity of the overall system and the combined influence of interrelated variables. For example, some areas with the highest temperature highs also have the lowest temperature lows. As elevation plays a role in lower air temperature at higher elevations, hillshade, slope, and aspect influence the amount of incoming solar radiation, thus adding to higher temperatures, particularly in the summer months, for the same localized areas.

Comparisons between topographic maps and spatial temperature plots show that temperature tends to be lower with higher elevation. Conclusions can also be drawn about aspect, hillshade, and slope. Typically, in the Northern Hemisphere, negating other variables, Southern-facing slopes (South/Southeast/Southwest) receive the most sunlight annually. If you compare the high and low heat maps in section 4.17 to the aspect maps, for example, there is a strong correlation between higher temperatures and south-facing slopes. As stated in the literature review, when comparing these variables to air temperature, there are many other factors to consider, like proximity to water and other typographic, physical, and biogeographic factors.

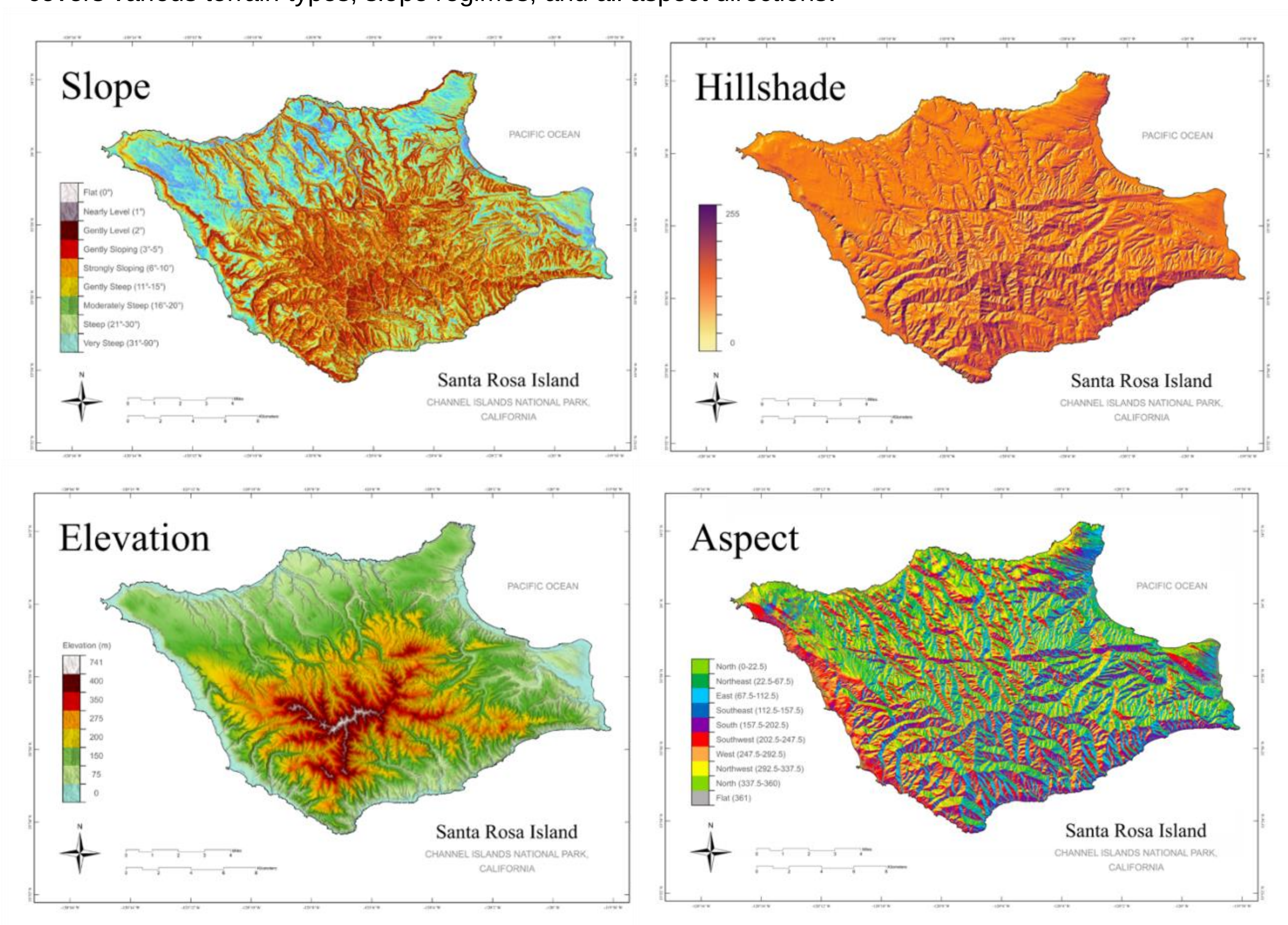
4.9 Topography of San Miguel Island

Figure 8. The topographic setting of San Miguel Island shows slope, hillshade, elevation, and aspect, derived from a 1m DEM and calculated from a total of 2.3 × 109 ground-classified lidar points. The SCI covers various terrain types, slope regimes, and all aspect directions.



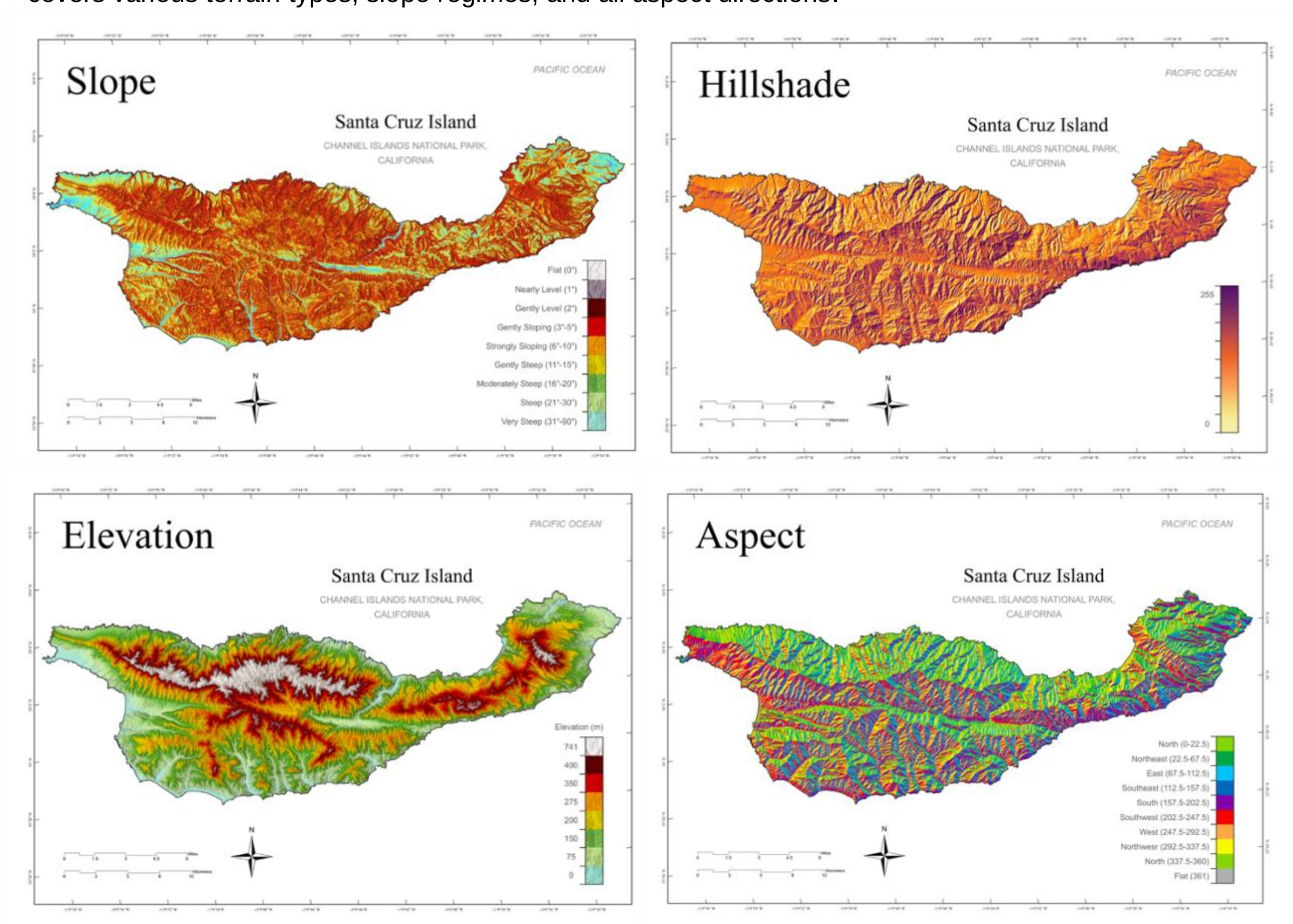
4.10 Topography Maps for Santa Rosa Island

Figure 9. The topographic setting of Santa Rosa Island shows slope, hillshade, elevation, and aspect, derived from a 1m DEM and calculated from a total of 2.3 × 109 ground-classified lidar points. The SCI covers various terrain types, slope regimes, and all aspect directions.



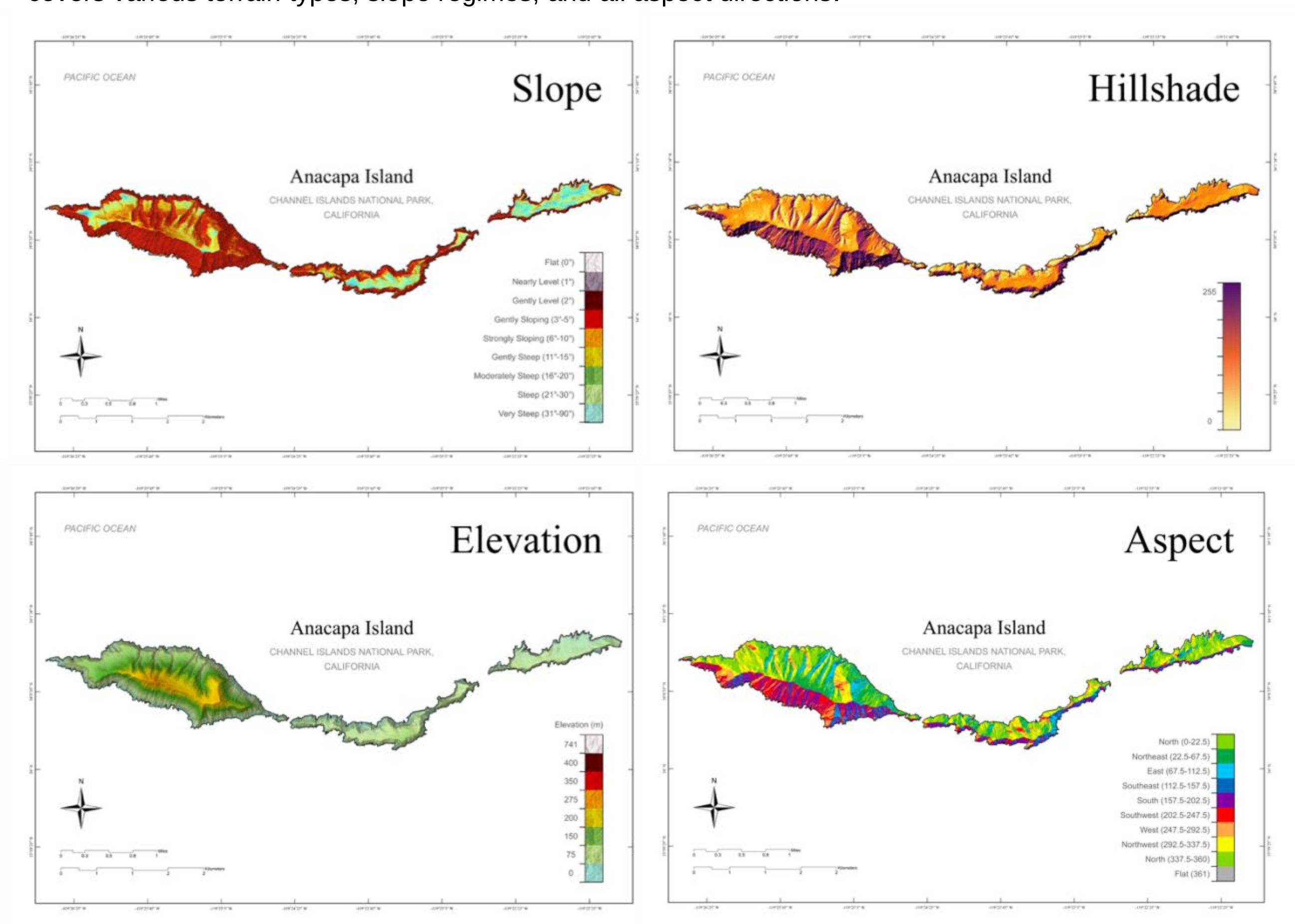
4.11 Topography Maps for Santa Cruz Island

Figure 10. The topographic setting of Santa Cruz Island shows slope, hillshade, elevation, and aspect, derived from a 1m DEM and calculated from a total of 2.3 × 109 ground-classified lidar points. The SCI covers various terrain types, slope regimes, and all aspect directions.



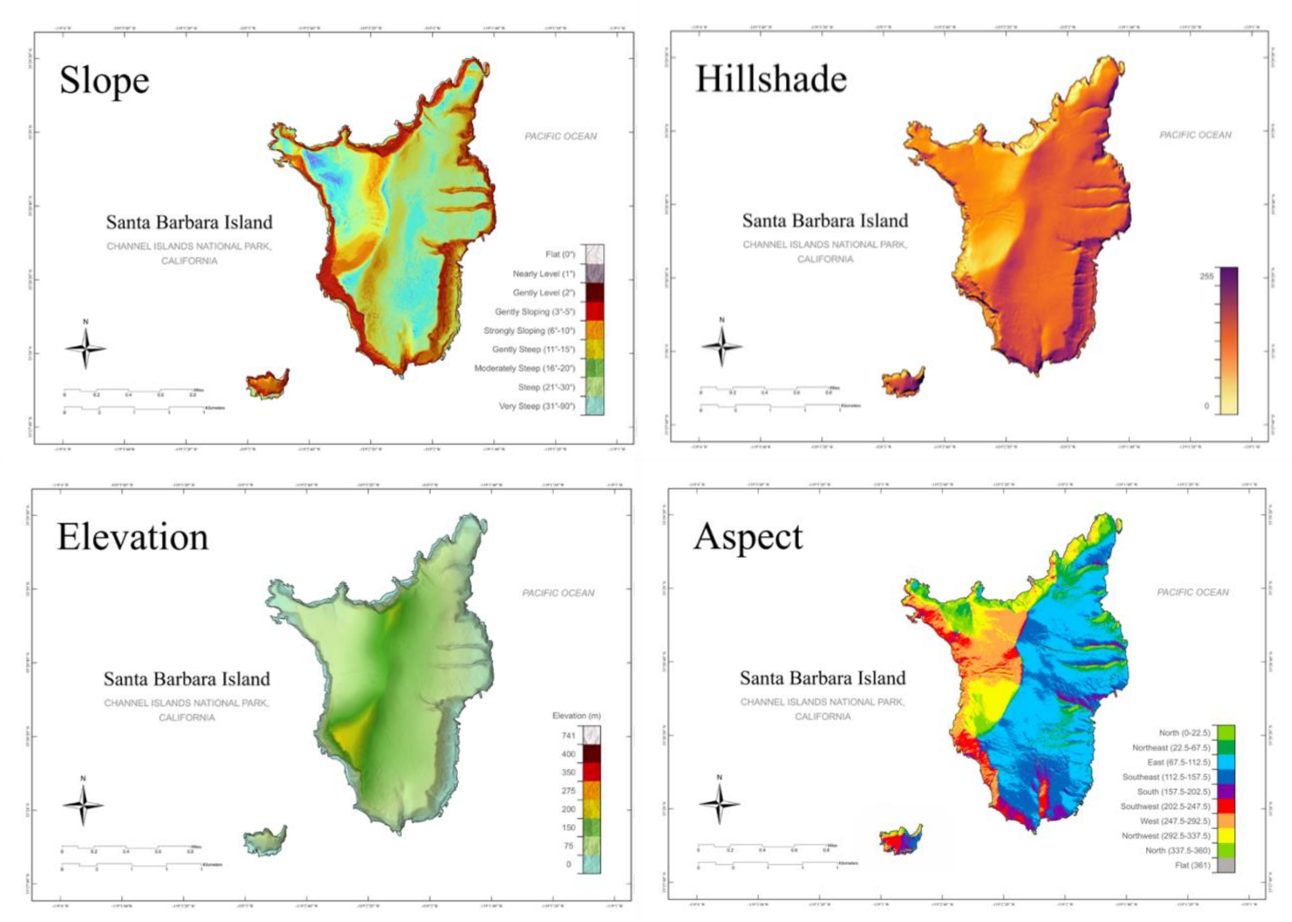
4.12 Topography Maps for Anacapa Island

Figure 11. The topographic setting of Anacapa Island shows slope, hillshade, elevation, and aspect, derived from a 1m DEM and calculated from a total of 2.3 × 109 ground-classified lidar points. The SCI covers various terrain types, slope regimes, and all aspect directions.



4.13 Topography Maps for Santa Barbara Island

Figure 12. The topographic setting of Santa Barbara Island shows slope, hillshade, elevation, and aspect, derived from a 1m DEM and calculated from a total of 2.3 × 109 ground-classified lidar points. The SCI covers various terrain types, slope regimes, and all aspect directions.



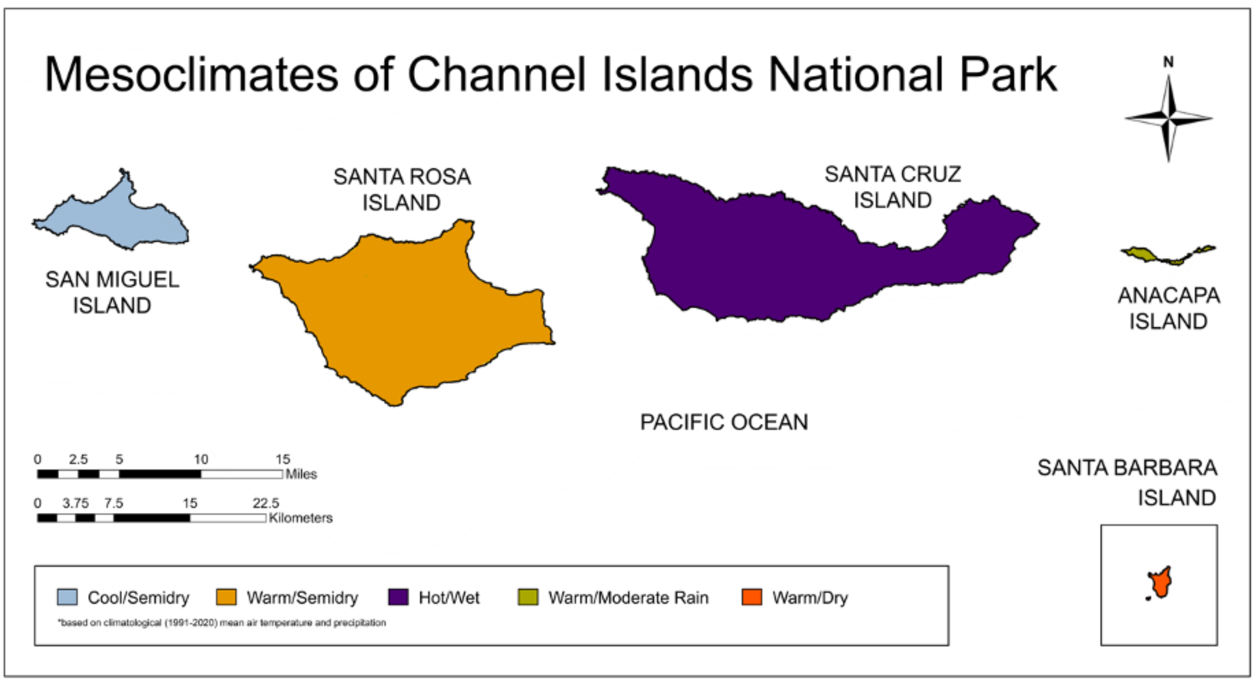
4.14 Mesoclimates of Channel Islands National Park

Table 3. Specific mesoclimate for each island and number of microclimates within each island's respective boundary based on the average annual temperature and average annual precipitation values between 1991-2020, the most recent three full decades. The data in this section was obtained from the PRISM Climate Group at Oregon State University, and specific information regarding the microclimate analysis within the Channel Islands National Park archipelago can be found in the following sections, 4.15-4.16.

Site	Mesoclimate	# of Microclimates
San Miguel Island	cool/semidry	6
Santa Rosa Island	temperate/semidry	8
Santa Cruz Island	hot/wet	10
Anacapa Island	warm/moderate rain	1
Santa Barbara Island	warm/dry	1

PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu, data table created 2 Jun 2023.

Figure 13. Mesoclimates of Channel Islands National Park based on average annual temperature and average annual precipitation values between 1991-2020, the most recent three full decades. San Miguel Island's mesoclimate is defined as cool/semidry; Santa Rosa Island's mesoclimate is warm/semidry; Santa Cruz Island's mesoclimate is hot/wet; Anacapa Island's mesoclimate is warm/moderate rain; Santa Barbara Island's mesoclimate is warm/dry based on the criteria defined in Table 4 in the next section.



Data source: Copyright © 2023, PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu. Map created 2 Jun 2023.

4.15 Microclimate Criterion used in the CINP Analysis

Temperature and precipitation are integral features of the habitats of all life and the most investigated physical impact parameters. The values in this study were divided into several categories ranging from 13°C to 17°C for average air temperature and between 300mm and 500mm of average annual rainfall, which are the average climatological temperature and precipitation ranges for Channel Islands National Park. Temperature parameters were selected by considering current publications (e.g., Baccini et al., 2008; Crisci et al., 2017; Dixon et al., 2009; López-Bueno et al., 2021) which use a temperature increment of 1°C when exploring thermal thresholds (section 2.3: Global and Continental Climate Change Trends). Distance was also a factor in creating these parameters. Section 4.2 (Table 2) states that microclimate scales are within < 1 m to ~270 m horizontally and up to ~800 m vertically, and mesoclimate scales are between ~800 m to ~10 km. For this study, the horizontal parameters were adjusted to include the location-specific variations in geography and physical climatology values. For example, each island is defined as a unique mesoclimate in this study for simplicity, and microclimates broadly maintained a 270m-800m horizontal and vertical scale, often stretching slightly further, to organize the precipitation and temperature silos more effectively. For context, Santa Rosa Island is 16km (10 miles) long and 24km (15 miles) wide. More information on thermal thresholds (section 2.3) and precipitation values (section 2.6) can be found in the literature review. The precipitation values in this section were defined based on the variety of rainfall in the region and compared to the current literature. The parameters in this report should not be used as the “standard” for determining microclimates in this region; instead, they are listed as a starting point for creating microclimate hypotheses and should be studied further. Future research requires hyper-local field measurements and observations to validate and monitor the presence of different microclimates.

Table 4. Classifications of specific microclimate criterion using average annual temperature and average annual precipitation values between 1991-2020, the most recent three full decades.

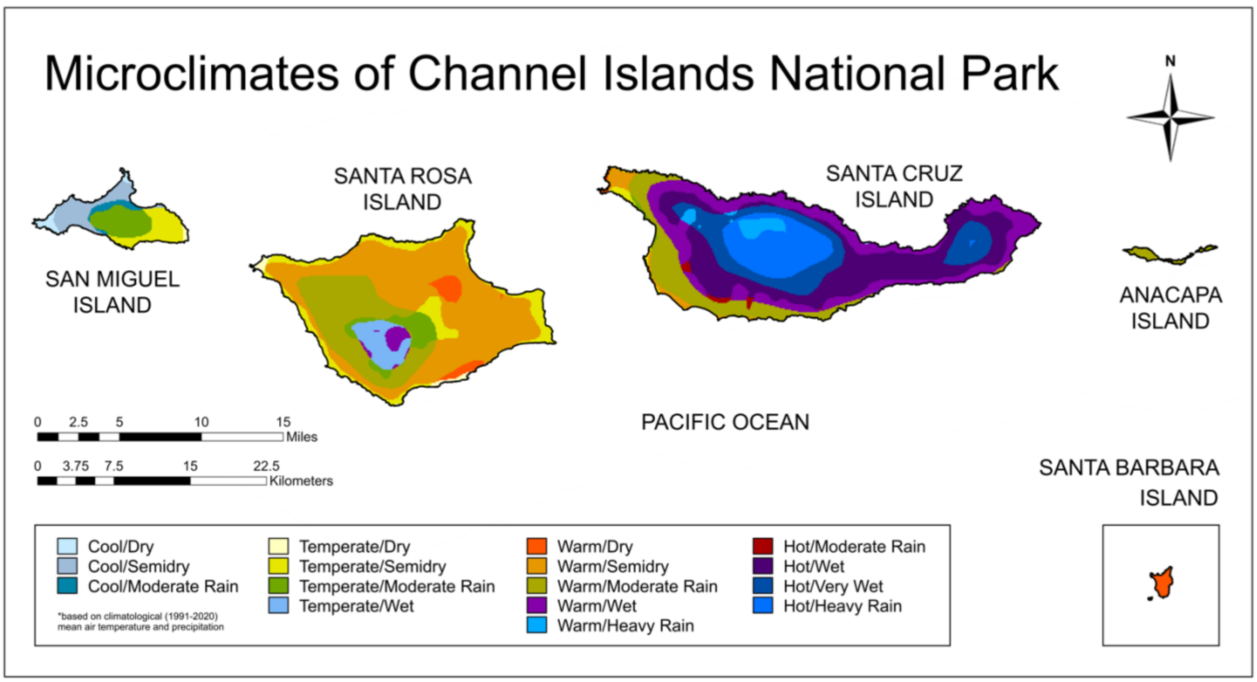
Climate Type	Annual Temperature (°C)	Annual Precipitation (mm)
Cool/Dry	≤ 14	≤ 320
Cool/Semidry	≤ 14	≥ 320 and ≤ 350
Cool/Moderate	≤ 14	≥ 350 and ≤ 390
Temperate/Dry	≥ 14 and ≤ 15	≤ 320
Temperate/Semidry	≥ 14 and ≤ 15	≥ 320 and ≤ 350
Temperate/Moderate	≥ 14 and ≤ 15	≥ 350 and ≤ 390
Temperate/Wet	≥ 14 and ≤ 15	≥ 390 and ≤ 450
Warm/Dry	≥ 15 and ≤ 16	≤ 320
Warm/Semidry	≥ 15 and ≤ 16	≥ 320 and ≤ 350
Warm/Moderate	≥ 15 and ≤ 16	≥ 350 and ≤ 390
Warm/Wet	≥ 15 and ≤ 16	≥ 390 and ≤ 450
Warm/Very Wet	≥ 15 and ≤ 16	≥ 450
Hot/Moderate	≥ 16	≥ 350 and ≤ 390
Hot/Wet	≥ 16	≥ 390 and ≤ 450
Hot/Very Wet	≥ 16	≥ 450 and ≤ 480
Hot/Extremely Wet	≥ 16	≥ 480

Data source: Copyright © 2023, PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu. Map created 2 Jun 2023

4.16 Microclimates of Channel Islands National Park

The five islands that make up Channel Islands National Park possess microclimates throughout, varying with proximity to the sea, protection from the wind, vegetation, soil type, water content, and topographic features such as elevation, slope, hillshade, and aspect, among others, as stated in the literature review in section 2. As such, macroclimate values can be understood as simplifying more fine-scale climate processes and understanding climate on varying spatial and temporal scales can provide a 'whole picture' approach. Figure 20 divides the island's historical climate values into sub-groups using mean climatological temperature and precipitation values using PRISM data at 800m resolution. The following microclimates are determined based on the specified microclimate criterion listed in section 4.15. San Miguel Island hosts six microclimates with overall dry, semidry, and moderately wet climate ranges and overall cooler temperatures than the other four islands; Santa Rosa Island hosts eight microclimates with overall warm and temperate temperatures and semidry to wet climate ranges; Santa Cruz Island hosts the most microclimates of all the five Northern Islands—ten, with a range of climate conditions from warm and dry to hot with heavy rain. Santa Cruz Island is coincidentally the most biodiverse island of the archipelago; Anacapa Island's microclimate is more homogenous with warm temperatures and moderate rain; Santa Barbara Island's mesoclimate is also homogenous, with warm/dry climate conditions based on the parameters defined in Table 4.

Figure 14. Microclimates of Channel Islands National Park based on average annual temperature and average annual precipitation values between 1991-2020, the most recent three full decades.

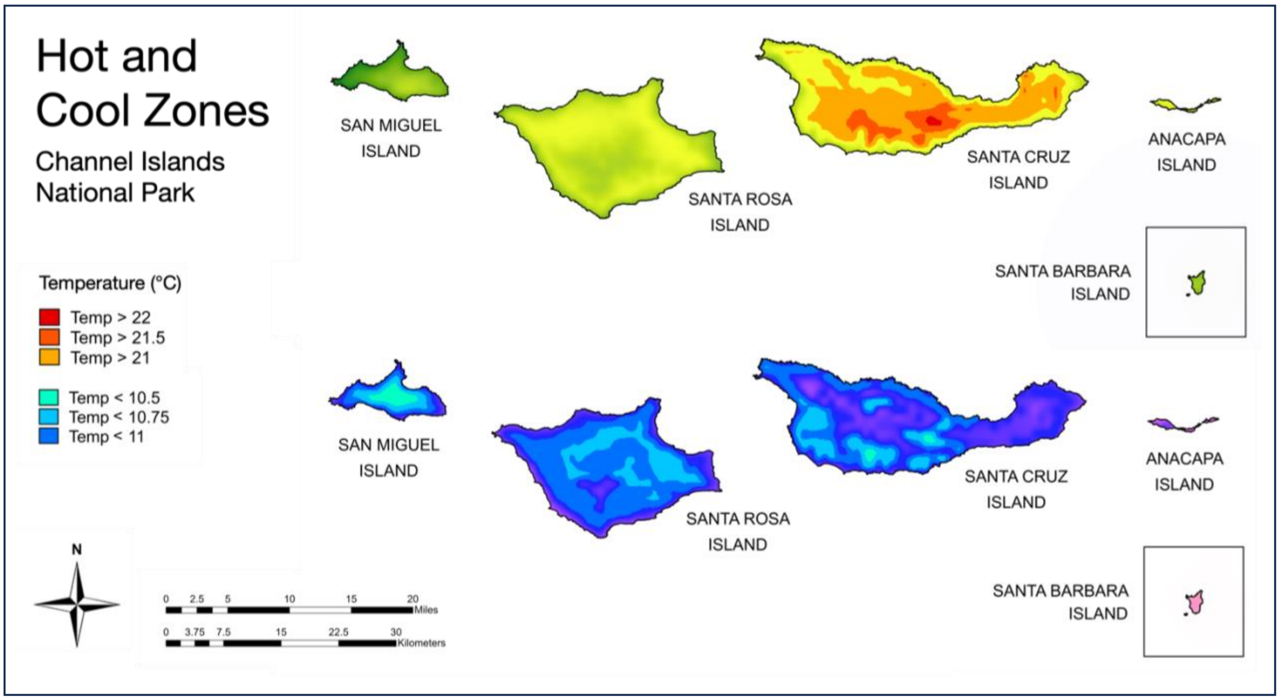


Data source: Copyright © 2023, PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu. Map created 2 Jun 2023.

4.17 Hot and Cool Zones of Channel Islands National Park

Using mean climatological temperature values obtained from the PRISM Climate Group, various high and low-temperature ranges were determined for CINP. The high and low-temperature anomalies were derived from long-term (30-year) climatological averages in Channel Islands National Park at 4km resolution. The map below illustrates areas that reach these temperature extremes. The color gradient follows a cool-to-warm color palette, with the highest temperatures in red and the coolest temperatures in turquoise. Some areas that host the hottest temperatures simultaneously host the coldest temperatures in different seasons. The high and low parameters chosen in this study were divided by 0.5°C to illustrate the highest and lowest deviations from normal within ranges that may affect temperature thresholds in this region. More information on temperature thresholds can be found in the literature review section 2.3 Global and Continental Climate Change Trends.

Figure 15. Hot and Cool Zones of Channel Islands National Park based on average annual temperature high and low values between 1991-2020, the most recent three full decades.



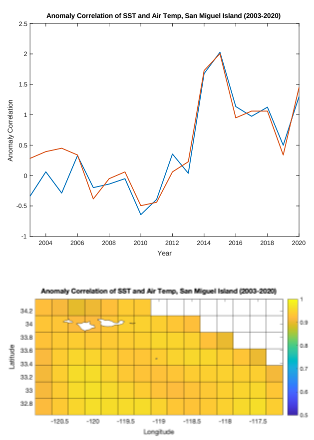
Data source: Copyright © 2023, PRISM Climate Group, Oregon State University, https://prism.oregonstate.edu. Map created 2 Jun 2023.

4.18 Coupled Climate Relationships and Feedback Loops Within CINP Boundary

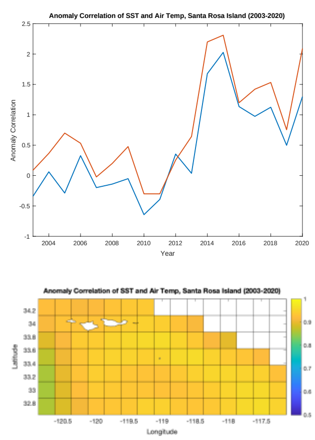
Sea Surface Temperature and Air Temperature. Figures 16A-E show the relationship between air temperature and SST for each island within the CINP boundary. For each island, the temperature fluctuates around the mean. However, the fluctuations are similar everywhere over the region. All SST and air temperatures fluctuate in lockstep for each island. The mean difference in temperature shows that the western region is colder than the eastern region. One variable is offset from the other because of the mean temperature. This was especially evident between 2014 and 2016, as the marine heatwave affected everything similarly. SST is a significant driver of air temperature and vice versa; as SST warms over the Channel Islands, so does air temperature.

Figure 16. (A) Time-series and spatial correlation of sea surface temperature (SST) and annual mean air temperature on San Miguel Island (2003-2020), **(B)** Time-series and spatial correlation of sea surface temperature (SST) and annual mean air temperature on Santa Rosa Island (2003-2020), **(C)** Time-series and spatial correlation of sea surface temperature (SST) and annual mean air temperature on Santa Rosa Cruz Island (2003-2020), **(D)** Time-series and spatial correlation of sea surface temperature (SST) and annual mean air temperature on Anacapa Island (2003-2020), **(E)** Time-series and spatial correlation of sea surface temperature (SST) and annual mean air temperature on Santa Barbara Island (2003-2020).

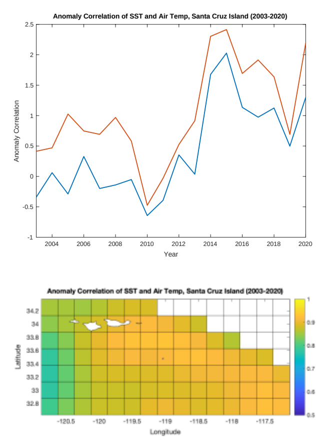
(A)



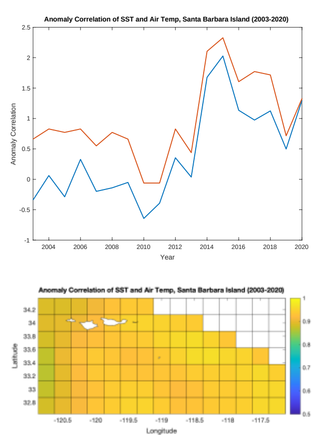
(B)



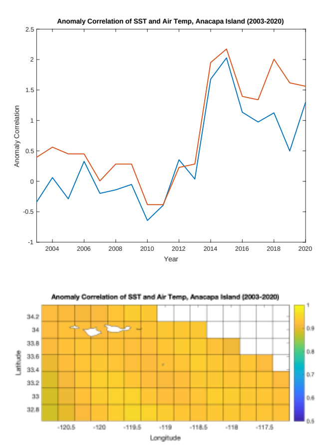
(C)



(D)



(E)



Air Temperature and Cloud Cover. Figures 17A-B show the relationship between cloud cover (CLC) and air temperature within the CINP boundary. Figure 17A shows the mean annual cloud coverage (CLC) and annual mean temperature correlation between 1995 and 2020. Figure 17B shows the monthly mean CLC (%) for each month over the CINP region between 1995 and 2020. There is a highly significant negative correlation between these variables. The P-value of 0.0003 indicates the relationship is unlikely to be due to random chance. In contrast, the R-value of -0.6956 indicates a moderate-to-strong negative relationship between the two variables.

Figure 17. (A) A point-by-point correlation of annual mean low cloud coverage (CLC) and annual mean air temperature within CINP boundary (1995-2020)

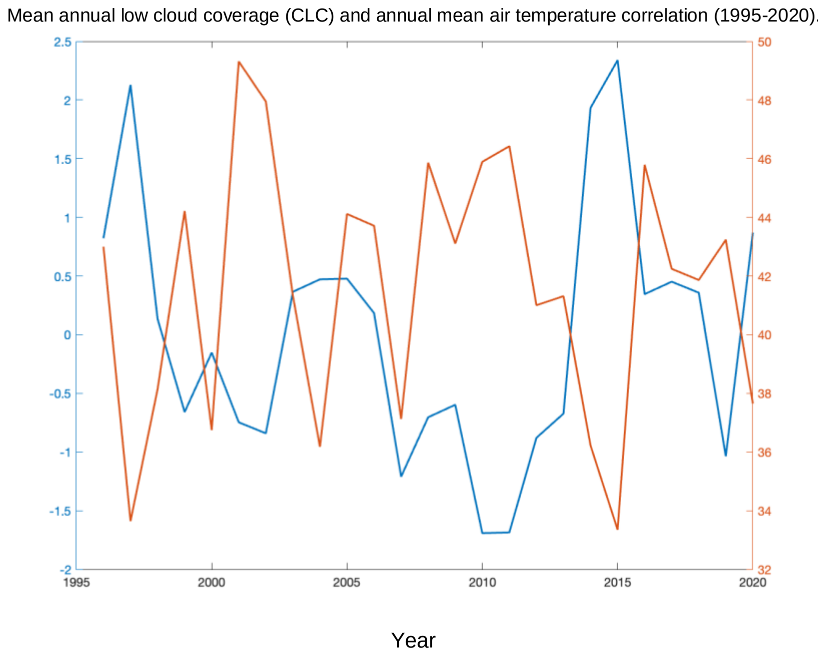
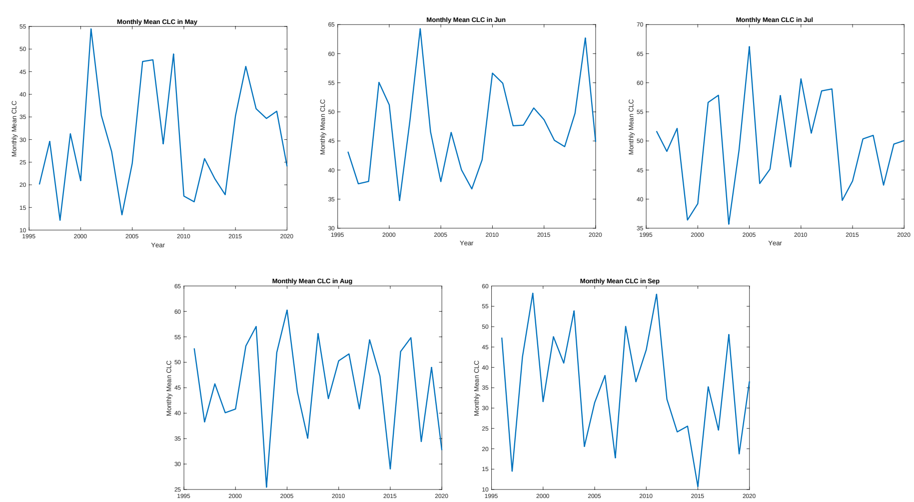


Figure 17. (B) Monthly mean cloud cover (CLC) % over CINP, May-September (1995-2020).



Sea Surface Temperature and Cloud Cover. The physical changes to atmospheric water vapor have manifested global changes in low cloud cover, fog, and annual precipitation patterns. These relationships were analyzed and quantified for the CINP boundary. A moderate-to-strong negative correlation was found between sea surface temperature (SST) and cloud cover. Figure 24A shows the time series negative correlation between SST and CLC for CINP. Figure 24B shows the negative spatial correlation between SST and CLC for CINP and the Southern California Bight.

Figure 18. (A) A point-by-point temporal correlation of annual mean low cloud coverage (CLC) and annual mean sea surface temperature within CINP boundary (1995-2020).

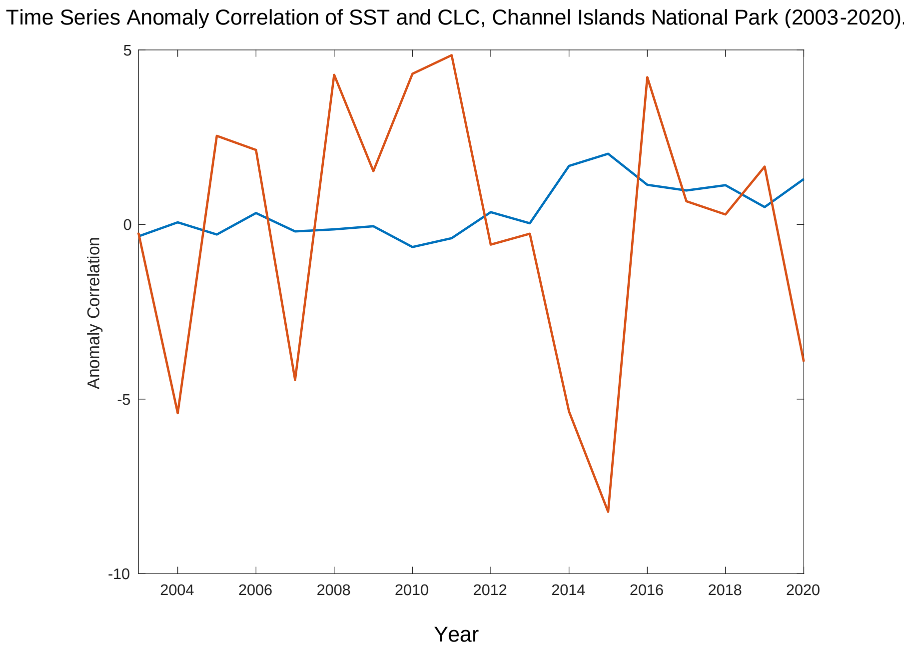
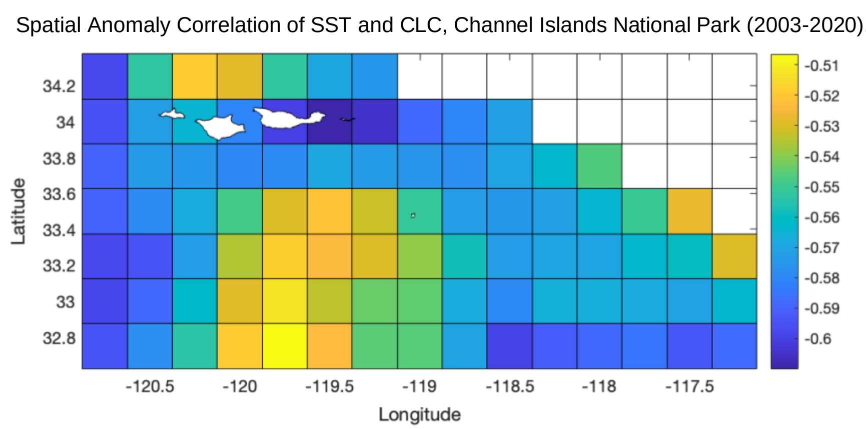


Figure 18. (B) A point-by-point spatial correlation of annual mean low cloud coverage (CLC) and annual mean sea surface temperature within CINP boundary (1995-2020).



5 Discussion

5.1 Complexity

Comparing historical weather and climatology values with local topographic, geographic, and biological conditions to define microclimate parameters is complex. It relies on high-resolution and time-relevant data and includes interdependencies from multiple variables consistently changing and affecting one another at different rates. For example, the accurate surface temperature depends on the ground's geological features to determine the heat capacity of the surface matter, the amount of solar radiation received, which depends on the angle of the sun at any given time, the topography of the landscape, and the local albedo and vegetation cover. Surface temperature also depends on soil depth, water content, and the soil type of each layer below the ground. Despite these challenges, high-resolution and detailed spatial data is becoming more accessible, allowing scientists to look at climate conditions more accurately. It is also necessary to incorporate observed data on a micro-scale and to monitor conditions such as temperature, land cover, and soil moisture in varied terrain to improve accuracy further.

5.2 Summary of Results

The study lays a foundation for future research and attempts to develop a characterization model for determining local microclimates. It provides managers with a synthesis of all available climate-altering criteria in this region. It can lead to a regional microclimate model that quantifies each variable's influence on the overall system. The high-resolution analysis of climate change in this region can advance the accuracy of local predictions and aid future vulnerability assessments. With this information, managers can more easily quantify the potential benefits of sustainable land-use practices and conservation efforts in Channel Islands National Park to mitigate the effects of climate change and the positive feedback loops that exacerbate it. Here are the main results of the study:

Climate Criterion Framework

The literature review in Section 2 provides an overview of all known criteria that affect Channel Islands National Park's climate conditions at various spatiotemporal scales. This framework can be used to weigh the influence of interrelated variables, more accurately predict climate change, anticipate climate trends, and identify climate refugia. Distinct variables are described in detail to provide a framework for predictive modeling for present and future research. Each variable plays a vital role in impacting the climate conditions on the islands; the following literature review covers global climate drivers, regional and local topographic climate drivers, biogeographic climate drivers, physical climate conditions and drivers, and land-atmosphere-ocean interactions and feedback loops unique to Channel Islands National Park. The following review isolates each variable and describes its impact and function, creating a whole-picture approach to conservation and natural resource management for this region.

Climatology at Various Spatiotemporal Scales

The results in Section 4 define parameters for discerning climatological conditions at macro, meso, topo, and micro scales for Channel Islands National Park. These parameters are then applied to climatological data concerning air temperature and precipitation, creating geospatial maps highlighting the diverse climate conditions across the five islands. Section 4.1 includes the study's micro, topo, meso, and microclimate scales. Section 4.13 shows a map of the determined mesoclimates and a table of the parameters used to identify them. Section 4.14-4.15 shows the results of identified microclimates among the five islands and the parameters used in the study. Looking at climate at these resolutions significantly enhances the precision of determining the park's current conditions. Furthermore, by contrasting these findings with other climate-altering criteria from the literature review, it becomes possible to gauge the potential impacts of future temperature increases and altered precipitation patterns on these hyper-local ecosystems. This approach provides valuable insight into fundamental local and regional patterns, aiding in predicting broader atmospheric, terrestrial, and oceanographic changes and their influence on the organisms inhabiting this region.

Topographic Mapping

Sections 4.9-4.13 provide four topographic maps for each island, including slope, aspect, hillshade, and elevation. These maps are compared to climatological air temperature maps with highs and lows for a more robust observation of the topography's influence on local climate. The results validate the terrain's influence on local climate, temperature variation, temperature gradients, and precipitation patterns and validate the climate modeling frameworks in previous sections. They can be used in future research to understand biodiversity and species migration, assess natural hazards, manage water resources, and for other climate adaptation and mitigation development.

Historical Climatology Analysis

Section 4.3-4.4 identifies historical and projected trends over the Channel Islands, and Section 4.5-4.7 analyzes historical sea surface temperature (SST), air temperature, precipitation, and cloud coverage (CLC). The trends indicate spatial SST, precipitation, and air temperature gradients among the five islands. Section 4.16 analysis indicates areas with the highest "highs" and lowest "lows" of air temperature within the park's boundary. This research can help determine areas suitable for refugia where species can adapt to climate change. An analysis of SST also indicates a marine heatwave event from 2014-2016 and provides context for where and when the event was at its peak. Tracking the frequency, duration, and intensity of heat waves surrounding the islands helps monitor the effects of climate change and understand its impact on the ecosystem.

Projections

Section 4.2 provides historical and projected macro-scale climatological conditions parameterized by the Köppen Climate System criterion. The projection indicates a shift in the Mediterranean climate type under the highest forcing scenario (RCP 8.5) globally and locally in CINP by the end of the century (2099). This projection is an essential indicator of expected changes to marine and terrestrial ecosystems. The literature review provides many projections for the Northern Channel Islands, including large-scale global changes to near-surface wind speed and the California Current System (Section 2.3: Global and Continental Climate Change Trends).

Land-Sea-Atmosphere Interactions

Section 4.17 identifies correlations between air temperature, SST, and CLC. Further assessment of these covariations may lead to a better understanding of the feedback loops, which can exacerbate the rate of change in this region. The interactions between land, ocean, and atmosphere reveal how positive feedback loops can amplify the effects of climate change, affect the water cycle, and increase uncertainty in climate models and projections. For example, ocean circulation patterns are projected to shift in this region, consequently influencing regional climates and weather patterns. Without accurate assessments of the positive feedback loops associated with climate change, the extent and pace of projected changes can be significantly underestimated.

5.3 Conclusion

Climate change is a persistent and growing threat to island ecosystems, threatening biodiversity and affecting ecosystem services in Channel Islands National Park and globally. Effective management in a changing climate requires a proactive approach to these impacts. Lack of detailed knowledge of the combined effects of physical, topographic, and biogeographic climate conditions at various spatial and temporal scales creates many challenges for conservation and resource managers. Evaluating the effectiveness of successful adaptation and mitigation projects is necessary to provide effective climate-smart management. The analysis proves that climate variability manifests differently in different regions. The five islands have different climate characteristics and, therefore, unique ecosystems. Each ecosystem has a different threshold to sustain ecological function in the face of climate change. There are five main takeaways from this study:

1. The strong coupling between the marine and terrestrial ecosystems shows how climate change affects both in lockstep
2. Shifting ocean currents and wind patterns drive temperature changes and cause feedback loops
3. Ecosystem downscaling is essential to understand and quantify these complex processes
4. Climate refugia, or areas that are likely to maintain a stable climate despite background climate extremes, are more present with the availability of multiple microclimates
5. Identifying microclimates and refugia are necessary climate change adaptation and mitigation strategies to inform conservation and natural resource managers on prioritizing their efforts

5.4 Future Research

Based on the findings in this study, recommendations for future research include:

1. The magnitude and frequency of projected changes to the California current system
2. Wind patterns (including Santa Ana Winds) and other decoupled changes can affect temperature gradients
3. Poleward and equatorward species distributions
4. Poleward and equatorward temperature fluctuations
5. Effects of increased frequency in heatwaves
6. Feedback loops between the terrestrial and marine environments, including fog inundation and correlations between the water cycle and vegetation change

In addition, high-resolution spatiotemporal field observations are necessary to validate projected changes, accurately identify microclimates, and locate climate refugia sites.

6 Risks and Limitations

When necessary, the developed framework should be repeated with more accurate or fine-resolution data. It can be adopted and implemented in other regions, which may necessitate a more robust analysis, different variables, or updated parameters. The preliminary study aims to build a reliable model for determining refugia sites that are resilient to a changing climate. Observations should follow to refine the methods and frameworks created in this report. There are substantial data gaps in fog and cloud cover, but these processes are essential for understanding microclimatic conditions. More fine-resolution case studies in more areas are desirable so more observations can be compared to the work. This study only provides a preliminary "starting point" for determining microclimates and refugia in this region. Future research and field observations are necessary to validate the conclusions, and the framework should be modified to fit the specific needs of the park's conservation efforts.

7 Acknowledgements

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