Technical Report:

Impacts of Increased Sea Surface Temperatures on the California Halibut, *Paralichthys californicus*

By Heal the Bay, in partnership with the Coastal Research Institute and Loyola Marymount University

Abstract:

The California halibut (*Paralichthys californicus*) has a valuable commercial and recreational fishery in California. Increasing ocean temperatures resulting from climate change could have significant implications on the geographic range and ecology of this species, impacting fisheries and fisheries management approaches. In this study, a quantitative compilation of values from 11 climate models were used to project increases in sea surface temperature (SST) in the near future (2021-2050). Future projections in this report follow the business as usual (BAU) climate scenario, using predicted temperature increases if there is no reduction in greenhouse gas (GHG) emissions from current levels. Results show increases in warming along the southern extent of the species range, exceeding the temperature threshold in which California halibut eggs arrest cell development (24 ^{o}C). These results could have future recruitment implications. Even if adult fish are able to tolerate these increased temperatures, they may not be reproductively successful, which could result in a decline in fish along the southern trailing edge of the species range. Warmer temperatures are also projected along the coast of California. Future annual average temperatures range between 20-22^{o}C within California Department of Fish and Wildlife's Southern stock, which is outside of the preferred egg temperature threshold, potentially impacting recruitment in this area as well. Fisheries management agencies should consider likely impacts from climate change and create management plans that are climate-ready and adaptive.

Introduction

Despite California halibut (*Paralichthys californicus*) being a commercially valuable fish, the fishery does not have a Fisheries Management Plan (FMP) and it is still in the stock assessment and research stages by California Department of Fish and Wildlife (CDFW). Climate change has a broad scope of impacts that affect the ocean, including increases in SST. Many species' range shifts have been documented in the ocean due to changes in temperature as a result of climate change (Payne 2016, Morley et al. 2018). An FMP is a management tool used to ensure long-term sustainability of a fishery and prevent overfishing through stock assessments and regulations that consider the species, the fishing community, and the entire ecosystem. Regional climate change impacts should be considered and incorporated into the future FMP for the halibut. This study aims to investigate how future ocean warming due to climate change may impact the species range and specific ecological characteristics of California halibut by looking at how egg development may be impacted by SST.

California Halibut Biology

California halibut has a well-established range (Figure 1) from the Quillayute River in Washington to Magdalena Bay in Baja, California (Haugen 1990). The California halibut is a commercially valuable and recreationally caught species. However, catch is most abundant from Point Conception in Central California down to the southern extent of the range (CDFG 2012). CDFW divides the state in half to manage California halibut. North of Point Conception is considered the North/Central stock, and below Point Conception is considered the Southern population. The last stock assessment by the CDFW in 2011 documented a 14% decline in the species in the southern region (CDFG 2011). However, Northern ("Central") California has seen a rapid increase since 1995 (CDFG 2011). It is not yet known if the low recruitment since the 2000s in Southern California is a population decline, or if the fish have moved to another region.

Different temperature sensitivities exist for the different life stages of the California halibut from the egg to larvae juvenile to adult (Gadomski and Caddell 1991). Impacts from climate change and a warming ocean will be strongest at the life stage that is most sensitive to temperature. For adults that live beneath the thermocline, SST and any changes in SST are not likely to have a big impact. However, California halibut eggs are known to be sensitive to temperature and they are pelagic, making them a good life stage for examining impacts from changes in SST (Payne 2016).

California halibut are multiple broadcast spawners that move inshore to reproduce, occurring near the coast in shallow waters (Clark 1931). There was a wide range of variability within the literature concerning when halibut spawn. According to Moser and Watson (1990), they spawn all year round, with peaks in February-March and in July-October. However, other studies suggest that spawning occurs from February to August with peaks in May, but can also extend through the fall (Haugen 1990). Another study suggests that the peak of spawning occurs winter-spring, with spawning halibut moving inshore April through May (Clark 1931). This variability suggests that they spawn all year round, with various peaks throughout the year, indicating that egg viability at different temperatures and multiple seasons is important to recruitment.

Spawning takes place in shallow coastal waters along sandy bottoms at depths of 6-20 m along the coast and outside of embayments (Haaker 1975). Although eggs previously were classified as demersal (Haaker 1975), they are currently known and established as pelagic (Allen 1988). The planktonic eggs have been found in the upper 30 m of the water column, hatching after 30 days (Lavenberg et al. 1986). A typical 5-year old female releases a batch of 300,000 eggs (CDFG 2011). Spawning can occur between 5-13 times a year, resulting in 1.5 to 7 million eggs every year per female of varying ages (Caddell et al.1990).

Spawning likely occurs from the San Francisco Bay to Magdalena Bay, due to the dispersal range of the halibut larvae (Ahlstrom and Moser 1975). When it comes to recruitment, stock size does not seem to be the determining factor. The level of depletion is related to natural mortality, among other factors (CDFG 2011). Egg survivorship was not examined here and could be a limiting factor in recruitment.

Juvenile halibut are often found in bays and estuaries, requiring shallow, protected waters to achieve optimal growth. California has lost approximately 80% of its estuary habitats (Stein et al. 2014), which is a possible compounding stressor on the California halibut in addition to fishing and climate change. And in Southern California, the decline in overall halibut landings corresponds with the decline in suitable shallow water bay and estuary habitats due to dredging and sediment fill (Wertz et al. 2004).

The eggs of the California halibut are more sensitive to increased temperatures than juveniles (Gisbert et al. 2003). Lab studies showed that at the 32-cell stage development in fertilized eggs, development is arrested at temperatures under 8^{o}C or over 24^{o}C, and an upper temperature range is seen for all stages of development at 28^{o}C (Gadomski and Caddell 1991). In captivity, extended high temperature periods above 20^{o}C caused the females to stop producing eggs (Gisbert et al. 2003). Based on this established sensitivity range from 8 to 24^{o}C, a more conservative range from 12 to 20^{o}C was utilized for this study.

Climate Change Impacts

Ocean temperatures have already increased as a result of climate change. In the last century alone, ocean temperatures have risen by 1^{o}C. According to future predictions, our oceans could face another 2-8^{o}C increase by 2100 (IPCC 5th Assessment 2014).

Geographic ranges of fish species are often closely tied to their thermal tolerance (Payne 2016). The temperature ranges and sensitivity of the California halibut at different life stages could have implications on the range or the recruitment success of the species. In a recent study, projected thermal habitat ranges were used to examine the migration of over 686 species (mostly demersal fish) off of the North American continental shelf (Morley et al. 2018). The study projected west coast fish populations to move north and west along the coast to find suitable thermal habitat. The potential for species range shifts are more dramatic on the west coast due to the weaker thermal gradient, as fish have to swim much farther to escape the higher temperature thresholds. In their model, some west coast species' thermal habitats moved by 1,500 km in future climate change projections.

Temperature alone has been used to analyze shifts in species geographic ranges, both oceanic and terrestrial, in previous studies (Payne 2016, Chen 2011). Specifically, SST along with catch per unit effort was used as a proxy to establish preferred habitat for a demersal fish (Tseng et al. 2011). In the study, Tseng et al. added 1, 2, and 4^{o}C to those identified habitat areas to examine the potential range shift of these preferred temperatures under various climate scenarios.

The leading and trailing edge of a species geographic range are the most impacted by effects of climate change, such as deviations in temperature, pH, DO, and salinity. Because the range edges are more at risk, special protections may need to be placed in these areas of vulnerable populations (Brandier 2010).

California Halibut Fishery Management

California halibut is a valuable fishery on the west coast of the United States and Mexico. Within state waters (three nautical miles), the California halibut fishery is managed by the state under the California Department of Fish and Wildlife (CDFW). The state uses a number of regulatory tools, including size limits (a minimum of 22 inches), gear restrictions (net mesh sizes, hook numbers, etc.) and effort limitations (number of permits sold) to regulate the California halibut fishery. At this time, there are no harvest control rules (e.g., an annual catch limit) to regulate the commercial take of California halibut. There is also no Fishery Management Plan (FMP) or Enhanced Status Report (ESR) for California halibut, however this fishery is top of the Marine Life Management Act Master Plan finfish prioritization list and additional management is currently in the first phase of development.

The California halibut fishery is divided into two sectors: commercial and recreational. Within the commercial fishery, California halibut can be caught using a variety of different gear, including trawl nets, gill and trammel nets, and hook-and-line. Each of these gear types is managed differently by the state. For catch by trawl net, California has designated trawl grounds where trawling is permissible, and the trawl fishery has a closed season in April and May of each year (California Commercial Fishing Regulations Digest, 2020). For commercial hook-and-line catch of California halibut, as with other commercial regulations, the state is divided into 20 distinct districts. Regulations for catch vary within these districts, including changes in limits on hooks per line, number of lines per vessel, and total number of hooks per vessel (California Halibut Commercial Hook-and-Line Map, 2019). Catch data from commercial fleets is collected via logbook and recorded by CDFW.

Recreational take of California halibut is also popular on the west coast. Recreational anglers catch California halibut from both boats and shore using predominantly hook-and-line gear. State regulation on recreational take of California halibut and other sport fishing targets also varies geographically. The state is parceled into five management areas for all recreational fisheries: The Southern, Central, San Francisco, Mendocino, and Northern. Recreational bag limits for California halibut vary from 3 to 5 fish north and south of Point Sur, Monterey County (2020-2021 California Ocean Sport Fishing Regulations, 2020). Catch data from the recreational fishery is collected by CDFW via online reporting and through the California Recreational Fisheries Survey (CRFS). As with other species, California halibut regulations are distinct based on geographic area and determined through assessments of fish biology, life history, and stock health.

Study Goals and Questions

Due to the established pelagic egg sensitivity of the California halibut to warmer temperatures, this study focuses on this most-sensitive life stage to estimate impacts from projected increased SST on egg viability. Understanding this can be informative to assessing potential impacts from climate change through a recruitment and geographic shift perspective. This study examines climate model predictions from 2021-2050 under the BAU scenario where nothing is done to mitigate or slow the rate of GHG emissions.The impact of those changes are assessed in California and at the southern extent of the species range. The temperature threshold of 12-20°C was specifically used in this study to represent egg suitability and preferred temperature range.

We examine how future SST increases due to climate change will impact egg development and recruitment of the California halibut and what the geospatial implications will be. We predict a trailing species range shift north driven by increasing temperatures due to egg sensitivity and reduced recruitment.

Currently, there is no FMP established for California halibut. This technical report is intended to make recommendations to CDFW to include a climate lens in the management development.

Methods

Temperature Threshold

As described in the Introduction, 12-20°C was used as the suitable temperature threshold for eggs in this study using SST as a proxy. At 8°C and 24°C, eggs arrested development (Gadomski and Caddell 1991). That study examined growth and survivability in 4°C increments, so it is not known how eggs would survive between 8-12°C and 20-24°C. To be conservative, 12-20°C was used as the preferred temperature range for egg survivability in this technical report.

Historical Halibut Suitability

To determine the locations historically suitable for California halibut spawning, a daily very high-resolution SST dataset supplied by NOAA was applied (Reynolds et al. 2007). The data were available at daily time scale on 0.25-degree horizontal grid globally for the period 1982 to present and were a combination of various observations including from satellites, ships, buoys, and Argo floats. Suitable days for egg survivorship were computed at each 0.25-degree grid point for the Pacific Ocean from approximately southern Baja California to Vancouver, Canada. If SST fell within the range 12 to 20°C it was considered a suitable day.

Future Halibut Suitability

To determine the impacts of climate change on suitable days for egg survivorship of California halibut, state-of-the-science climate change projections from the Coupled Models Intercomparison Project Phase 5 (CMIP5) (Taylor et al. 2012) were used in the latest IPCC report (IPCC 2013). SST output from 11 coupled atmosphere ocean global climate models (AOGCMs) was extracted for a historical period (1976–2005) and future period (2021–2050) under the Representative Concentration Pathway (RCP) 8.5 (Meinshausen et al. 2011). While RCP 8.5 represents the highest GHG concentrations or BAU pathway, it matches the current trajectory of GHGs (Fuss et al. 2014). Moreover, substantial differences between RCP 8.5 and other RCPs only begin to appear in the mid-21st century (IPCC 2013).

The SSTs from the AOGCM simulations were used to determine the climate change signal ΔSST, i.e., the difference in temperature between the future and historical climate. The signal was determined as the average over the historical and future periods at each gridpoint for each of the 11 ensemble members (Figure 2):

$$\Delta SST = SST_{RCP85} - SST_{hist}$$

where SST_{hist} and SST_{RCP85} are the 30-year SST average for the historical and future simulations. As a surrogate for 2021 to 2050 SSTs for RCP 8.5 SST_{future}, this climate change signal is then added to the NOAA observations (Figure 3):

$$SST_{future} = SST_{NOAA} + \Delta SST$$

Where SST_{NOAA} is the daily NOAA SST data. Applying the change in climate to the observations removes model bias assuming that each model's bias remains the same in the future and historical climate. A deficiency of the approach is that it retains the climate variability of the historical climate which is likely to change with a warmer climate. Nevertheless, it is frequently applied for impact studies since results can be sensitive to model biases which are reduced in this approach (Kang 2019, Sylla 2018). Once the future SSTs were computed, the same method used to determine suitable days using the NOAA SST observations was applied to determine future suitable days.

Results

The established geographic range of the California halibut is from the Quillayute River in Washington to the Magdalena Bay in Baja California from CDFW (Haugen 1990) (Figure 1). On modeled data alone, there is at least a 1-1.4°C increase in temperature projected across the west coast (Figure 2). At Magdalena Bay specifically, this is particularly concerning. Average annual SST at the trailing southern edge of the species range reaches 27.5°C, and eggs arrest development at 24°C (Gadomski and Caddell 1991), which could potentially reduce recruitment in the region.

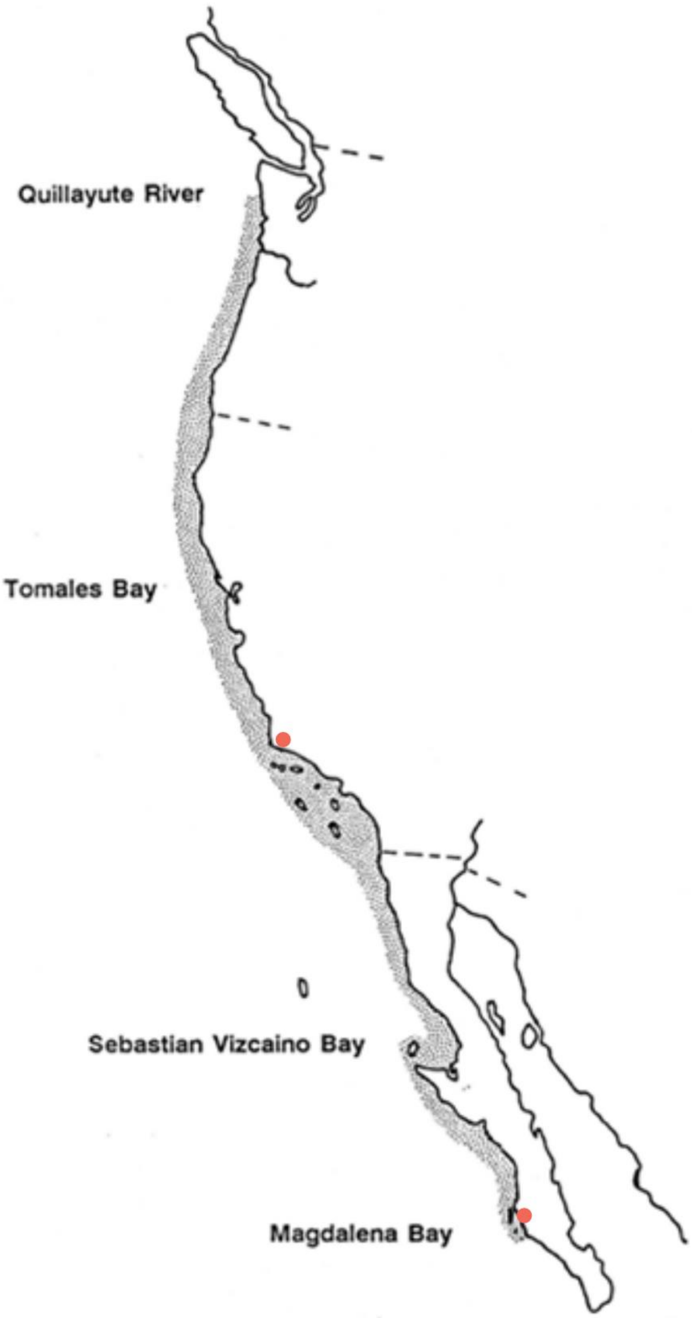

FIGURE 1. Geographic distribution of the California halibut, *Paralichthys californicus*.

FIgure 1. Range of California halibut, replicated from Haugen 1990 (11.9.2020). Points of note in the CA halibut range are shown with red circles; the northern marker is at Point Conception and the southern marker is at Magdalena Bay.

The outputs from the modeled data on an annual average from the past (Figure 2A) to the future (Figure 2B) were used to create the difference map (Figure 2C), which was used to correct for bias in the maps used in Figure 3.

A. Baseline (1982-2005) **B) RCP 8.5 (2021-2050)** **C) Difference (RCP 8.5-Baseline)**

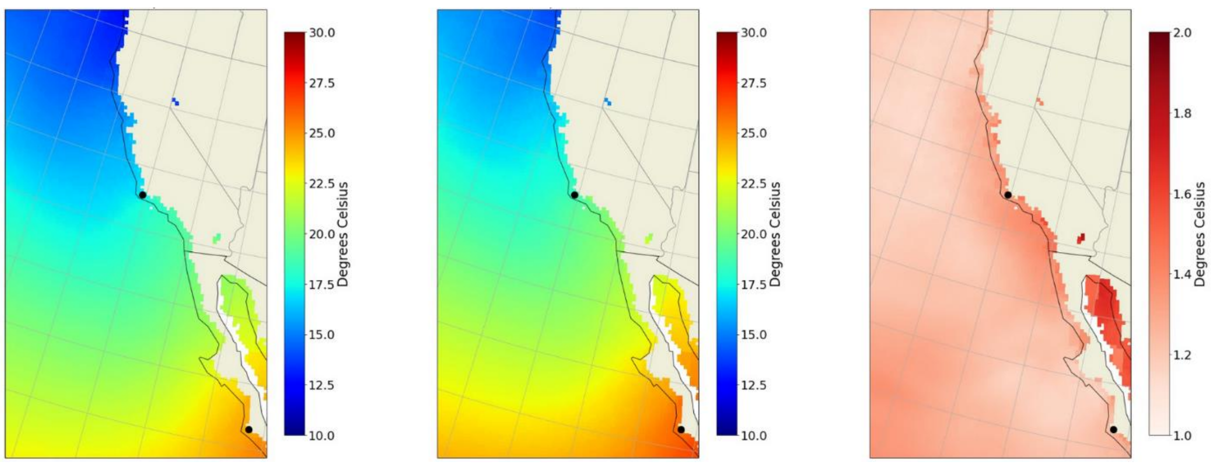

Figure 2. **Surface Temperature Past vs. Future Comparison:** A) Past baseline projected by the climate models simulation of average temperature from 1982-2005; B) the predicted average temperatures under the RCP 8.5, BAU scenario from 2021-2050 for the range of the California halibut in California to its southern extent in Baja; C) difference between the modeled past and future temperatures in degrees Celsius. Points of note in the CA halibut range are shown with black circles; the northern marker is at Point Conception and the southern marker is at Magdalena Bay. ***Note: any past data that are from 1982-2005 are from the climate models or climate models + adjustments; any past data from 1982-2010 are observed data from NOAA.*

To adjust for biases in the model output data, the observed NOAA daily annual average historical data (Figure 3A) were added to the difference between the modeled baseline output and modeled future output (Figure 2C, Figure 3B) to create a bias adjusted map (Figure 3C). This process was used to normalize the data toward the future and correct for any past biases from the modeled past projections. Most maps in Figures 2 and 3 are used to help readers understand the methodology for bias correction. The bias correction was determined to be fairly accurate and effective (Appendix).

In future BAU projections, there is a trend of warmer waters moving north (Figure 3C). From Point Conception to the California/Mexico border (Figure 3C), the future annual average range is from 20-22°C. Historically, from NOAA observation, this same region's annual average range was from 15-18°C (Figure 3A) . For the adjusted annual projected SST, Magdalena Bay averages 27.5°C (Figure 3C).

A. NOAA (1982-2010) B) Temperature Change (RCP 8.5- BS) C) RCP 8.5 (2021-2050)

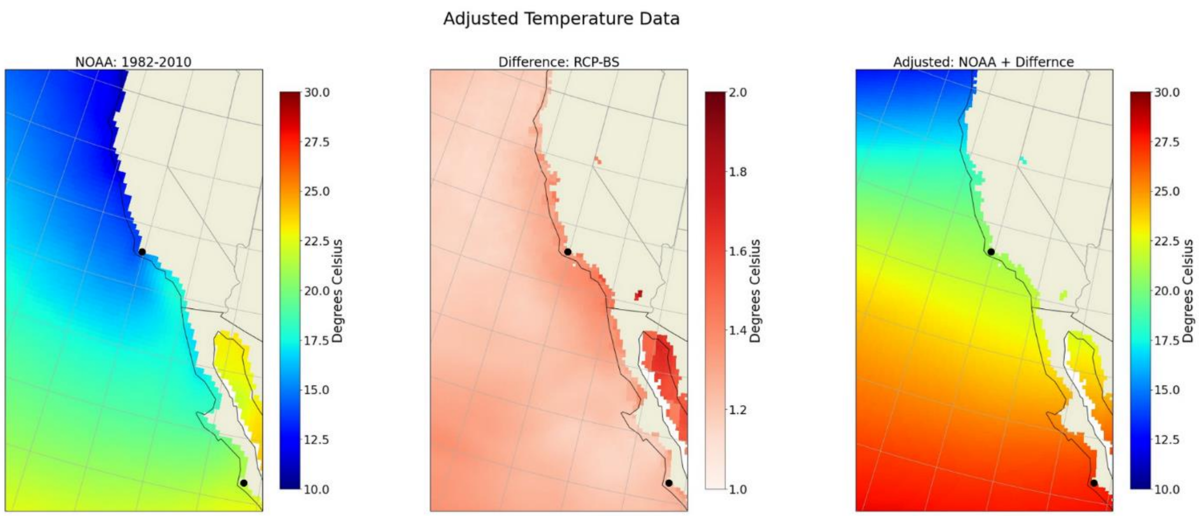

Figure 3. Average Annual Temperature Maps: A) Historical NOAA observations from satellite data (1982-2010); B) temperature change between the RCP 8.5 (BAU) and past baseline simulations from the climate models (same as Figure 2C); and C) future projection which is the sum of panels A and B. Points of note in the CA halibut range are shown with black circles; the northern marker is at Point Conception and the southern marker is at Magdalena Bay. ***Note: any past data that are from 1982-2005 are from the climate models or climate models + adjustments; any past data from 1982-2010 are observed data from NOAA.*

The adjusted map for historical baseline (Figure 4A) demonstrates that for 200-310 days of the year, Southern California remains within the optimal egg temperature threshold between 12°C and 20°C. In the projections for the BAU future climate outputs (RCP 8.5) from the models, the optimal temperature threshold includes much more of Northern California within that range, with Central and Southern California falling below (Figure 4B).

A. Hist. Baseline (1982-2005) B) RCP 8.5 (2021-2050) C) Difference (A-B)

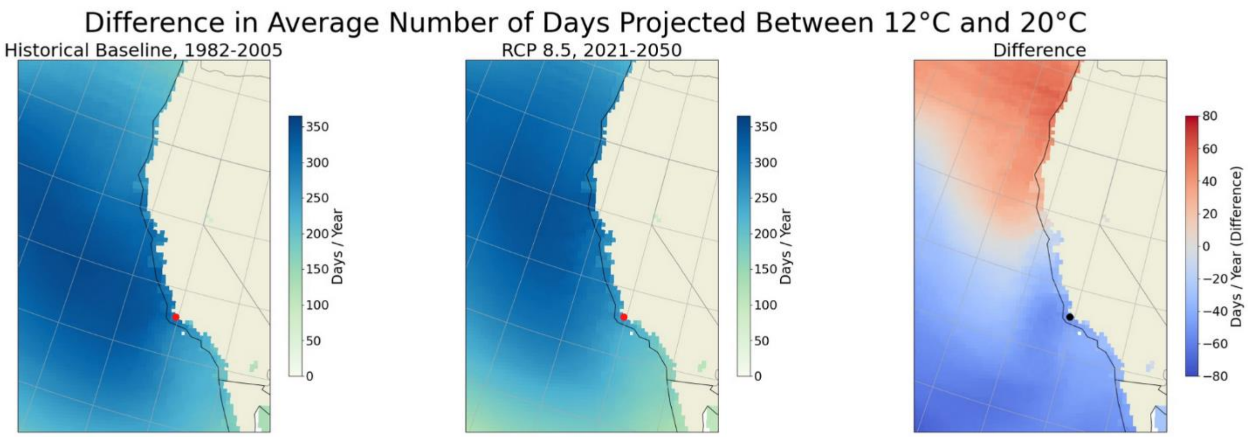

FIgure 4. Difference in Average Number of Days Projected in the 12-20°C Thermal Tolerance Range: A) The adjusted historical baseline from 1982-2010 for average number of days in the preferred thermal range for eggs; B) the average projected RCP 8.5 (BAU) map ranging from 2011-2050; C) the projected difference between historical average days and the projected average days in a BAU scenario. . Points of note in the CA halibut range are shown with red and black circles, with the northern marker at Point Conception.

Examining the map in Figure 5 in more detail, the number of days remaining inside the suitable range in the future from the Southern population from Point Conception down to the Southern California border decrease by 25-45 days due to increased temperatures. In the trailing edge of the species range in Baja, there are anywhere from 15-40 days fewer annually where the temperature would exceed 20°C, as the highest viable temperature threshold for eggs. At Magdalena Bay, it's much closer to 15 days. It is much warmer in Magdalena Bay under historical observations (Figure 3A), which is why the small increase could still have an impact, however, not as big an impact as in more northerly waters. In Northern California, the average number of annual days increase to as much as 40 days more within the preferred temperature range.

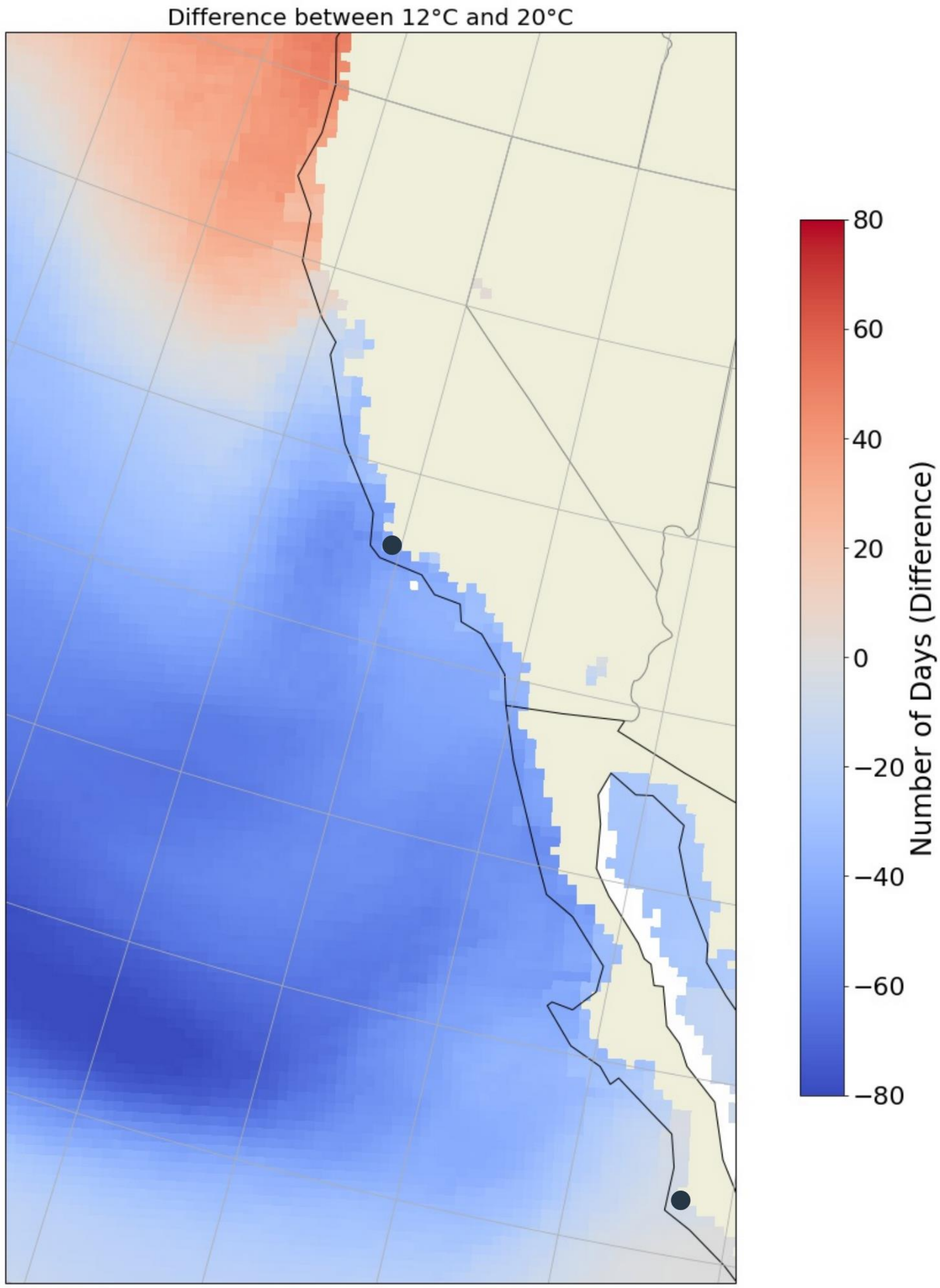
Difference between 12°C and 20°C
80
60
40
20
0
−20
−40
−60
−80
Number of Days (Difference)

Figure 5: The Contrast in Future Days Outside of Suitable Thermal Egg Tolerance. In this map, the range of the California halibut is exhibited from the northern California border to the trailing edge of the species at Magdalena Bay. This is the larger version of Figure 4C to show the contrast in greater detail. Points of note in the CA halibut range are shown with black circles; the northern marker is at Point Conception and the southern marker is at Magdalena Bay.

Discussion

Annual future projections out to 2050 demonstrate an additional 25-45 days per year that are too warm for egg viability in the CDFW-defined southern stock population of California halibut from Point Conception down to the Southern California border (Figure 5). Those days are in addition to the historical annual average of around 65-185 days out of the year for the southern population where the SST is outside of the 12°C -20°C optimal threshold (Figure 4A). Considering the difference, that could be a total of 230 days out of the year that are unsuitable for egg survivability in the Southern California Bight. In this region, there is a projected annual increased temperature range from 20-22°C (Figure 3C), which is much higher than annual NOAA observed averages of 15-18°C (Figure 3A). Although 22°C is above the optimal range, we do not necessarily know what impact this would have on egg development.

Research suggests that in Northern/Central California, there has been a rapid increase in California halibut stock since 1995 (CDFG 2011). This raises the question about if the low recruitment since the 2000s in Southern California is from a population decline or the movement of fish to a different region. Based on the results from this study, it is possible that California halibut are already responding to increases in ocean temperatures.

Across the entire west coast there will be at least a 1-1.4°C increase in projected SST (Figure 2C). At the southernmost end of the range for California halibut in Magdalena Bay, this temperature increase could have serious implications. Future projections for SST in the area are approximately 27.5°C (Figure 3B). This increase from a historical average of 22°C (Figure 3A) to an annual future average of 27.5°C suggests that there would be poor recruitment at the southern boundary of the species range, assuming the halibut still spawn, as the eggs would likely arrest in early stage development at or before 24°C (Gadomski and Caddell 1991).

Recruitment is also thought to be negatively affected by warm waters (Berkson 1990). In 1987-1989, the California halibut fishery saw a much higher recruitment than in 1981-1983, which is believed to be a result of the warmer waters brought on by El Niño in that time frame (Berkson 1990). If the eggs can't successfully survive at the southern trailing edge of their geographic range, there will likely not be successful recruitment and eventually there will likely be a population shift north to cooler waters. This implies a species range shift north if recruitment is less successful in Magdalena Bay.

Many assumptions were made in this analysis. Neither upwelling nor depth were taken into account in this technical report, which we acknowledge have impacts on oceanic temperatures. We also acknowledge that California halibut eggs are pelagic and not just found on the surface. However, as discussed in the Introduction, rising sea surface temperatures have been used as a proxy in previous studies, and California halibut spawn nearshore where SST is likely a good proxy for preferred temperature. There are many additional factors outside of a controlled lab environment that could negatively impact eggs and their development and recruitment in the ocean. Here, we are using SST as a first step to understand how egg development, and the resulting California halibut recruitment, might be negatively impacted in the future due to increasing SST from climate change. This is a model that can be used for many other species as well, some of which are already underway at the Coastal Research Institute and Loyola Marymount University.

Future Study Recommendations

Future studies should examine how frequently these increased temperatures would last to analyze the extent of the impact. Another recommendation is to investigate where exactly the 24°C isotherm line exists now and in the future, and how often the threshold is exceeded to have a greater geographic understanding of the extent of egg thermal tolerance.

Climate velocity (a metric to examine the speed and direction/rate of a species range shift due to temperature impacts from climate change) is a great tool to examine impacts and could be examined in the future for California halibut. It is a more nuanced approach to calculate climate impacts for the species that would take into account adult species, depth, direction, and movement from climate change impacts throughout the species range (Morley et al. 2018).

Fisheries Management

Overall, an increase in SST by at least 1°C will result from climate change by the 2021-2050 time-frame within most of the California halibut range, which may have implications on the species geographic range. This will likely result in lower recruitment on the southern extent of the species range, which would result in the geographic edge eventually moving north to a more suitable temperature threshold where egg development would still be successful. We recommend that CDFW look at fisheries management through a climate lens when developing their FMPs. California's fisheries, including California halibut, are regulated based on geography. This analysis shows there may be northward range shifts of California halibut in the coming decades. CDFW is currently moving forward with a stock assessment, an ESR, and an eventual FMP for California halibut, and these potential climate change related range shifts need to be taken into account for this fishery to be adaptive and climate ready.

Climate-adaptive fisheries management not only mitigates negative impacts on fish stocks, but is also more profitable and beneficial for the fishery as a whole (Free et. al. 2020). Based on these results, we highly recommend CDFW develop climate-adaptive fisheries management for the California halibut and incorporate adaptive measures in the FMP. These measures include adjustable harvest rates, flexible management districts, the establishment of transboundary cooperation across the entire range of California halibut, and regularly planned adaptive interventions at five year intervals. We urge CDFW to use this analysis as a reference for potential range shifts and recruitment and disbursement changes when adapting management districts for California halibut and as a template for future analysis of climate impacts on California's fisheries.

Conclusion

Future climate modeling from this report shows increased SST may cause decreased egg viability and recruitment for the California halibut, with potential consequences of stock range shifts northward. These results represent potentially substantial shifts in geographic range, recruitment, and distribution of this species that would have serious implications for the fishery. Climate-adaptive fisheries are not only beneficial to stocks, but to the economic viability of the fishery, and climate models should be used to create adaptive management strategies and prepare for future climate scenarios. Climate-ready fisheries management must consider climate impacts now, as it is no longer a problem of the future.

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Appendix

As compared to the yearly average number of days that fall within the temperature threshold and historical time range (Figure 5A), we can see that there is a very small difference in standard deviation, lying between 0-2 days. This shows that bias correction for historical data is fairly accurate.

A) Average Number of Days between 12-20°C B) Standard Deviation

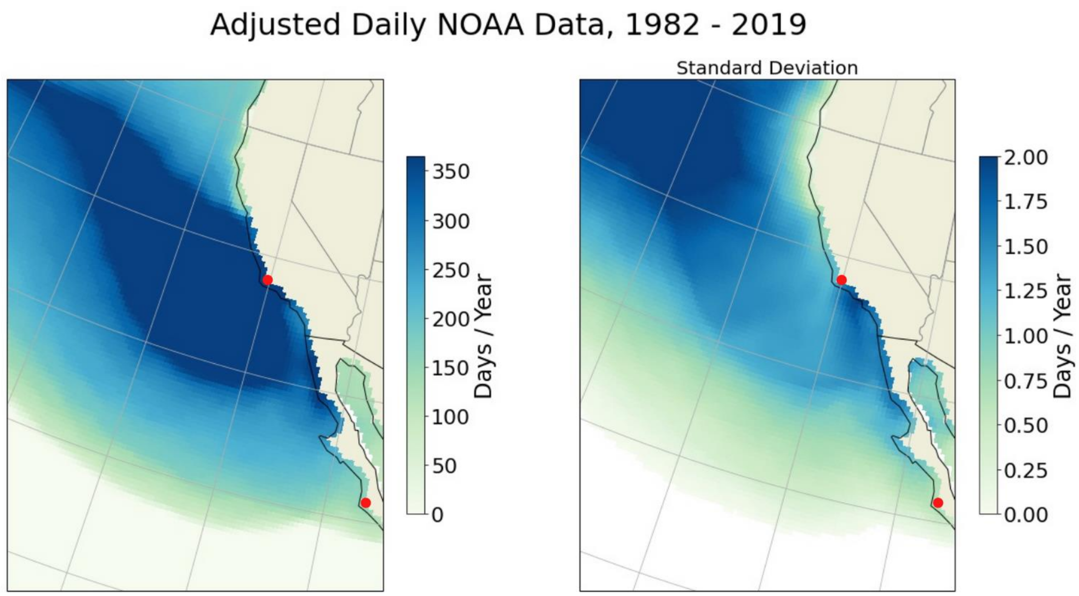

Figure 1. Adjusted Daily Historical Baseline from 1982-2019: These maps demonstrate the standard deviation (B) we would expect to see based on the adjusted historical NOAA data (A) that has been bias corrected and is within the preferred egg temperature range. Points of note in the CA halibut range are shown with red circles; the northern marker is at Point Conception and the southern marker is at Magdalena Bay.