Appendix E. Developing Indicators of climate change and variability

This appendix is intended to (1) update the Council on research advances that support climate-informed decision-making for managed and protected species in the CCE, and (2) continue the ongoing "conversation" between the CCIEA team and the PFMC on how best to present climate considerations in the CCIEA-ESR. This effort stems from an EAS recommendation to incorporate climate change information into the ESR for Council management considerations (Supplemental EAS Report 1, March 2021, Agenda item I.2.b) and has been improved based on recommendations from the SSC-ES (Agenda Item H.1.a SSC-ES Report 1 March 2023). We are eager to expand the provision of forward-looking climate information as Council needs, CCIEA team workload, and page limits allow.

Based on feedback from the PFMC and its associated subcommittees, this year's appendix divides the information presented into three categories: the continued discussion on how we present such information, short-term predictions, and long term forecasts. As outlined below, these three sections are designed to provide context for the use of forward-looking climate information and then offer examples of the types of information that can be provided on two timescales: short term forecasts (i.e., what will happen in the next year), and long-term projections (i.e., what trends can be expected over multi-decadal timescales).

1. Discussion of sources of uncertainty in climate predictions and projections, to contextualize the use of this information in decision making. There are a number of sources of uncertainty, including how the climate will evolve, how climate is related to biological responses, and how those relationships may change over time.

    From this section, we highlight our discussion of the differences in uncertainty between short-term predictions and long-term projections, and reiterate our thesis that although imperfect, forecast information can support improved outcomes over time.

2. Discussion of the potential impacts of the ongoing El Niño of 2023-24, predicted ocean conditions in the coming months, and the relevant indices that might be used to forecast and track the impacts of El Niño on the CCE.

    Here, we highlight our comparison of the ongoing event vs the most recent large El Niño of 2015-16, and stress our conclusions that even though El Niños have a lot of inherent variability between events that make direct quantitative forecasts difficult, we can draw many inferences that are useful for management; e.g., the preconditioning of the system during 2023 should mitigate some of the effects of the current El Niño.

3. Projections of long-term shifts in the distribution and abundance of managed species under climate change scenarios, as well as associated vulnerability and risk for West Coast fishing fleets. This section highlights recent work stemming from the Groundfish, Climate Change, and Communities in the California Current (GC5) and Future Seas projects.

Lastly, from this section we highlight new findings suggesting that sablefish and shortspine thornyhead will decline substantially in abundance by the end of the century, and as a result of greater exposure and economic dependence, risk due to climate change is predicted to be greater for more northern groundfish fishing fleets. Similarly, a marked northward shift in the latitudinal center of gravity for sardine, and continued boom/bust cycles for sardine and anchovy were projected. Based on these shifts, it was concluded that successful future fishing could depend on the ability to switch between a diverse set of target species and the ability to take advantage of new opportunities in terms of fishing location, port, and species.

The main body of this appendix will be available in the supplemental briefing materials for the March 2024 Council meeting under Agenda Item H.1.a, Supplemental CCIEA Report 2: 2023-2024 California Current Ecosystem Status Report Appendices.

E.1 Uncertainty in Climate and Ecosystem Predictions

A key consideration when using forward-looking climate information to support decision making is the level of uncertainty in this information. In this context, one must recognize that forward-looking information will not be perfect, but will be able to identify more likely outcomes. Similarly, one should expect that while decisions made based on this information will not be perfect, they will be better than they would be without it - if one could win 60% of blackjack hands they would become rich over time, despite losing individual hands along the way.

We highlight three key sources of uncertainty: (1) uncertainty in how the climate itself will evolve, (2) noise in environmental and ecological relationships, and (3) changes over time in environmental and ecological relationships (also known as "nonstationarity"). We describe each source of uncertainty, and detail how it is accounted for in physical and biological models.

Short-term predictions and long-term projections of climate conditions
In short term climate predictions (i.e., what will happen in coming weeks and months), the greatest source of uncertainty is internal variability. This internal variability is unpredictable change that occurs due to the naturally chaotic nature of the climate, i.e., the "butterfly effect", in which very small changes at one time can lead to large changes later on. In order to account for this uncertainty, climate forecasts (like weather forecasts) are actually made up of many forecasts started from slightly different conditions- i.e. an ensemble of forecasts. From this ensemble, one can generate a probability of what will happen given uncertainty (e.g., "30% chance of rain"). When working with such forecasts, it is critical to also conduct retrospective analyses of predictive performance so that forecasts can be presented alongside information about how accurate they are likely to be.

Unlike short-term predictions, in long-term climate projections (i.e., multiple decades in the future), the primary sources of uncertainty are in human actions (e.g., how will emissions change?) and in the sensitivity of the climate to those changes. In order to account for these uncertainties, scientists use an ensemble of projections, utilizing multiple emissions scenarios and models with different climate sensitivities, to generate a range of possible future outcomes rather than trying to predict a single outcome. The aim of projections is different from predictions; in predictions we are trying to predict what will happen in a given place and time (e.g., a marine heatwave will occur off Oregon in September), while in projections we are trying to predict trends over long periods of time (e.g., marine heatwaves off Oregon will be warmer on average at the end of the century than they are now).

Noise in environmental and ecological relationships

Often, our understanding of responses between environmental variables, or between species and their environments, are based on empirical correlations. For example, during El Niño events, there is a tendency towards warmer, less productive conditions in the CCE. However, these relationships do not reflect a perfect 1:1 match; El Niño events shift the probability of a given outcome, but don't guarantee it. For example, cold CCE conditions can occur during El Niño (e.g., Fiedler and Mantua 2017). Thus, when drawing information from correlative relationships one must realize that individual years may deviate from the "expected" outcome, but the relationship still provides useful information (i.e., enabling predictions that are better than if climate were ignored altogether).

Nonstationarity in environmental and ecological relationships

Non-stationarity refers to when a relationship between variables has changed such that past correlations no longer apply. Such instances have been documented in the literature, either between physical variables (e.g., Litzow et al. 2020) or between marine species and their environment (e.g., Myers 1998, Szuwalski and Hollowed 2016, Litzow et al. 2018). An example for the northeast Pacific is the relationship of sardine and anchovy populations with the PDO; we have seen the breakdown of the paradigm that the positive PDO phase is beneficial to sardines with negative PDO phase beneficial for anchovy (Chavez et al. 2003). In some cases, nonstationarity may actually represent a change in the ecosystem dynamics (e.g., adaptation; Ward et al. 2022), while in others it indicates that the correlative relationship was not capturing the relevant dynamics to begin with and should be replaced with something more robust. Scientists have several means of mitigating potential concerns of nonstationarity: (1) develop more mechanistic environmental-biological relationships (e.g., modeling species responses to proximate ocean temperatures and other conditions rather than large-scale climate indices), and (2) following the approach of the climate community, use ensembles of ecological models with different formulations to capture uncertainty and identify robust responses. For example, the Future Seas project (Section E.3) illustrates both approaches by developing multiple models for sardine that are structurally very different and seeing what future changes are consistent across them.

Another pertinent example within the CCE also involves the PDO index. For the past several years, the PDO has been negative, which normally would indicate cool and productive coastal waters, yet we have instead seen repeated coastal warming due to marine heatwaves, and mixed productivity. Litzow et al. (2018; 2020) examined the relationship between the variables underlying the PDO and NPGO relationships, and their use as indicators of salmon survival in the Gulf of Alaska. They found that there had been a change in the correlations of these indices with the modes of SST variability pre and post 1989, thus slightly altering the relative "meaning" of what these indices were describing physically. Furthermore, Feddern et al. (2024, in prep) examined SLP and SST relationships through 2023, and found that the underlying relationships of SLP and SST have further changed during the recent "MHW era" (2014-current), which likely will confer different relationships between climate indices such as the PDO and NPGO and certain ecological observations. Thus although the PDO state still generally describes the overall system and therefore retains usefulness, regional responses may vary potentially due to shifting correlations between these basin-scale indices and local processes; a feature we have documented in the current and past IEA ESR's.

E.2 Potential impacts of the 23-24 El Niño

West coast scientists are actively developing and evaluating capabilities for seasonal (1-12 month) forecasts of CCE conditions and ecosystem responses. For this year, we focus on the ongoing El Niño, expectations for ocean conditions in the CCE, and discussion of potential impacts of these climate drivers on the biology of the CCE.

Forecasting the El Niño-Southern Oscillation (ENSO)

By mid-2023, it became evident that El Niño would likely develop during winter 2023-24. In June 2023, the Climate Prediction Center (CPC) predicted an ~85% chance that a moderate to strong El Niño would occur. These predictions are based on an ensemble of forecasts from climate models (analogous to weather forecasts). At the time of writing (Feb. 2024), a strong El Niño is ongoing. The latest CPC forecast suggests that El Niño will persist into spring before returning to a neutral ENSO state (79% chance by May; Fig. E.1), and subsequently to La Niña over the summer and fall (>50% chance).

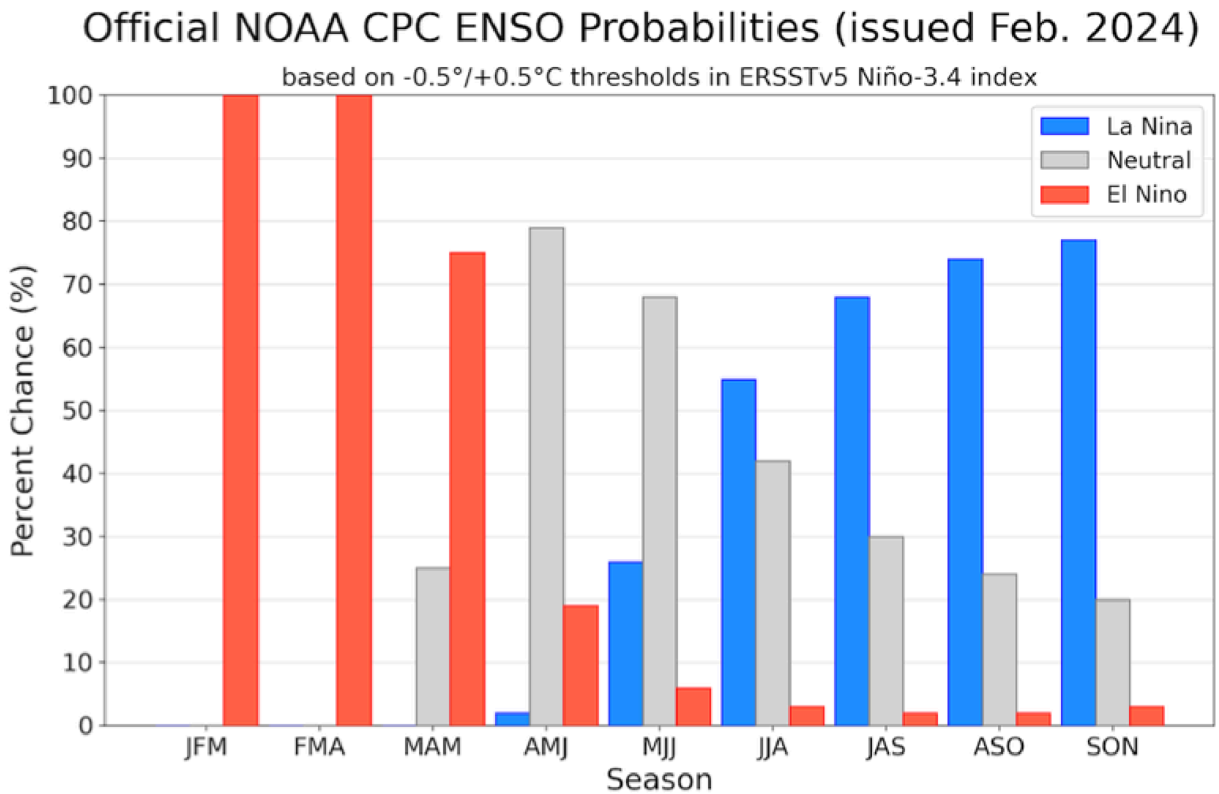

Figure E.1 CPC ENSO forecast, indicating the changes of El Niño, La Niña, or ENSO-neutral conditions for 3-month periods based on an ensemble of climate model forecasts. Accessed Feb. 15, 2024 at https://iri.columbia.edu/our-expertise/climate/forecasts/enso/current/.

Forecasting physical conditions in the CCE

While ENSO is the dominant source of predictability for conditions in the CCE, there is not a perfect correspondence between the two (see Section E.1). For example, the Southern California Temperature Index (SCTI; https://spraydata.ucsd.edu/products/socal-index/) – a measure of subsurface temperature off Southern California based on underwater glider measurements - is highly correlated with the Oceanic Niño Index (ONI), and thus shows a response of southern California waters to El Niño. However, the indices sometimes diverge – for example, in 2014-15, when influences other than ENSO drove extreme local warming (Fig. E.2). Similarly, the SCTI shows that southern California temperatures have cooled slightly since late 2023 while tropical Pacific temperatures remain elevated.

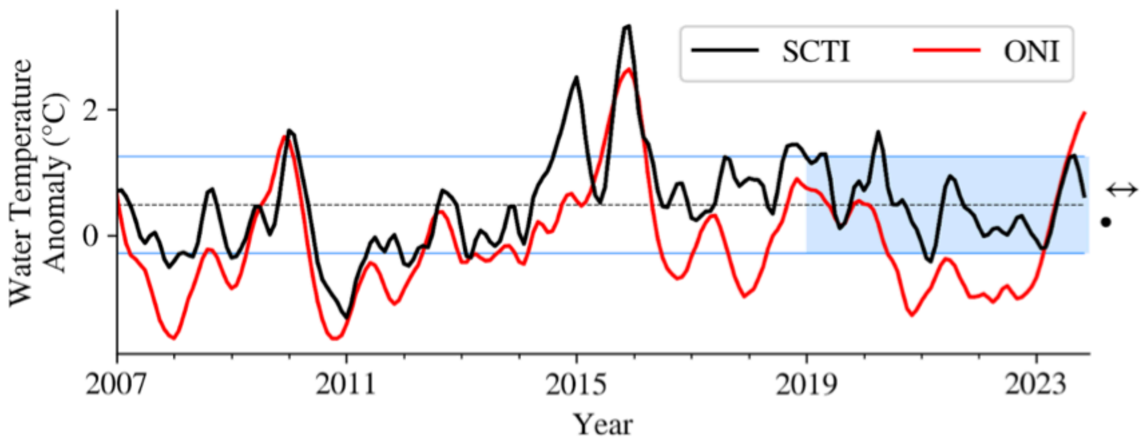

Figure E.2 The Southern California Temperature Index (SCTI) and Oceanic Nino Index (ONI). Blue shading highlights the last five years, with dashed line and thin blue lines indicating the long term mean and standard deviation, respectively, for SCTI. The arrows and dot to the right indicate that the recent 5-year period shows no significant trend and is within the historical variability.

Newly developed global marine heatwave (MHW) forecasts provide tailored predictions of MHW activity in the coming months; the latest forecasts (from Feb. 2024) suggest an elevated risk of MHWs (~50%) continuing through March before declining (<10%) into summer and fall ([Fig. E3](#)).

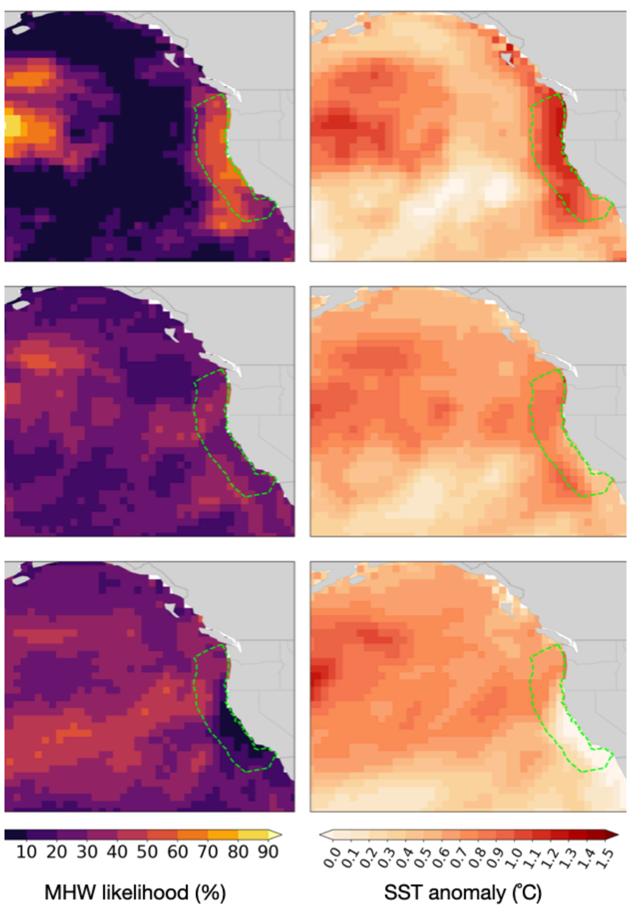

Figure E.3 Forecast likelihood of marine heatwaves in the Northeast Pacific Ocean through spring/summer 2024. (Left) Forecast MHW probability and (right) forecast SST anomaly for three months (top-bottom; March, May, August). The U.S. EEZ is outlined in green. Forecasts are updated each month and are available from psl.noaa.gov/marine-heatwaves.

Potential Impacts: Context from the 2015-16 El Niño

When considering potential impacts during a strong El Niño, we first look to prior events. During the last such event, in 2015-16, many physical CCE conditions were characteristic of El Niño – warmer than normal coastal waters, changes in source waters, stratification, and transport, lower nutrient availability, and lower overall surface productivity. In contrast, strong upwelling-favorable winds were counter to the typical El Niño response. Biological impacts included decreases in high-energy prey (lipid-rich copepods off OR), eggs of small pelagics (CalCOFI region), and high-energy forage species in general. Salmon faced poor conditions due to drought, warmer streams and below average snow-water equivalent. Larger predators such as sea lions and fur seals had trouble finding good forage, which led to unusual mortality events. On the positive side, 2016 saw increases in commercial landings (driven by a few species), and anecdotal reports of catching warm-water HMS species earlier, farther north, and closer to shore than normal. Impacts in the CCE during the last major El Niño (2015-16) were summarized in the CalCOFI State of the California Current report (McClatchie et al. 2016) and the annual IEA-ESR from 2015-16 (Harvey et al. 2016; Harvey et al. 2017).

While 2015-16 provides a useful reference for 2023-24, several significant differences between the events are worth noting. Most importantly, prior to the 2015-16 El Niño the CCE was still in the throes of the unprecedented marine heatwave known as "The Blob". Coastal temperatures were already extremely warm (Jacox et al. 2016), with many impacts (e.g., species distribution shifts) having already occurred. In contrast, heatwaves in 2023 remained mostly offshore (with occasional intrusions into coastal waters summer/fall) and did not penetrate nearly as deep into the water column. Additionally, the prey fields were vastly different leading into these two El Niños. Recent years have seen record levels of anchovies in the southern part of the CCE, an increase in sardine to the north, and abundant lipid-rich copepods and krill. None of these conditions were present in 2015. One similarity between the two events was the abundance of rockfish larvae/juveniles, which were extremely high in both 2015 and 2023, perhaps related to locally favorable upwelling conditions (Leising et al. 2015).

Potential Impacts in 2024

In December 2023, the CCIEA team met to discuss potential impacts of the ongoing El Niño, and compiled the following opinions regarding various aspects of the CCE for the upcoming 2024 season (Table E.1). These potential impacts reflect conditions with an *increased likelihood* of occurrence. They are based on expert opinion building on past observations, and current and predicted ocean conditions.

In summary, ecosystem conditions are generally expected to decline in 2024 due to the ongoing El Niño and associated impacts. However, impacts are likely to be mitigated by the preconditioning of the system during 2023, specifically a robust prey assemblage and limited pre-existing impacts of marine heatwaves along the coast. Current forecasts also expect that this El Niño, and associated CCE warming, may not last as long as past strong El Niños. While available tools and knowledge allow us to identify likely conditions in the months to come, we will continue to carefully monitor relevant local ecosystem indices such as regional snow-water equivalent, ocean temperature, upwelling, habitat compression, copepod species richness, krill abundance and adult size, and the abundance of other prey species, such as anchovy and larval rockfish.

Species/index	Potential Impact
Snow water equivalent	More initial snowpack forecast, but likely warmer weather transitions to rain instead of snow
Habitat compression	Habitat compression through spring
Copepods	Increase in southern (lipid poor) species and increase in species richness
Krill	Lowered abundance, lower adult sizes
Anchovy	Continued relatively high numbers but likely lower than past few years
Market squid	Lower abundance and northward shift
Rockfish	Dominated by larvae
Sablefish	Larger and closer to shore
Salmon	Poorer conditions for all stages
Sea lions	Reduced pup weights/productivity
Harmful algal blooms	Increased HAB activity and subsequent closures

Table E.1. Potential CCE impacts during 2024, assembled by the CCIEA team

E.3 Projections of species distributions and abundance and risks for fishing fleets

Climate change can have complex impacts on the distribution and abundance of managed and protected species. Many natural resource and conservation scientists use species distribution models (SDMs) to help understand environmental niches and habitat usage of key species. In last year's report, we presented long-term projections of sardine distribution under different climate scenarios (Smith et al. 2021, Harvey et al. 2023). This year, we summarize recent research on (1) how the distributions and abundance of West Coast groundfish and CPS may change under projected climate change, and (2) the social-ecological vulnerability and risk for groundfish and CPS fishing fleets due to changing ocean conditions.

These results stem from two pioneering projects: Future Seas (https://future-seas.com) and Groundfish, Climate Change, and Communities in the California Current (GC5; https://www.integratedecosystemassessment.noaa.gov/regions/california-current/gc5-ecosystem-research) . These projects, which both conduct end-to-end analyses linking climate to fish, fisheries, and communities, aim to inform strategic planning and inform Council actions to improve adaptive capacity. In the sections below, groundfish results are from GC5 while CPS results are from Future Seas.

E.3.1 Projected changes in distributions and abundance

E.3.1.1 Groundfish

Focusing on the Dover sole-thornyhead-sablefish (DTS) groundfish complex, Liu et al. 2023 project that sablefish and shortspine thornyhead will decline substantially in abundance by the end of the century due to changes in bottom temperature and dissolved oxygen under multiple climate change scenarios (Fig. E.4). These species will shift offshore, deeper, and further away from current core fishing grounds (Fig. E.5). In contrast, Dover sole is expected to stay at a similar abundance or even increase in abundance in the California Current (Fig. E.4). The contrasting changes among species may cause a spatial reshuffling of primary and secondary target species, and create a different groundfish fishery in the future than exists today.

The results of this study for sablefish seem to contrast with the recent boom in juvenile sablefish that has been discussed in Section 3.4 of the main report. However, both phenomena can simultaneously be true: episodic good recruitment years can still be expected under climate change, even if long-term abundance is declining or the species is shifting its distribution. Moreover, an environmental driver may have different effects on different life history stages—increases in temperature, for example, could be beneficial for recruitment but deleterious for growth or survival. These are all questions that the CCIEA and NMFS researchers are planning to pursue further, namely: How does climate change affect fisheries on a short-term (1-5 years) basis? How can we reconcile estimates for century-scale shifts with short-term stochastic events like episodic recruitment pulses?

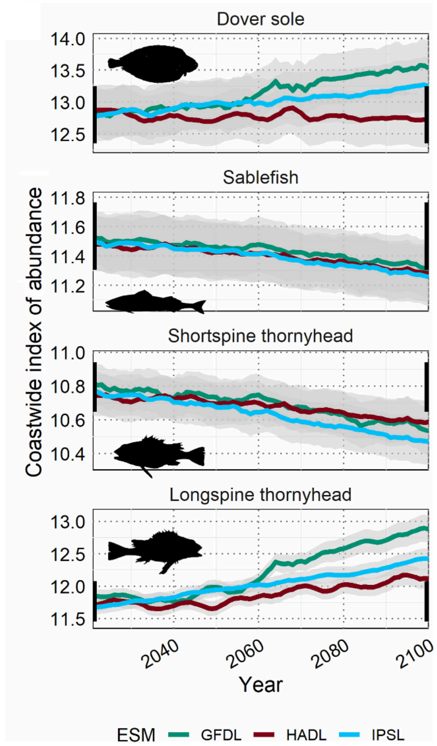

Figure E.4: Projected ensemble abundance indices for the four species comprising the DTS groundfish complex under three different climate models, presented as 5-year running averages. Solid lines are median projection values, and ribbons display ±1 SE. Black vertical bars denote the range of historical variability in the abundance index for each species from 1985 to 2010. GFDL, HADL and IPSL correspond to the three Earth system models (ESM) used to develop dynamically downscaled projections of bottom temperature. All three ESMs project warming within the California Current, with magnitudes of mean bottom temperature increases by 2100 ranging from <0.5°C under the GFDLmodel to >1.1°C under the HADL model. From Liu et al. *2023.*

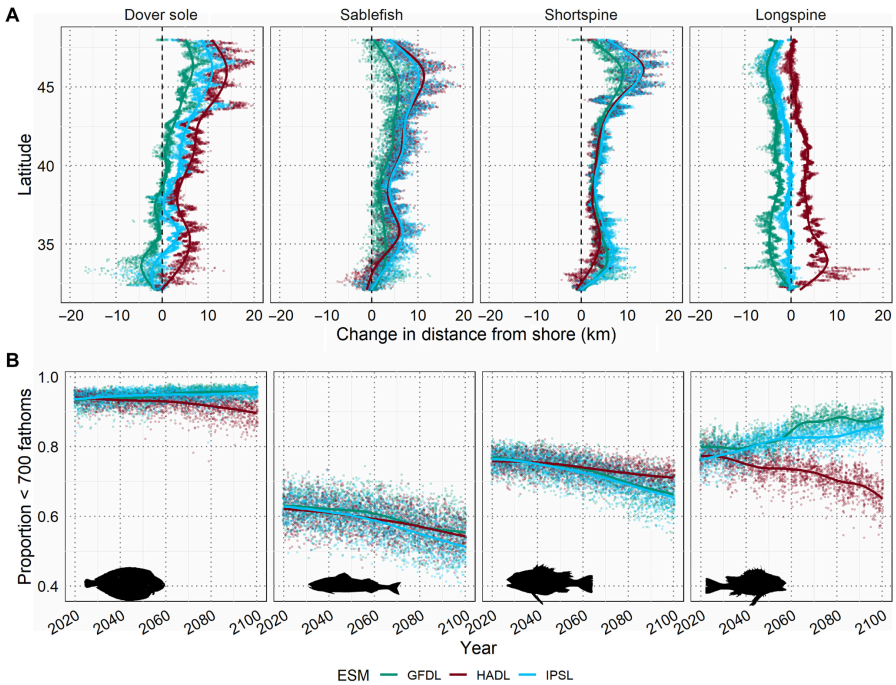

Figure E.5: (A) Projected change in the weighted distance from shore centroid of groundfish species' distributions, comparing the 2075–2100 mean to the 1985–2010 baseline period. Values to the left and right of the dashed vertical line at 0 indicate species whose distributions are expected to shift onshore and offshore, respectively. Individual points indicate values from one simulation of the 100 performed for each species and CCROMS-ESM projection (panels). Lines are locally estimated scatterplot smooths. (B) Projected changes in depth distribution for each species, displayed as the proportion of summed catch in areas shallower than 700 fathoms, the current depth limit of allowable bottom trawling. Points and lines are as described in (A). GFDL, HADL and IPSL correspond to the three Earth system models (ESM) used to develop dynamically downscaled projections of bottom temperature. From Liu et al. 2023*.*

E.3.1.2 Coastal pelagic species (CPS)

SDMs were developed for several key CPS through the Future Seas project. Models were trained using observations from NOAA fisheries-independent trawl surveys, and dynamically downscaled projections from three different earth system models (Pozo Buil et al. 2021) to consider future shifts in their distributions through the year 2100. Results show a marked northward shift in the latitudinal center of gravity for sardine (Fig. E.6), and this shift was more pronounced and occurred earlier in the ESMs with stronger warming (IPSL and Hadley). In contrast, less migratory species such as anchovy do not show substantial northward shifts in their distribution in the future (Fig. E.6). These results suggest that the degree to which species will move poleward in the future is strongly dependent on their ecology.

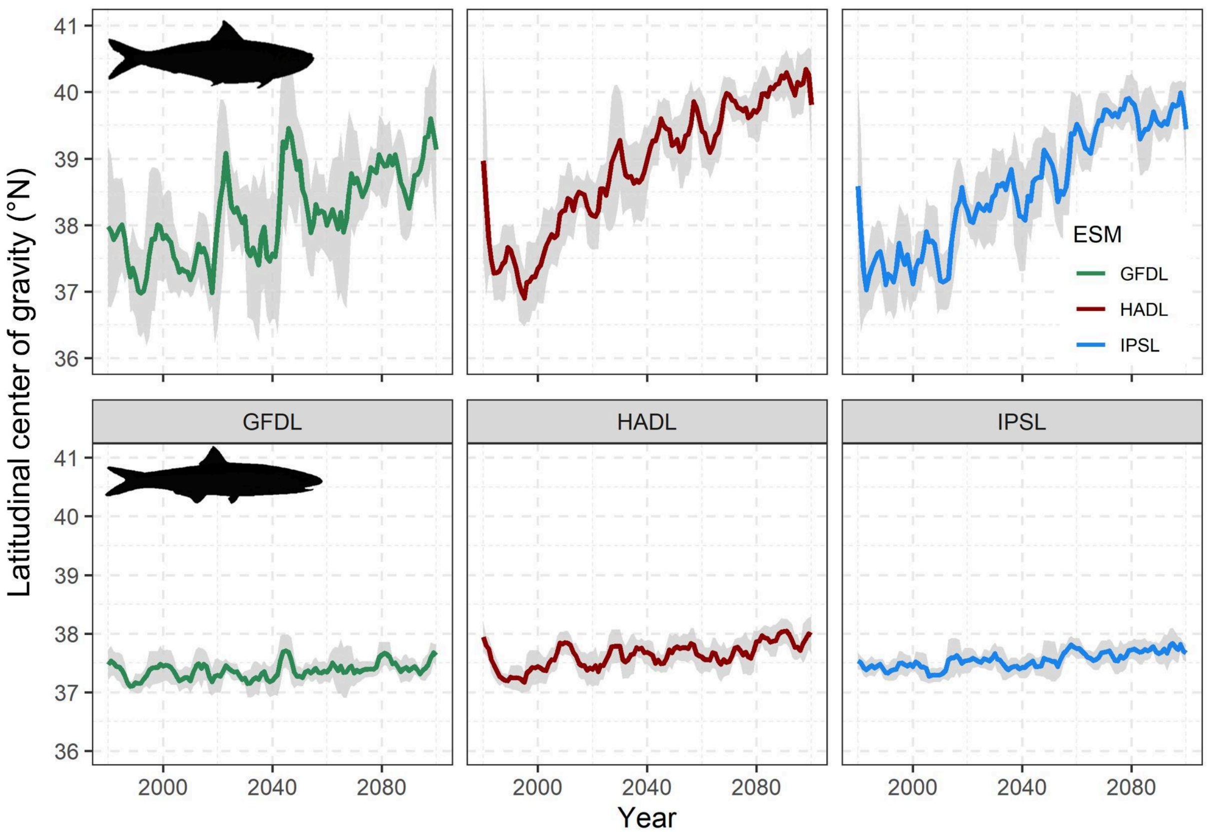

Figure E.6: Projected shifts in distribution center of gravity during the month of April for Pacific sardine (top) and northern anchovy (bottom) from three different dynamically downscaled earth system models (ESMs: Pozo Buil et al. 2021). Solid lines are 5-year running means, and ribbons display ±1 SD.

Changes in center of gravity for sardine distributions primarily reflected an increase in suitable habitat in the northern California Current System during cooler months (Fig. E.7). SDM projections also show a corresponding slight decrease in suitable habitat in the southern study area. However, the sardine SDM is assumed to primarily capture the northern subpopulation of sardine. Southern subpopulation fish, which are currently most prevalent off Baja California, may increase their presence in U.S. waters in the future as water temperatures continue to warm.

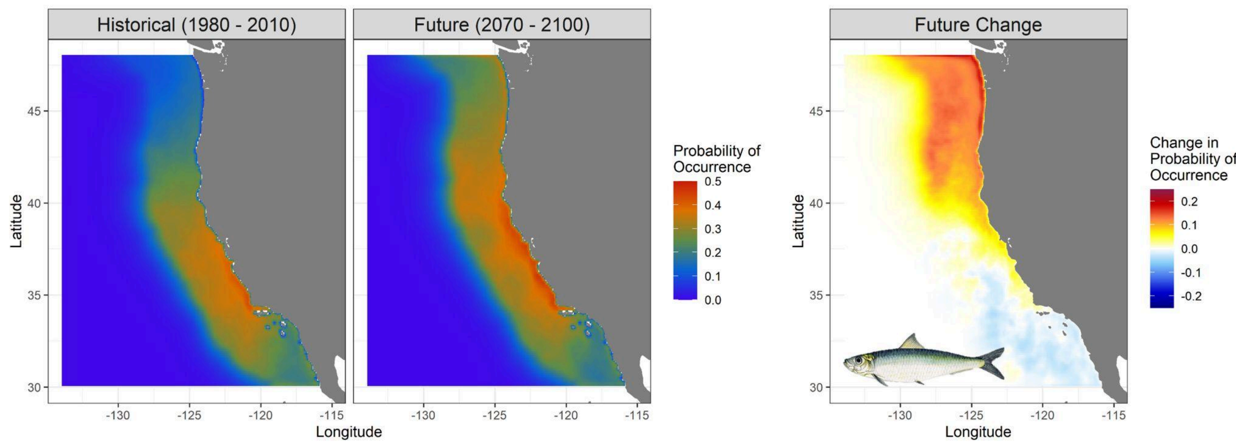

Figure E.7: Projected shifts in sardine distribution for the month of April from a dynamically downscaled earth system model (GFDL: see Pozo Buil et al. 2021). The left maps show mean April distributions for the end of the 20th and 21st centuries, while the map on the right shows the difference between the two time periods.

To generate projections of future abundance for sardine and anchovy, a mechanistic, age-structured population dynamics model was developed for sardine (Koenigstein et al. 2022) and anchovy (Koenigstein et al. in prep). These models resolve early life history processes of sardine and anchovy in detail, with early life stage survival being affected by projected changes in temperature, upwelling, and planktonic food availability (Koenigstein et al. 2022). Furthermore, egg production per individual varies with adult food availability, with females in better condition producing more eggs. Ensemble projections were driven by the downscaled ocean-biogeochemical projections from ROMS-NEMUCSC (Pozo-Buil et al. 2021), extended by a newer hindcast including recent years under warm ocean conditions (2011-19).

Results show that booms and busts in sardine and anchovy dynamics are projected to continue into the future driven by natural variability in plankton, ocean temperature, and offshore transport. A likely increasing trend in sardine biomass to early 2000s abundance levels is projected by the 2030-2050s, due to increased recruitment following higher early life history stage survival. There is only a temporary increase during 2061-2080 in the risk of sardine abundance falling to collapsed levels projected under the GFDL earth system model, relative to the 2000-2019 period (red in Fig. E.8). This “no catch” abundance level approximately corresponds to the 150,000 mt cutoff in the current sardine harvest control rule. By contrast, the risk of anchovy being in a ‘bust’ state shows a generally increasing trend under climate change (red in Fig. E.9). This is because anchovy biomass shows only temporary 'booms' driven by planktonic food availability, and dependent on the coincident timing of good egg production and good early life stage survival.

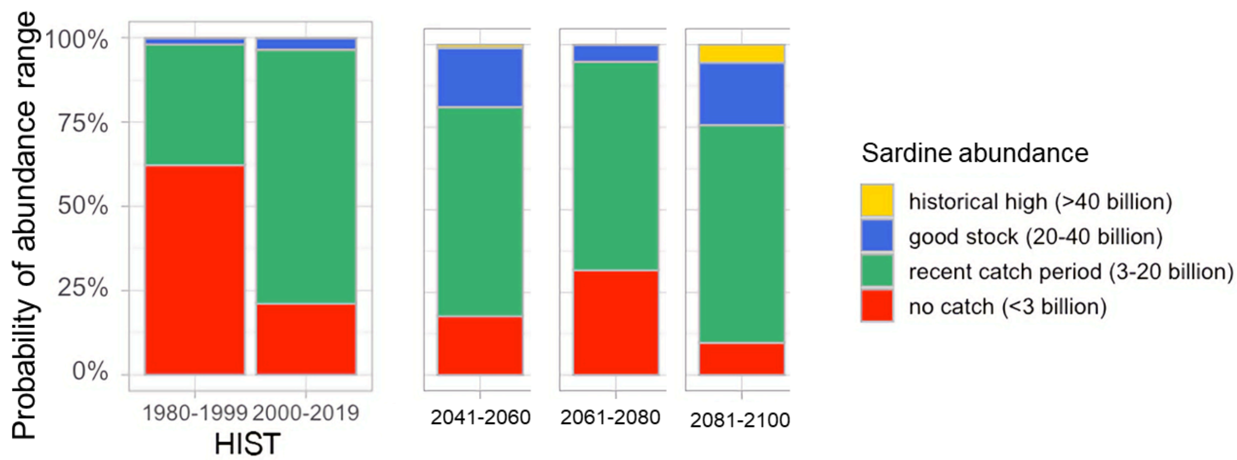

Figure E.8: Probability of sardine abundance across 20 years periods being in a specified abundance range during model calibration (HIST) and under projections from GFDL (Pozo-Buil et al. 2021), including ecological uncertainty (nine ensemble model configurations) and thermal uncertainty (early life history temperature sensitivity ranges). Sardine abundance is separated into four ranges (bottom to top): 1. "No catch": sardine below the harvest cutoff (<3 billion sardine); 2. "recent catch period": sardine harvested at up to 1990s–2000s peak abundance (3–20 billion); 3. "good stock": sardine above to twice of 1990s–2000s peak levels (20–40 billion); and 4. "historical high" sardine at or above 1930s abundance (>40 billion). The probability was computed as the fraction of years in each 20-year period and across the 9 ensemble model configurations and different temperature sensitivities that abundance was in a specific abundance range.

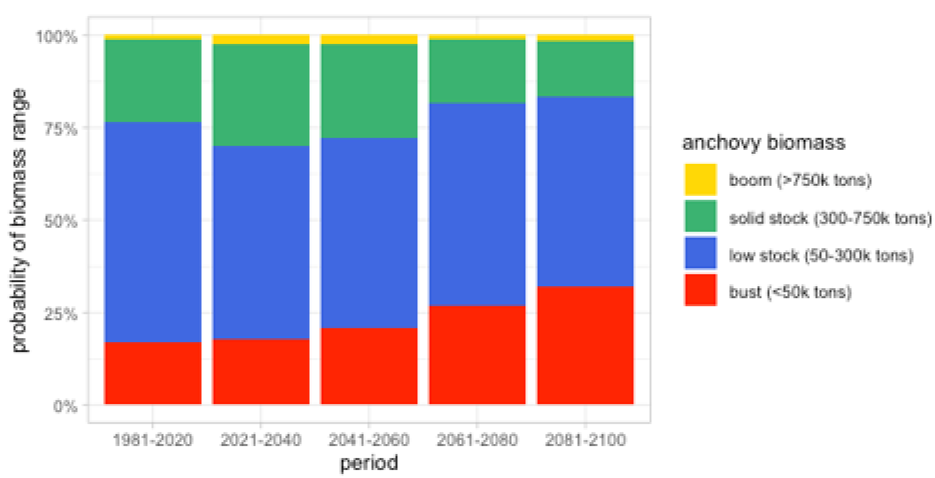

Figure E.9: Probability of anchovy biomass across 20 years periods being in a specified biomass range during model calibration (HIST) and under projections from GFDL (Pozo-Buil *et al. 2021), including ecological uncertainty (eight ensemble model configurations) and thermal uncertainty (early life history temperature sensitivity ranges). Anchovy biomass is separated into four ranges (bottom to top): 1. "Bust": anchovy biomass below 50k tons; 2. "Low stock": anchovy biomass between 50k and 300k tons; 3. "Solid stock": anchovy biomass between 300k and 750k tons; and 4. "Boom" anchovy biomass above 750k tons. The probability was computed as the fraction of years in each 20-year period and across the 8 ensemble model configurations and different temperature sensitivities that biomass was in a specific abundance range.*

These models and the Atlantis ecosystem model are also being used to generate potential future scenarios of recruitment, growth, and natural mortality for CPS Management Strategy Evaluations (MSEs). An MSE for sardine was developed to evaluate robustness of the assessment and harvest control rule to projected changes in sardine recruitment (Wildermuth et al. 2023). No indication of increased assessment error was found under projected changes in sardine recruitment (Fig. E.10). Furthermore, it was shown that the current sardine assessment process and frequency can effectively track changes in the population status of sardine, making current management rules robust to changes in sardine recruitment as compared to more static approaches (Wildermuth et al. 2023). Other harvest control rules that are responsive to environmentally driven changes by using dynamic reference points were also found to improve outcomes compared to static management (Wildermuth et al. 2023). Notably, this analysis revealed that stock dynamics, and thus management success, are more sensitive to climate-driven changes in recruitment than to the harvest strategies we tested. Management performance for sardine in a changing climate likely depends on 1) frequent, responsive monitoring and assessment, and 2) understanding and modeling drivers of climate-driven changes in recruitment dynamics, more than on refining the shape of current harvest control rules.

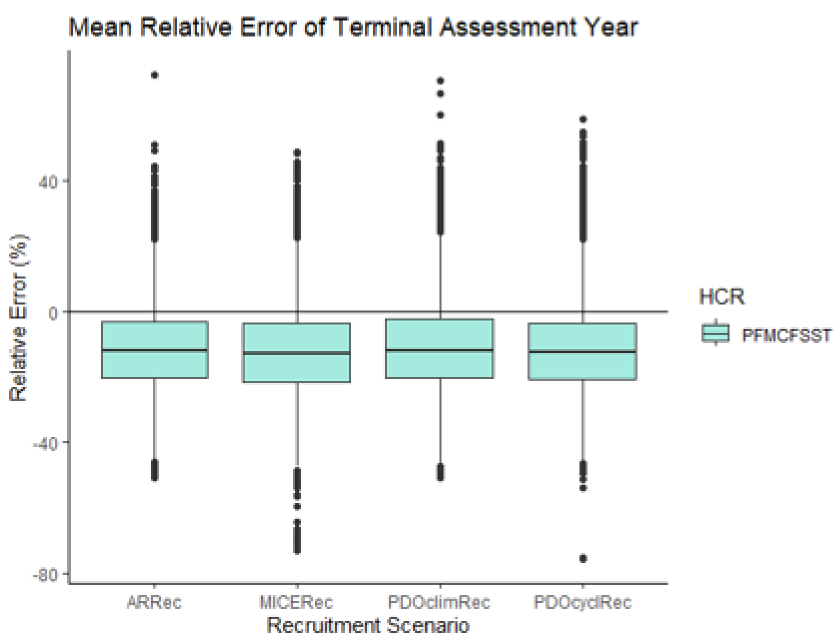

Figure E.10: Relative assessment error in each terminal (assessment) year of the simulated assessment model for each reference recruitment scenario under the current PFMC sardine harvest control rule (HCR). Individual boxplots represent error between the simulated assessment estimate of age 1+ biomass for that year and the operating model biomass across iterations and simulation years. In each plot, the center horizontal bar is the median, hinges represent the 25% and 75% quartiles, and whiskers are the upper and lower 95% confidence intervals. The MICERec and PDOclimRec scenarios are the climate driven recruitment scenarios. See Wildermuth et al. 2023 *for more details.*

E.3.2 Social-ecological vulnerability and climate risk for fishing fleets

E.3.2.1 Groundfish

The projected impacts of climate change on managed species and the associated risks for fishing fleets can vary geographically, having important implications for how local and regional fishing communities may best adapt to future ocean change. A recent study (Samhouri et al. 2024) evaluated how climate risk to West Coast bottom trawl groundfish fleets may be reduced through shifting fishing operations to focus on new species via fisheries diversification (an approach they term "adapt in-place"). They also explored how climate risk to these fleets may be reduced through shifting operations to new and more distant fishing grounds (an "adapt on-the-move" strategy). These strategies were evaluated in light of projected exposure of fishing grounds (Fig. E.11) to changing bottom temperatures and the economic dependence of fishing fleets on groundfish (or sensitivity).

Under multiple climate change scenarios, groundfish fleets at more northern latitudes are expected to experience higher local temperature change within their present-day fishing grounds (Fig. E.11) and will also have to travel farther to keep pace with changing bottom temperatures in their present-day fishing grounds than fleets at southern latitudes. Compounding this greater exposure, economic dependence tended to be highest for fleets landing at ports in northern California, Oregon, and Washington.

Largely as a result of greater exposure and economic dependence, risk due to climate change is predicted to be greater for more northern groundfish fishing fleets (Table E.2). Adapting in place by diversifying fisheries portfolios is less effective at mitigating climate risk for northern fleets than adapting on the move to follow ocean temperatures associated with target species (climate risk increases more from south to north in Fig. E.12a than in Fig. E.12b). The approach used here is scalable to other fleets and regions, and can be informative for identifying actions that leverage existing adaptation potential and build fisheries that are more resilient to climate change.

Table E.2. Summary information describing the components contributing to greater or lesser risk due to climate change for bottom trawl groundfish fleets. Red shading/font indicates greater exposure and sensitivity, and lower adaptive capacity, while blue shading/font indicates the opposite. Overall, fleets from Eureka, CA, and north are more at risk from climate change and more likely to be able to ameliorate impacts of climate change through greater mobility rather than by diversifying the fisheries they target. Exposure indices are based on present-day conditions relative to those expected at the end of the century (see Samhouri et al. 2024 for details).

	Exposure		*Sensitivity*	*Adaptive Capacity*	
Groundfish Fleet	**More or less than 1C of anomalous warming?**	**To fish at today's bottom temperature: need to move more or less than 50m deeper?**	**More or less than 50% of fishing revenue from groundfish?**	**More diversified than average?**	**Fishing grounds more than 50km from port, on average?**
Puget Sound	More	More	More	No	Yes
South/Central WA	More	More	Less	Yes	Yes
Astoria	More	More	More	Yes	Yes
Newport	More	More	Less	Yes	Yes
Coos Bay	More	More	Less	Yes	Yes
Brookings	More	More	Less	Yes	Yes
Crescent City	More	More	More	No	No
Eureka	More	More	More	No	No
Fort Bragg	Less	Less	More	Yes	Yes
San Francisco	Less	Less	Less	No	No
Monterey	Less	Less	More	No	Yes
Morro Bay	Less	Less	Less	No	No
Santa Barbara	Less	Less	Less	Yes	No
Los Angeles	Less	Less	Less	No	No

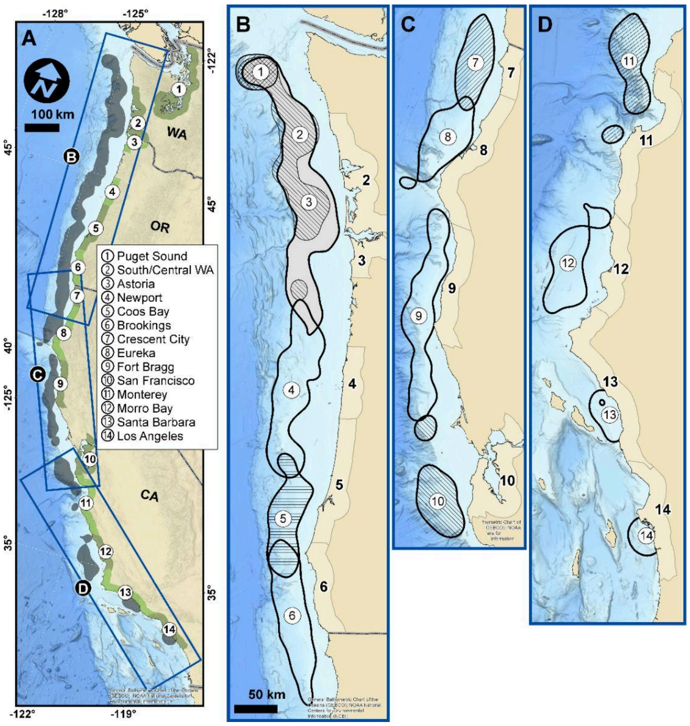

Figure E.11: (A) Fishing footprints from 2011-2019 (dark gray regions) for U.S. West Coast groundfish fleets, based on logbook data. Alternating light/dark green regions on land delineate the 14 port groups, which are numbered with corresponding names listed in inset legend. Three enlargement maps to the right show the 14 port groups landing bottom trawl-caught groundfish on land (numbered), but with distinct, individually delineated fishing footprints (corresponding circled numbers) associated with fleets fishing off Oregon and Washington (B) and California (C, D). From Samhouri et al. 2024*.*

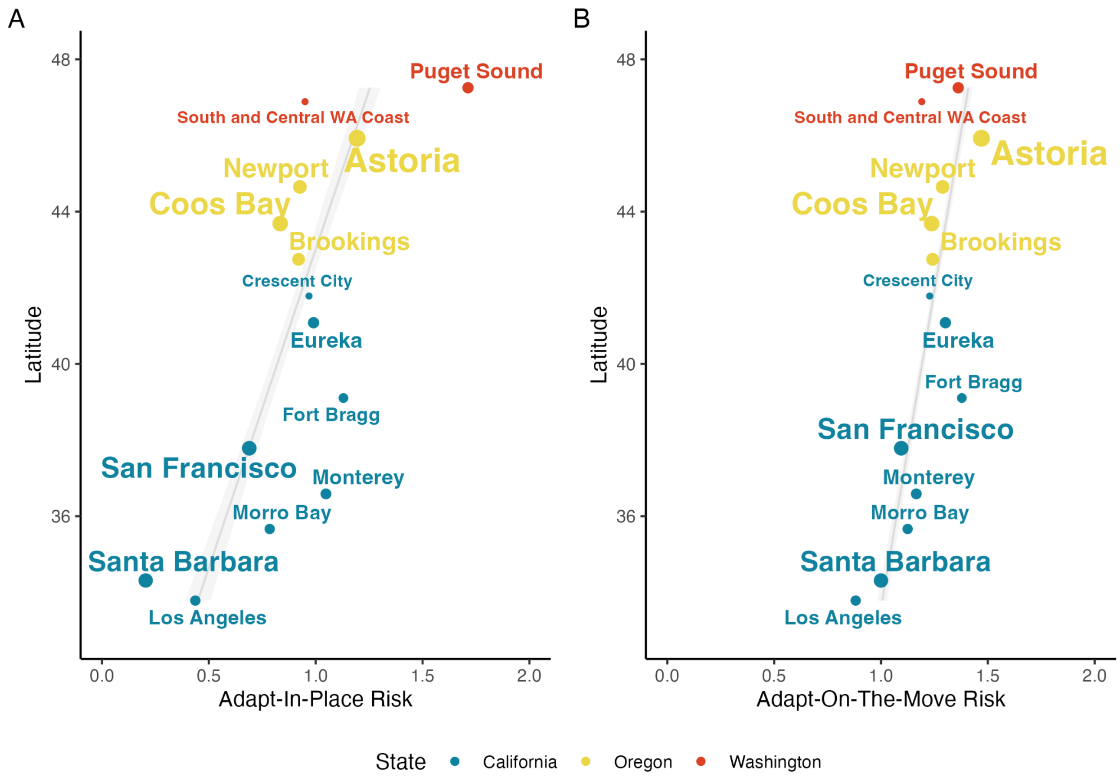

Figure E.12. Coupled social-ecological risk due to climate change for groundfish fleets on the U.S. West Coast. (A) Assuming fleets change target species while remaining in current fishing grounds (adapt in-place) does not reduce risk as much for more northern fleets as (B) assuming fleets shift fishing grounds while targeting current species (adapt on-the-move). Larger points and font sizes indicate fleets composed of a greater number of vessels, and these relationships were statistically significant ($p < 0.001$). Colors correspond to the state in which each port occurs (blue: California, yellow: Oregon, red: Washington). From Samhouri et al. 2024.

E.3.2.2 Coastal Pelagic Species (CPS)

The projected changes in CPS availability highlighted in Section *E.3.1.2* will also impact the future resilience of CPS-dependent fishing communities. Quezada et al. (2023) investigated the historical CPS landings per vessel in response to shifts in CPS availability, to understand how the fleet may respond to future changes. Shifts in availability were derived from SDM output averaged over CPS fishing grounds near the relevant port areas for the CPS fishery. The definition of CPS fleet was broader than just those vessels with a limited entry permit for CPS, and included all vessels that targeted a CPS at least three times between 2005 and 2014, and derived more than 5% of their average annual revenue from CPS. Since CPS participants' responses to shifts in availability might depend on specific characteristics, such as scale of operation (i.e. revenue), dependence on CPS, average landing location, range of travel, and diversification, the first step in the analysis was to define different fleet segments within the CPS fleet based on those characteristics. Vessels clustered into eight different CPS fleet segments (Fig. E.13) based on their characteristics, such as being industrial or small scale, as operating largely in the Pacific Northwest or the Southern California Current region or over a large area (roving), and as specializing on squid or sardine, or targeting a diverse set of CPS (forage fish diverse or squid-sardine generalists), or targeting CPS only sporadically (opportunists).

Quezada et al. (2023) found that responses to historical shifts in species availability were dependent on vessel strategies (e.g., opportunist v/s specialist fleets), in addition to market conditions, regulations, and availability of other target species. This work also highlights that existing characteristics of some fleet segments, such as the ability to switch between a diverse set of target species, can confer future adaptation potential. Successful future fishing may require the ability to take advantage of new opportunities in terms of fishing location, port, and species, as well as the ability of decision makers and industry to make forward-looking investment decisions in terms of fishing infrastructure to adapt to future conditions.

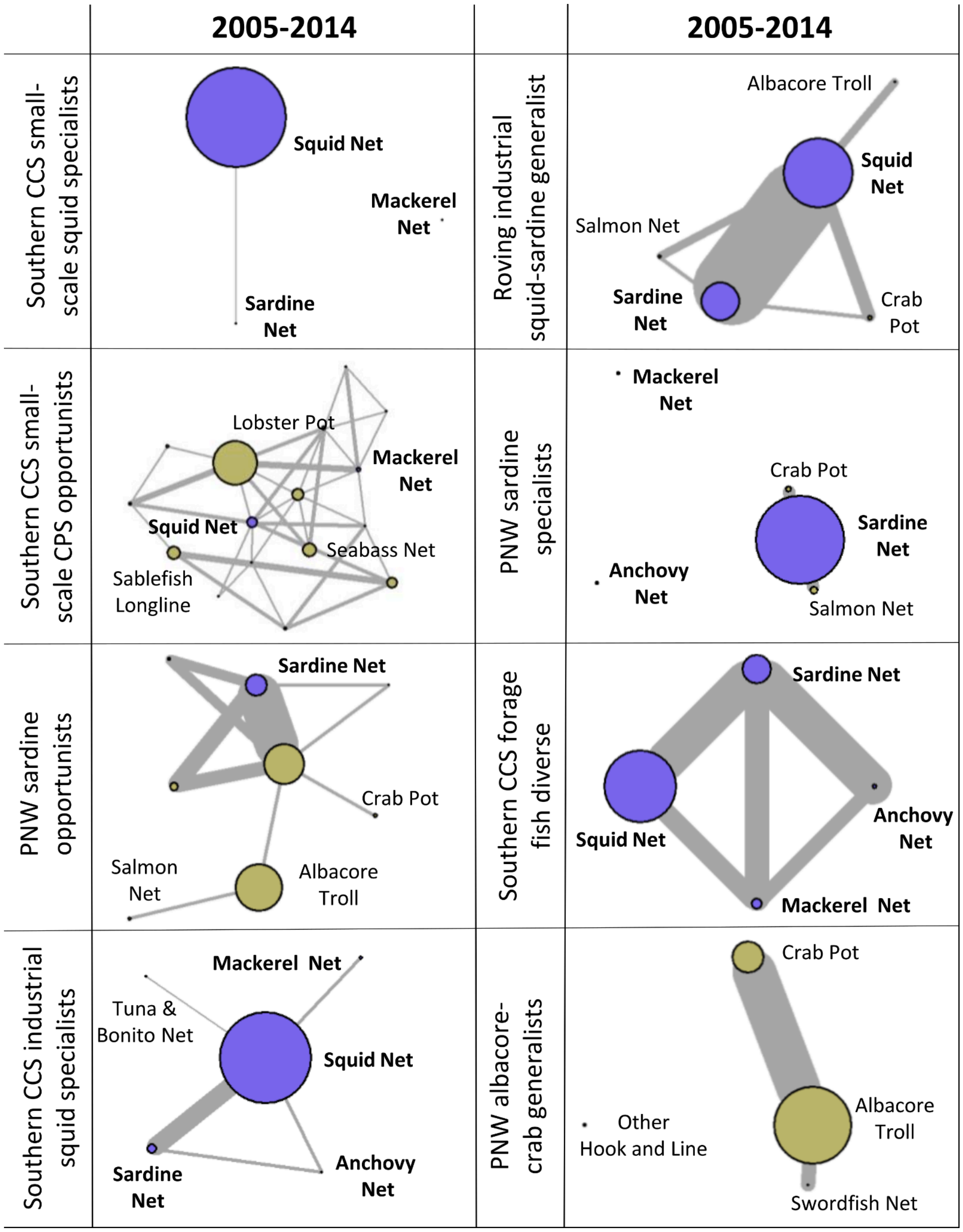

Figure E.13: Participation networks for each CPS fleet segment for 2005-2014. CPS-associated metiers are shown in blue with their labels bolded; everything else is shown in beige. Nodes represent fishing metiers, and their size represents their percent contribution to total revenue generated by each fleet segment during each time period. The width of the lines connecting the nodes represents the percentage of vessels in each fleet segment participating in each pair of fisheries. See Quezada et al. 2023 for a detailed description of each fleet segment.

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