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Projecting climate change impacts from physics to fisheries: A view from three California Current fisheries

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ABSTRACT

Motivated by a need for climate-informed living marine resource management, increased emphasis has been placed on regional end-to-end modeling frameworks designed to project climate impacts on marine ecosystems and evaluate the efficacy of potential management strategies under changing conditions. The ‘Future Seas’ project was initiated with a focus on three fisheries (Pacific sardine, swordfish, and albacore tuna) in the California Current System (CCS). This work leverages a suite of climate, ocean, ecosystem, and economic models to project physical, ecological, and socio-economic change, evaluate management strategies, and quantify uncertainty in model projections. Here we describe the components of the modeling framework, considerations underlying choices made in model development, engagement with stakeholders, and key physical, ecological, and socio-economic results to date, including projections to 2100. Our broad aims are to (i) synthesize a large body of climate and fisheries research that has been conducted, and continues, under the Future Seas umbrella, and (ii) provide insight and recommendations to those pursuing similar efforts for other applications and in other regions. In general, our results indicate that all three species will likely shift their distributions (predominantly poleward) in the future, which impacts accessibility to fishing fleets, spatial management, and quota allocation. For similar integrative climate-to-fisheries projections, we recommend attention is given to: recognizing potential biases arising from differences between the climate products used for ecological model fitting and those used for model projection; how sources of projection uncertainty are prioritized, incorporated, and communicated; and quantitatively linking scenarios – especially socio-economic scenarios – with climate and ecological projections.

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1. Introduction

Climate change is impacting marine systems and the communities and economies that rely on them globally (IPCC, 2022). Impacts include changes to ocean physics and biogeochemistry, species distributions and abundance, fisheries catch, and food web structure and function (Doney et al., 2012; Poloczanska et al., 2013; Pecl et al., 2017; Lotze et al., 2019; du Pontavice et al., 2020; Cooley et al., 2022). Altered ecosystem states can translate to changes in global fisheries production and uncertain economic futures (Blenckner et al., 2015; Free et al., 2019; Lam et al., 2016; Ding et al., 2017; Cheung, 2018). The United Nations declared 2021–2030 the 'Ocean Decade' in recognition of the unprecedented challenges facing sustainable ocean development, and a core goal of the Decade is predicting ocean conditions and their impact on human well-being and livelihoods (Ryabinin et al., 2019). Climate model projections are a critical foundation for responding to and planning for a changing marine environment, and investigations of the social-ecological system informed by regional ocean projections can help us meet our global, regional, and national obligations towards ecosystem and social resilience and sustainability (Busch et al., 2016; Hollowed et al., 2020). While components of these social-ecological systems are often examined individually, coordinated efforts that link processes from physics to fisheries can be highly effective when applied strategically to address key knowledge gaps (Fulton, 2010).

The 'Future Seas' project (https://future-seas.com) focuses on enhancing climate-ready management by linking high-resolution ocean models of the California Current System (CCS; Pozo Buil et al., 2021) with ecological and social models. Future Seas was built 'from the bottom up' by producing a base of modeled physical and biochemical CCS conditions, to which subsequent ecological and economic models are connected (Fig. 1). The end goal is to produce coupled climate-ecological-social models to evaluate management strategies resilient to future change in the CCS. Of the seven common types of coupled social-ecological models applied for ecosystem-based management identified by Kasperski et al. (2021), the Future Seas project has to date used four: Management Strategy Evaluation (MSE), fisher behavior, social vulnerability, and end-to-end. This first phase of the project has focused on quantifying rates of change in the physical and biogeochemical environment and the potential impacts of this change on three U.S. West Coast fisheries, as well as exploring strategic climate-ready management options to increase their sustainability. The ocean projections are produced by a high-resolution ocean model coupled to a biogeochemical model, and are available for use in any type of coupled modeling, making our recommendations and lessons learned about climate-ready management in the CCS directly applicable to other efforts in this region.

2. Aims and organization of this article

Our overarching aims are to summarize the structure and results of Future Seas as well as to provide guidance for others pursuing similar efforts. To that end, we present the modeling framework and justifications for its design, main findings to date, next steps for projecting physical-ecological-social change in the CCS, and general recommendations that are broadly applicable to similar projects.

Sections 3 and 4 convey key considerations when initiating this type of project and how they were applied under Future Seas. Section 3 outlines the setting of Future Seas, which provides the context and motivation for its design, and Section 4 outlines the modelling methodology. These sections provide an example of how one can build a modeling infrastructure based on the physical, ecological, and socio-economic context of specific fisheries. Sections 5 and 6 are tailored to readers who are interested specifically in the three CCS fisheries addressed under phase one of the Future Seas project. Section 5 summarizes physical, ecological, socioeconomic, and management results to date, and Section 6 discusses future plans. Section 7 gives recommendations that are generally applicable for those pursuing similar projects tailored to other regions, species, and management questions. Key definitions and acronyms are defined in Table 1.

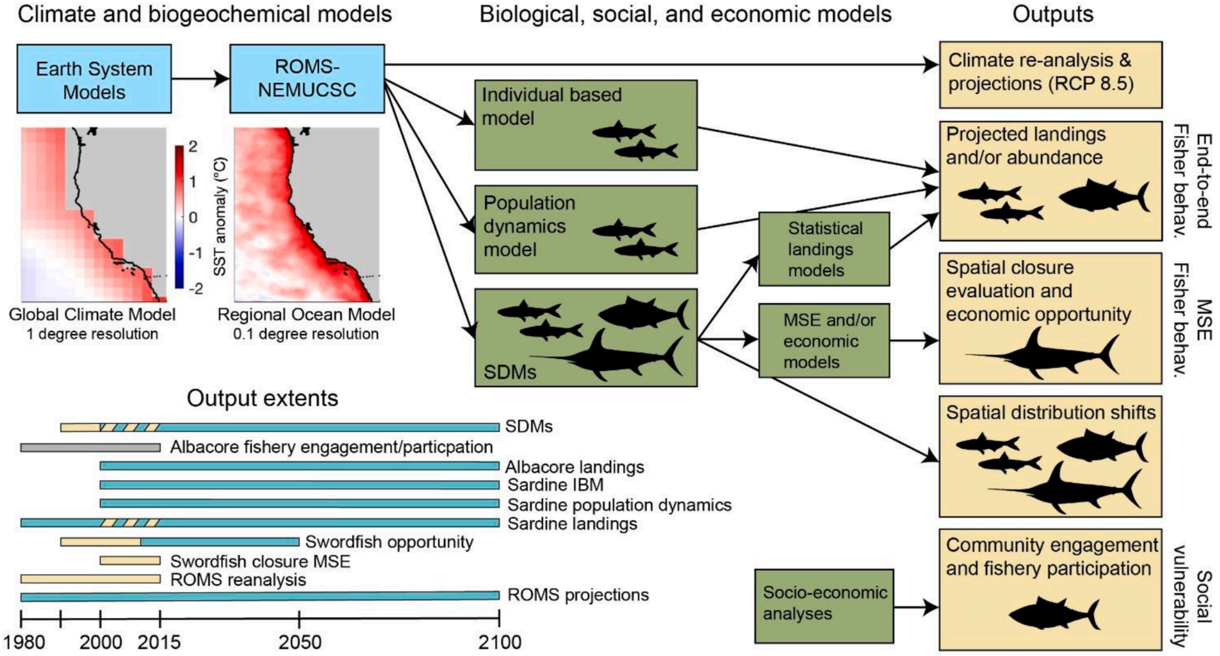

Fig. 1. Schematic of the first phase of the Future Seas project. High resolution ocean models are used to generate retrospective ocean hindcasts and re-analyses, and to dynamically downscale global climate projections to provide the foundation for a range of modeling approaches aimed at quantifying and projecting aspects of three species and their U.S. West Coast fisheries: Pacific sardine (the purse seine fishery), swordfish (the drift gillnet fishery), and North Pacific albacore (the surface hook-and-line fishery). Silhouettes of species indicate relevant models and outputs. For output extents, blue indicates output forced by climate projections, yellow by ocean reanalyses, and gray indicates no climate models were used. Coupled social-ecological outputs are identified according to type: MSE, end-to-end, fisher behavior, and social vulnerability. Key definitions and acronyms are defined in Table 1. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Definition of key terms and acronyms in the context of this paper. The relationship between the reanalysis and projection results in terms of model fitting and prediction is especially important and is discussed in Section 7.3. Some definitions are based partly on those in IPCC (2021a).

Term	Definition
Hindcast	A historical simulation, forced by boundary conditions that are constrained by observations (e.g., accurate winds, air temperature, etc.). Provides a realistic representation of historical conditions and a baseline against which future change is measured.
Reanalysis	Similar to a hindcast, provides a realistic representation of historical conditions. In addition to the realistic boundary conditions used in the hindcast, a reanalysis also assimilates available observations (e.g., from satellites or in situ platforms) to further improve fidelity of the model to nature.
Forecast	Prediction of what conditions will be some time in the future (typically days to several years). Forecast success depends on skillfully representing the ocean state at the forecast's initialization, and simulating the ocean's evolution over the forecast window. Data assimilation is thus often used to improve forecast initialization and subsequent forecast skill. Unlike climate projections, forecasts are intended to represent the actual ocean conditions in specific years.
Prediction	In climate and physics, prediction is synonymous with forecast. In ecology, prediction is output from a fitted model(s) calculated using new input data, so projections, forecasts, and hindcasts are all types of prediction.
Projection	A long-term (multidecadal) simulation of the ocean's response to future emissions of greenhouse gases and aerosol concentrations. Ocean projections are intended to assess the evolution of the multi-decadal mean and variability of ocean conditions (i.e., the "ocean climate"), not to predict the conditions during a specific year. They are dependent on, for example, future emission scenarios and technological and socio-economic developments, which may or may not be realized.
Downscaling	Using statistical and/or dynamical methods (e.g., high-resolution regional ocean models) to translate coarse scale information (e.g., from a global climate model) to finer resolution information. Downscaling typically also includes a bias correction step to adjust for biases in the global model (e.g. Section 4.1).
Management strategy evaluation	A type of closed-loop simulation which includes variability in ecological and/or management processes (Puntet al., 2016). The simulation has one or more operating models used to predict the ecological system (e.g. the abundance of fish). This is coupled to an assessment model which simulates the human dimension (e.g. fishing) and management strategies (e.g. catch quotas), which then feeds back into the operating model (e.g. through an updated fishing mortality). It is termed 'closed-loop' because feedback from the assessment model influences the state of the operating model at each time step.

Acronyms: CCS: California Current system; CCLME: California Current large marine ecosystem; COG: center of gravity; CPS: coastal pelagic species; DGN: drift gillnet fishery; ESM: earth system model; GCM: general circulation model (also global climate model); HMS: highly migratory species; IATTC: Inter-American Tropical Tuna Commission; IBM: individual based model; MSE: management strategy evaluation; NEMUCSC: an adapted version of the North Pacific ecosystem model for understanding regional oceanography (NEMURO); PFMC: Pacific Fisheries Management Council; PNW: Pacific Northwest; RCP: representative concentration pathway; ROMS: regional ocean modeling system; ROMS-GFDL: downscaled projection forced by the NOAA Geophysical Fluid Dynamics Laboratory ESM2M model; ROMS-IPSL: downscaled projection forced by the Institut Pierre Simon Laplace CM5A-MR model; ROMS-HAD: downscaled projection forced by the Met Office Hadley Center HadGEM2-ES model; SDM: species distribution model; WCPFC: Western and Central Pacific Fishery Commission.

3. The physical, ecological, and socio-economic setting of future seas

In a project, like Future Seas, which describes and models parts of a complex system, it is important to understand the broader setting. This setting should motivate and constrain design of the modeling and analysis framework, and provide broader context for the results. Here, three fisheries in the CCS provide an example of how physical, ecological, and fishery information – including stakeholder input – can be considered in the design of end-to-end climate-fisheries projects.

3.1. *Key aspects of the environmental setting*

The CCS is a dynamic and productive eastern boundary upwelling system with strong linkages among large-scale climate, local ocean conditions, and living marine resource dynamics. It stretches from southern Canada to northern Mexico, encompassing the entire west coast of the contiguous U.S. (Fig. 2). The CCS exhibits strong patterns of high- and low-frequency variation in ocean climate and productivity (Baumgartner et al., 1992; Checkley and Barth, 2009; Koslow et al., 2014), and recently a series of intense warming events has impacted numerous species and fisheries (Cavole et al., 2016; McCabe et al., 2016; Wells et al., 2017; Santora et al., 2020; Harvey et al., 2020; Fisher et al., 2021; Weber et al., 2021). Projections of conditions in the CCS indicate that climate change will continue to impact the physical, biogeochemical, and ecological realms (e.g. Rykaczewski and Dunne, 2010; Marshall et al., 2017; Morley et al., 2018; Howard et al., 2020; Pozo Buil et al., 2021; IPCC, 2021b), including changes in the timing, intensity and spatial heterogeneity of upwelling (Rykaczewski et al., 2015; Brady et al., 2017; Xiu et al., 2018). These projected changes, and their attendant uncertainty (e.g., Brady et al., 2017), necessitate management strategies that are robust and responsive to a variable and changing climate. The development of these strategies is aided by projections of potential future physical and biogeochemical conditions in the CCS, which can be regionally tailored (e.g. through dynamical downscaling) to represent key mesoscale ocean features and processes (Hollowed et al., 2009; Drenkard et al., 2021; Pozo Buil et al., 2021).

3.2. *Key aspects of the ecological setting*

The CCS hosts a complex food web (Horne et al., 2010; Koehn et al., 2016), and a diversity of forage species supports a rich assemblage of predators while acting as a buffer to productivity cycles of some forage species (Madigan et al., 2012; Kaplan et al., 2017). There are strong links between the environment and lower-trophic level fish abundance and productivity, but the large seasonal, annual, and decadal scale variation in conditions makes identifying mechanisms challenging (King et al., 2011). As a result, there is mixed support for synchrony (i.e. common environmental sensitivity) in fish assemblage structure and commercial catches in the region (Thompson et al., 2019; Siple et al., 2020; Ong et al., 2021). In addition, the interplay between fishing and climate fluctuations may increase the rate of change in forage populations (Essington et al., 2015). For higher trophic level predators, the CCS has been described as both attractive and retentive due to the nutrient-rich upwelled waters, drawing species that migrate to the region to forage or breed (Block et al., 2011). Climate change is predicted to bring new changes in prey availability and predator distribution throughout the CCS (Hazen et al., 2013; Cheung et al., 2015; Morley et al., 2018).

The first phase of the Future Seas project focuses on three species and their main commercial fisheries in the U.S. CCS (Fig. 1): Pacific sardine (*Sardinops sagax*), swordfish (*Xiphias gladius*), and albacore (*Thunnus alalunga*). Each species is economically valuable in the CCS, and selecting them as case studies allows us to explore climate change impacts given diverse ecological drivers, fishery characteristics, and management priorities.

Sardine is an iconic species of the CCS, characterized by highly

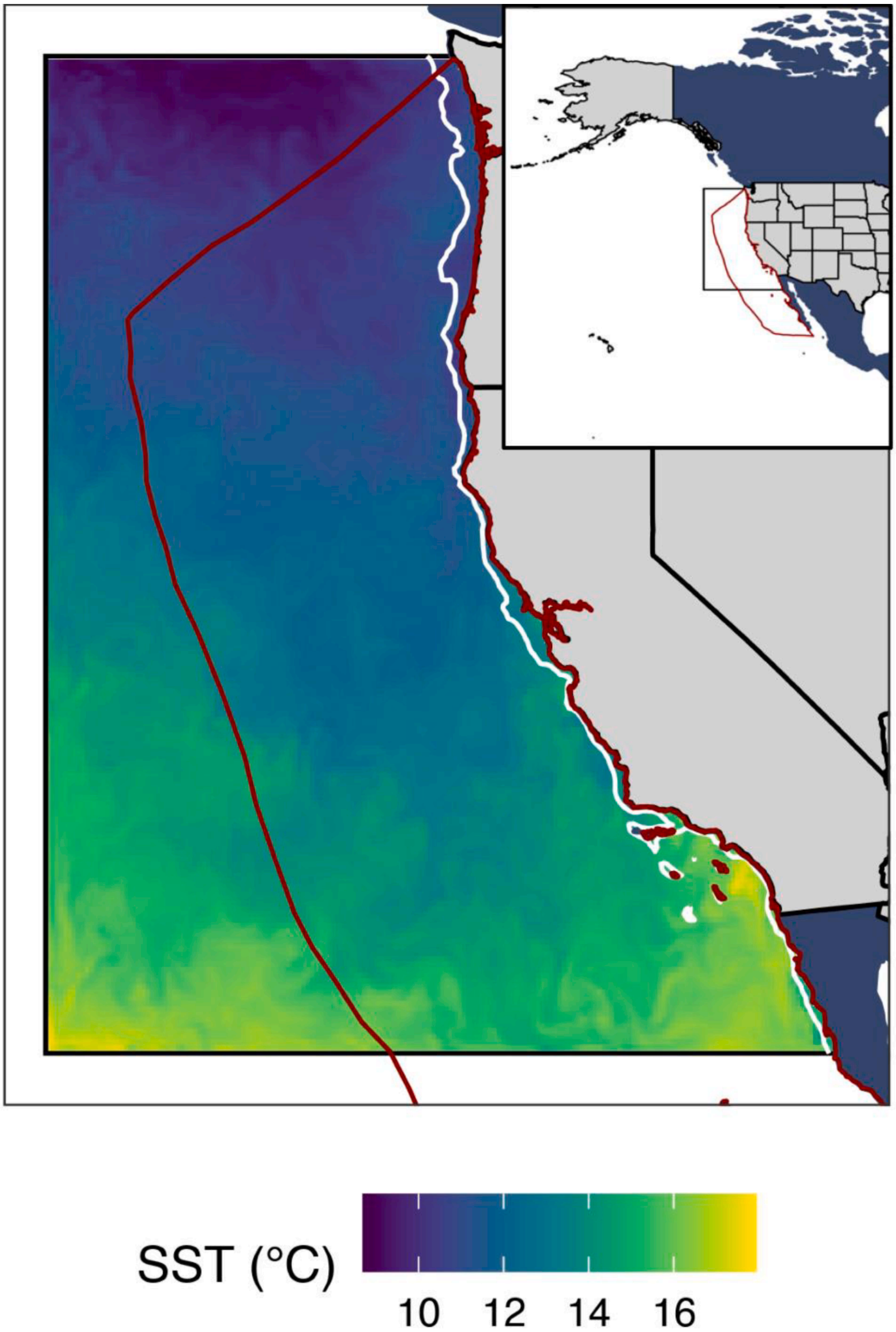

Fig. 2. Map of the ROMS domain (black box, with color representing SST from the ROMS reanalysis for a sample day - April 20, 2020). The California Current Large Marine Ecosystem is outlined in red. The 200 m isobath is shown in white, and is a measure of the limit of the continental shelf. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

variable and 'boom-bust' recruitment (Baumgartner et al., 1992) with dramatic consequences for the fishery (Ueber and MacCall, 1992; Kuriyama et al., 2020). Sardines are important forage for the ecosystem (Kaplan et al., 2017), and show interannually variable migration and spatial distribution (Barange et al., 2009; McDaniel et al., 2016). Many studies link sardine dynamics to environment and climate conditions (Deyle et al., 2013; Jacobson & MacCall, 1995; Lindegren et al., 2013; McFarlane et al., 2002) although the relationships can be variable and the mechanisms unclear. There are two subpopulations of sardine defined for the CCS (Smith, 2005), and the northern subpopulation - distributed between northern Baja California and British Columbia - is the focus of U.S. management and our study. The southern subpopulation spawns in and typically inhabits the waters of Baja California, but can move into U.S. waters during warmer months. The habitat of the northern subpopulation has been linked to numerous environment and climate variables, especially sea surface temperature (SST) and surface chlorophyll (Zwolinski et al., 2011; Muhling et al., 2019). This subpopulation has a broad thermal niche, but increased presence when SST is 11–16.5 °C (Muhling et al., 2019).

Swordfish are a highly mobile and globally distributed oceanic species. They are caught in the eastern Pacific with large-scale and artisanal fishing gears including longlines, gillnets, harpoons and to a lesser extent recreational gear (IATTC, 2017). There is evidence of stock structure in the Pacific, with fish caught off California assumed to be part of the Western and Central Pacific stock (IATTC, 2017), but with some mixing with the Eastern Pacific Ocean stock in the Southern

California Bight (Sepulveda et al., 2020). Swordfish distribution in the CCS is correlated with numerous environmental variables, including SST, surface mixing, and frontal features (Brodie et al., 2018; Scales et al., 2018), with greatest presence when SST is 16–20 °C. Swordfish can exhibit frequent vertical movement related to basking and foraging, and at night inhabit mostly surface waters (Sepulveda et al., 2018).

North Pacific albacore is considered to be one stock throughout the North Pacific, and spawning is restricted to tropical and subtropical waters in the Western and Central Pacific (Reglero et al., 2014). Albacore in the CCS are primarily immature juveniles that migrate during spring and early summer, and return to spawning grounds when mature (~5–6 years). Their distribution in the CCS is correlated with numerous dynamic variables, including SST, chlorophyll, and surface mixing (Zainuddin et al., 2008; Nieto et al., 2017; Muhling et al., 2019), and their seasonal- and age-based migration has been linked to the North Pacific transition zone (Polovina et al., 2001). Catches of albacore in the CCS are generally highest where SST is 15–20 °C (Muhling et al., 2019).

3.3. Key aspects of the socio-economic setting

CCS fisheries have important economic, social, and cultural value. The U.S. West Coast fishery system is characterized by its high levels of diversity, productivity, and variability, and CCS fisheries have long been an important contributor to coastal livelihoods, cultures, and economies (McEvoy, 1986; PFMC, 2022). In the modern era, many fishers across California, Oregon and Washington have historically participated in multiple fisheries, shifting effort within and between years in response to changes in species distribution and abundance, regulations, and market drivers (Kasperski and Holland, 2013; Fuller et al., 2017; Frawley et al., 2021, Fisher et al., 2021). Though access to marine resources was once largely unrestricted, limited entry licensing regimes, harvesting guidelines, spatiotemporal closures, and/or catch quotas were applied to many West Coast commercial fisheries in the 1970s, 80s, and 90s in order to combat overharvesting and to rebuild fish stocks. Following the passage of the Magnuson-Stevens Fishery Conservation and Management Act in 1976, the Pacific Fishery Management Council (PFMC) was created and charged with the management of the U.S. West Coast Exclusive Economic Zone (3–200 nautical miles offshore), development of relevant fishery management plans, and coordinating with individual states and the National Marine Fisheries Service (NMFS) to oversee their implementation.

Although a record number of regional stocks are now considered rebuilt or sustainably managed from a biological perspective (NOAA Fisheries, 2020), there are ongoing concerns about the social sustainability of the commercial fishing industry associated with the consolidation of access rights and fishing equipment (Russell et al., 2018), the "graying of the fleet" (Cramer et al., 2018), and ongoing environmental justice concerns related to the establishment of closed areas or gear constrictions (Mason et al., 2019). In recent years, climate change has emerged as a focal issue for fisheries stakeholders and management as shifting environmental conditions have resulted in changes in marine animal distribution and abundance and unfamiliar interactions between resource users, target species, seafood markets, and protected species (Richerson and Holland, 2017; Holland and Leonard, 2020; Santora et al., 2020). In recognition of this, the PFMC has developed the Climate and Communities Initiative (https://www.pcouncil.org/actions/climate-and-communities-initiative), which is aimed at communicating the effects of climate change in the CCS among fishery managers and stakeholders, and to identify ways to incorporate such understanding into PFMC decision making.

Sardine in the CCS has an infamous history of high harvest and collapse in the early-mid 20th century. In U.S. waters, sardine are managed by the PFMC under the Coastal Pelagic Species (CPS) Fisheries Management Plan (Appendix A). Sardine are caught primarily with round-haul gear, and the same fleet will target other CPS species, including northern anchovy (*Engraulis mordax*), Pacific mackerel (*Scomber japonicus*), and market squid (*Doryteuthis opalescens*). Sardine undergo regular stock assessment incorporating annual acoustic and trawl surveys, and are subject to a catch quota including a 'cutoff' abundance of 150,000 mt, which stops directed fishing when the subpopulation falls below this level. Due to low abundance, the sardine fishery closed in 2015, which coincided with a large marine heatwave and raised concerns about the vulnerability of this fishery to climate change.

Swordfish are important for commercial and recreational fishers in the CCS, and information on their redistribution is of management interest. Swordfish in the CCS are managed internationally by the Western and Central Pacific Fishery Commission (WCPFC) and the Inter-American Tropical Tuna Commission (IATTC), and in U.S. waters of the CCS by the PFMC which includes swordfish in its highly migratory species (HMS) Fisheries Management Plan (Appendix A). Swordfish in the U.S. waters of the CCS are predominantly caught commercially by the drift gill net (DGN) fishery. This is a small and declining limited-entry fishery and subject to extensive scrutiny due to bycatch issues (Mason et al., 2019; Savoca et al., 2020), and numerous regulations (such as time-area closures) are currently in place (Urbisci et al., 2016). One of the most scrutinized bycatch groups are sea turtles, and two spatially static closures (the large Pacific Leatherback Conservation Area, and the Loggerhead Conservation Area) exist strictly to reduce turtle bycatch.

The U.S. west coast commercial albacore fishery was historically important off California, but in the past 10–15 years has operated primarily out of Pacific Northwest (PNW) ports in Oregon and Washington. The fishery uses surface gear (hook-and-line and troll) and is not limited-entry, although there are some gear restrictions and vessels must hold a permit. Like swordfish, the North Pacific albacore fishery is managed internationally by the IATTC and WCPFC, and along the U.S. West Coast by the PFMC under the HMS Fisheries Management Plan (Appendix A). The stock is considered not overfished, and while the WCPFC has established a limit reference point, no formal harvest strategy or target reference points have been adopted (ISC Albacore Working Group, 2021). However, an international MSE process was recently conducted to assess performance of alternative management strategies and associated reference points to aid development of harvest strategy for North Pacific albacore by the two regional fisheries management organizations (ISC Albacore Working Group, 2021). There is potential for ongoing albacore spatial distribution shifts to impact U.S. landings, which may have broad impacts given the importance of albacore fishing in the harvest portfolios of West Coast fishers.

3.4. Stakeholder input

Fishery stakeholders were engaged from the onset of Future Seas to motivate specific research directions and strategically address management and fisher concerns. Engagement of stakeholders in research, especially research with management implications, is considered important for the uptake of model results and success of related management plans, and can enhance scientific understanding of complex systems (Mackinson et al., 2011; Aminpour et al., 2020,; Weiskopf et al., 2022). Direct stakeholder input occurred through two workshops and through semi-structured interviews (Appendix B). Semi-structured interviews have a set of questions but also allows new topics to be raised during the interview based on stakeholder answers (Bernard, 2017). Key concerns and themes which emerged from this engagement are summarized in Appendix B. Stakeholders included commercial fishers and industry representatives, fishery managers, fishery scientists, and non-governmental organization representatives. The first workshop occurred within the first six months of the project (March 2018) and was focused on introducing the project and broad objectives to a variety of stakeholders across the three fisheries. The main goals were to get feedback on the project, discuss proposed methods such as management strategy evaluation, and identify key issues and priorities and related management objectives that could be examined in the context of climate change. The second workshop in October 2018 had similar goals but focused specifically on CPS (especially sardine and squid). It was intended that stakeholder feedback and input be used to prioritize and guide our research. Key stakeholder concerns and themes included: change in target species distributions and abundance, fishery and ecosystem impacts of these changes, diverse issues related to changes in management strategies, and how well our modelling represents reality (Appendix B). While much of our research output does align with stakeholder concerns, we were not able to explore some desired issues in detail (e.g. sardine harvest strategies, squid abundance and distribution) due to limited data availability and resources.

4. Modeling framework and design

A modeling and analysis framework should be tailored to specific project goals, should be informed by the context of the project (Section 3), and should balance feasibility and realism. Also important is to capture key system and organism uncertainties in the design where possible. This task is not necessarily straightforward, so to aid similar projects we offer the example of how it was handled under Future Seas. We first describe the physical and biogeochemical modeling, and then for the ecological and fishery analyses we describe a series of intentional choices: (i) which models to use and why, (ii) how environmental information is incorporated, (iii) which management modeling framework is best suited to addressing stakeholder concerns, and (iv), what are the relevant metrics of change produced by the models. This article is not focused on technical details (which are reported in the cited studies or appendices) but more on the broad rationale. Details of the analyses and models, including data and code availability, are reported in Appendix C.

4.1. Physical and biogeochemical modeling

The structure of the ocean modeling was designed with consideration of several key needs and constraints: (i) resolving fine-scale physical and biogeochemical variability associated with coastal upwelling and mesoscale features, (ii) capturing uncertainty in potential future climates, (iii) resolving the evolution of ocean changes throughout the 21st century, and (iv) ensuring computational feasibility. Historical and future ocean conditions were simulated with a CCS configuration of the Regional Ocean Modeling System (ROMS). The ROMS domain covers 30-48°N and offshore to 134°W (Fig. 2), with a horizontal resolution of 0.1° (~10 km) and 42 terrain-following vertical levels (Veneziani et al., 2009). For the analyses described in this article, we use three types of model outputs based on this same ROMS domain. Each is described in detail in the associated references, so we provide only a short overview here (and in Table 1) and expand on the roles of different outputs in Section 7.3. First is a series of *historical reanalyses* (1980–2021; Neveu et al., 2016, oceanmodeling.ucsc.edu) – data-assimilative historical runs that provide our best estimate of the physical ocean state used for fitting ecological models. Second is a *hindcast* (1980–2010; Pozo Buil et al., 2021) – a realistic historical simulation without data assimilation but including biogeochemistry, which provides a baseline representation of the historical mean state against which future change can be quantified. Third is a set of three *projections* (1980–2100; Pozo Buil et al., 2021) which are forced by output from CMIP5 earth system models (ESMs) under a high emissions scenario (Representative Concentration Pathway (RCP) 8.5, Riahi et al., 2011). The three ESMs used to force projections – GFDL-ESM2M, HadGEM2-ES, and IPSL-CM5A-MR (hereafter abbreviated to GFDL, HAD, IPSL) – were chosen to span the range of physical and biogeochemical change in the CCS projected by the models in the CMIP5 ensemble. Model spread was prioritized over multiple scenarios as the former is the dominant source of physical and biogeochemical uncertainty in the CCS (Pozo Buil et al., 2021).

Projections employ a 'delta method' for applying climate change signals. In this approach, the changes in atmospheric and oceanic drivers projected by global climate models are applied to an observationally constrained estimate of contemporary ocean conditions, thus correcting regional biases common to global climate projections (e.g., Stock et al., 2011). Unlike many downscaling efforts (Drenkard et al., 2021), the Future Seas effort enlisted a 'time-varying delta' method that allows us to simulate the full 1980–2100 period (Pozo Buil et al., 2021). In contrast to the more common 'fixed delta' method that compares discrete future and historical periods, the time-varying approach allows us to provide the temporally evolving ocean conditions needed to study future ecosystem states that may reflect the integrated effects of conditions over several decades (Drenkard et al., 2021). Finally, the hindcast and projections are coupled to NEMUCSC – a CCS-specific version of the NEMURO biogeochemical model (Kishi et al., 2007; Fiechter et al., 2021). NEMUCSC includes three limiting macro-nutrients, two phytoplankton groups, three zooplankton groups, three detritus pools, and oxygen and carbon cycling. For computational efficiency, ROMS and NEMUCSC are run in successive steps (i.e. offline coupling), enabling a faster run time that is especially useful for biogeochemical parameter calibration and sensitivity studies.

4.2. Ecological and fishery modeling – Which models and why

Our models and analyses (Fig. 1) were selected to balance the project's aims and the priorities of the stakeholders and management against feasibility and flexibility. A key example of this balance was including population dynamics in models for sardine, but excluding this from swordfish models. Population dynamics or abundance was included in all sardine models due to the highly variable abundance of sardine – this is of great stakeholder interest, and excluding abundance would likely lead to less accurate models of their distribution. For swordfish we felt confident focusing on high resolution spatial models (which are more relevant to current management priorities) while excluding population dynamics because the status of swordfish stocks in the North Pacific and CCS is relatively stable and not overfished (ISC Billfish Working Group, 2018) and because processes such as recruitment occur outside the CCS. Modelling population dynamics at a fine spatial scale is a great challenge, so it is common in projections to focus more on spatial distributions or more on abundance trends.

Given the focus of stakeholders on questions of future environmental change and spatial distribution shifts, we developed and projected correlative species distribution models (SDMs) for sardine (Muhling et al., 2020), swordfish (Appendix D), and albacore (Appendix E). These SDMs were then linked to correlative landings models to project the potential impact of distribution shifts on fishery landings for both sardine (Smith et al., 2021a) and albacore (Appendix E). The albacore model also leveraged a population dynamics model used in the recent North Pacific albacore MSE (ISC Albacore Working Group, 2021), to ensure that the impact of changes in biomass (driven by management strategies or productivity) could be linked to changes in the availability and community landings derived from the SDM. The sardine and albacore landings models assess potential consequences of climate driven shifts in habitat for community-level landings to enable managers to better understand climate risk and develop strategies to increase resilience of affected communities. We also developed an analysis that evaluates SDM performance to measure the timescales of ecological predictability (Brodie et al., 2021), which allows us to better identify the scales of environmental covariates that should be prioritized in SDM development.

Additional priorities for stakeholders and managers in the swordfish fishery are bycatch and spatial management, so we linked correlative SDMs with an economic model to evaluate how distribution shifts can affect the opportunity costs of spatial closures (Smith et al., 2020), and used SDMs to provide the ecological dynamics in a complex MSE model to evaluate the effectiveness of static and dynamic spatial closures for the management of bycatch (predominantly turtles) in the DGN fishery

(Smith et al., 2021b). The MSE also included an agent-based model to simulate fishing effort, which was deemed essential given the need for flexible responses of simulated fishers to dynamic closures. Projecting the MSE was deemed non-essential given the additional uncertainty of projecting the agent-based model and simulating the associated fishing effort, and because the management implications given future species redistribution could be inferred from historical patterns and interannual variation.

To explore the potential future abundance and distribution of sardine, we projected an individual-based model (IBM) of sardine coupled to ROMS and MEMUCSC (Rose et al., 2015; Fiechter et al., 2021), as well an ensembled age-structured population dynamics model (Koenigstein et al., 2022). Alongside the SDM-based landings projection, these two models provide diverse and comparable approaches to exploring the future of sardine. All three models were projected to 2100 based on output from the three downscaled projections, allowing us to evaluate uncertainty associated with both climate and fishery models. The IBM is a complex framework that can incorporate individual-level processes and is entirely mechanistic and operates at a fine temporal and spatial scale, whereas the environmental-informed population dynamics model can also incorporate mechanism but is more coarsely resolved, but does allow for more rigorous fitting to fishery-dependent time series.

And finally, due to broad concerns about availability of fish to fisheries, and in the case of albacore stakeholder concerns relating to the West Coast fishery's 'open access' status, we developed models and analyses to explore community engagement and fishery structure and participation. The community and processor engagement analysis uses dimension reduction to measure the relative involvement of communities in a fishery (e.g. Himes-Cornell and Kasperski, 2016; Appendix F), which is useful for managers as it can identify the most relevant areas for risk assessment and management. This analysis prevised a metric similar to the social indicator used in NOAA's ecosystem status reporting (Colburn et al., 2017; Harvey et al., 2020). The analysis of albacore structure and participation allows more insight into how a fishery is structured, and provides an assessment of longitudinal changes impacting the fishery system and the fishery's trajectory. This uses a broad 'methodological triangulation' analysis, detailed in Frawley et al. (2021).

4.3. *Ecological and fishery modeling – How environmental information was incorporated*

For the SDMs, environmental information was included as habitat correlations, predicting the spatial distribution as probability of presence of sardine (Muhling et al., 2020; Smith et al., 2021a), the probability of presence of swordfish (Appendix D) or the catch rate of swordfish and key bycatch species in the DGN (Smith et al., 2021a; Smith et al., 2021b), and the catch rate of albacore (Appendix E). Of note was the addition of a 'sardine abundance' covariate in the sardine SDM, which can allow for abundance-dependent habitat associations (Muhling et al., 2020). For the SDM-based projection of albacore landings, we also incorporated a transition zone index directly into the landings model (Appendix E), as albacore are known to use the North Pacific transition zone (the region where the North Pacific subtropical and subpolar gyres meet) as a migration pathway to the West Coast. This landings analysis can be enhanced for consideration of environmental effects on productivity either implicitly by using scenarios of future productivity trends (i.e. in recruitment, mortality, and growth; e.g. Punt et al., 2016) or explicitly by directly integrating an environmental index into the population model (e.g. Haltuch et al., 2019). The SDM-based MSE for swordfish additionally includes the environment in the assessment model, where environmental information is used to build spatial closures (Smith et al., 2021b).

In the IBM and population dynamics models of sardine, the environment is included mechanistically, which allows the exploration of causal relationships and production of outputs other than spatial distributions, although functional forms and parameter values can be more challenging to estimate. In the IBM, environmental drivers (primarily temperature and zooplankton prey) influence several properties of sardine individuals, such as growth, survival, reproduction, and movement behavior (Rose et al., 2015; Fiechter et al., 2015). Zooplankton concentrations are determined from the NEMUCSC component of the coupled model. In the population dynamics model, SST determines spawning location and early life stage survival, nanophytoplankton and microzooplankton biomass (also from NEMUCSC) determine late larval and juvenile survival, and adult sardine consumption and egg production are influenced by diatom, mesozooplankton, and krill biomass (Koenigstein et al., 2022). Environmental information from the ROMS reanalysis was used to fit all the SDMs, while the ROMS-NEMUCSC hindcast was used to fit and tune the IBM and population dynamics models. The downscaled ROMS-ESM projections were used to drive sardine projections and compare the state of the sardine population under historical and future periods (see Section 7.3 for a discussion of integrating historical and future products, and a recommended workflow).

The community engagement analyses for albacore links port-level landings with vessel and processor spatial information. These analyses do not incorporate dynamic environmental variables, and nor does the fishery structure analysis of the albacore fishery. These types of analyses are not designed for incorporation of environmental variables; however, these analyses provide a means to infer potential broader impacts of spatial distribution shifts on the fisheries.

4.4. *Ecological and fishery modeling – Management modeling framework*

Of keen interest to stakeholders are projections of landings, and both our sardine and albacore landings projections needed to make assumptions about highly uncertain future fishery characteristics, such as the location of ports, fishing effort, management regulations, and the abundance of other target species. For sardine, the SDM-based simulation, the IBM, and the population dynamics model approach this differently. In the SDM-based simulation, future uncertainty is addressed by assuming all future conditions – except for sardine habitat and their spatial distribution – are the same as those in an historical reference period (Smith et al., 2021a). The structure of the linked landings model is such that this analysis also evaluates whether the current seasonal quota allocation scheme, or the landings of other CPS, might constrain future landings. In the IBM, an agent-based fleet model simulates fishing originating from five west coast ports, with daily fishing effort determined by accessibility to nearby sardine individuals and expected revenue from catch. And in the age-structured population dynamics model, accessibility of the stock to the California and PNW fleets is determined by its dynamic spawning location, while total landings are governed by a statistical relationship of yearly fishing quota to stock abundance in the previous year. The albacore landings projection is similar to the SDM-based analysis of sardine, but with some key differences driven by species and fishery differences. For example, albacore availability to West Coast vessels are impacted by environmental conditions outside our ROMS domain, and albacore availability is linked to vessel size. Thus, the model was stratified by vessel size, and the center of gravity (COG) was used as a more robust measure of albacore distribution and availability (Appendix E). Like sardine, future fishing effort was based on a sample of historical effort, in order to avoid unrealistic extrapolation.

Analysis of management strategies for swordfish involved a risk assessment of an existing spatial closure (the Loggerhead Conservation Area; Smith et al., 2020), a projected risk assessment of existing spatial closures, and an MSE comparing static and dynamic spatial closures (Smith et al., 2021b). These studies explored strategic issues related to the sensitivity of static management in a dynamic and changing ocean. The projected risk assessment incorporated climate projections from the three ESMs to 2050, but the Loggerhead Conservation Area risk assessment and the MSE were historical and used the ROMS reanalysis for 1991–2009 and 1991–2000, respectively. The projected risk assessment of existing spatial closures allowed us to evaluate the potential impact of existing spatial closures on DGN fishers given a potential climate-driven redistribution of swordfish. However, to allow a tractable analysis, we assumed a constant swordfish price and fishing costs, and we ignored the Loggerhead Conservation Area, due to the challenge of predicting future El Niño years (Welch et al., 2019).

Our analysis of long-term changes to the structure and function of the albacore troll and pole-and-line fishery (Frawley et al., 2021) used participation networks (Fuller et al., 2017). This method enabled us to describe social-ecological linkages and feedbacks that inform how U.S. West Coast fishers participate and shift effort among fisheries. By exploring the consequences of overlapping changes in albacore ecology, seafood markets, and fishery regulations for diverse user groups, we identified patterns and processes likely to mediate the distribution of economic and non-economic fishery benefits in response to future changes in climate and/or governance.

4.5. Ecological and fishery modeling – Key metrics

For the SDMs, the key metrics are typical of these models: ‘probability of presence’ for models created from presence-absence data, and ‘catch rate’ for those created from fishery-dependent catch data. These are metrics of ‘habitat suitability’, which is generally the expected probability or abundance of a species in a given habitat. These catch rate models account for fishing effort, which becomes an input in SDM predictions. COG is also a key metric as it summarizes a general change in a finely resolved SDM. The SDM-based landings simulations of sardine and albacore ultimately quantify (respectively) percentage change in landings due to sardine spatial redistribution (Smith et al., 2021a), and the change in landings per vessel (Appendix E). Additional metrics evaluated for the SDMs were model predictive performance under anomalous environmental conditions (Muhling et al., 2020), and model predictive performance that can be attributed to each of the decomposed elements of SDM covariates (i.e. climatology, low frequency signal, high frequency signal; Brodie et al., 2021).

The metrics evaluated in the IBM and population dynamics models reflect their additional complexity. For the IBM, they include the historical and future sardine population biomass, spatial distribution of adult sardines and eggs, and regional annual catch. In the population dynamics model, metrics include stock abundance and age structure, landings by two fleets, latitudinal distribution shift of the stock, and the contribution of different biological processes to increases or decreases during the projection. Due to the focus on spatial management and bycatch, key metrics for the swordfish MSE and risk assessment are overlap of swordfish with closures (which as an economic metric becomes ‘lost opportunity’; Smith et al., 2020), rates of catch and bycatch, and the bycatch:catch ratio (Smith et al., 2021b; also called the reduction ratio, Dunn et al., 2016).

The community and processor engagement analysis for albacore uses factor analysis to reduce dimensions of input variables to engagement indices (Himes-Cornell and Kasperski, 2016), which in our study are a commercial harvesting index and a commercial processor index. Indices are derived for each community with documented historical participation in each fishery, based on the number of participating vessels owned, volume of the species landed by participating individuals, and ex-vessel value of that landed volume (for the harvesting index); or derived from the number of participating processors, volume landed at these processors, and the ex-vessel value of that landed volume (for the processor index). Note that the harvesting index is based on where vessel owners live (not necessarily where landings are made), and the processor index is based on the location of landings irrespective of where the vessels are from. Further detail of this method can be found in Appendix F.

For the longitudinal analysis of structure and participation for the albacore fishery (Frawley et al., 2021), the key metrics evaluated were changes in total catch and effort, the proportion of active fishing vessels targeting albacore, the relative diversification of different fleet segments targeting albacore, and the node strength and centrality of albacore in the participation networks of different fleet segments.

5. Results

Key results and uncertainties are summarized in Table 2 and detailed below. Uncertainties in Table 2 include those results which vary among ESMs, are unlikely to be precise due to (for example) being difficult to parameterize, or are key unmodelled aspects.

Table 2

Summary of main results for each reported model or analysis. Key uncertainties are the results that may not be well resolved or that differed among ESMs.

Model/Analysis	Key results	Key uncertainties
ROMS-NEMUCSC projection	Increased surface warming, stratification, and subsurface nitrate enrichment and deoxygenation	Rate of warming; changes in conditions (especially nutrients and oxygen) in coastal areas
Climate envelope analysis	Climate novelty in the CCS increases from 5 to 10 % in 2040 to almost 100 % by 2090	Rate of warming greatly alters timing and magnitude of novelty
Sardine SDM	Sardine habitat shifts northward	Rate of habitat shift; suitability of near-shore habitat; potential for non-stationarity in responses (Muhlinget al., 2020)
Sardine SDM-based landings projection	Sardine landings shift northward (higher at northern ports, lower at southern ports)	Amount of change in total landings; whether landings of southern sardine subpopulation will increase
Sardine IBM projection	Sardine habitat and landings shifts northward; Long-term abundance relatively stable with increasing from 2070	Magnitude of high-frequency abundance change not well modelled; end-of-century population state
Sardine population-dynamics projection	Sardine habitat and landings shifts northward; abundance recovers from current lows	Magnitude of abundance change due to model configuration
Swordfish SDM	Swordfish habitat suitability generally increases, and shifts northward	Predictability of fine scale habitat suitability (Brodieet al., 2021)
Swordfish spatial closure ‘lost opportunity’ projection	Swordfish distribution shifts unlikely to change impact of current spatial closures	Future change in fishing gear and subsequent bycatch patterns
Swordfish spatial closure MSE	Dynamic closures often more effective than static, but create practical challenges for fishers and managers	The occurrence of rare species within their suitable habitat
Albacore SDM	Albacore habitat shifts north and potentially inshore	The continuation of a migration corridor for albacore to reach the CCS
Albacore landings projection	Landings decrease in Southern California but increase or are stable elsewhere; fishing effort increasingly straddles the U.S./Canada border	Rate of warming, which impacts magnitude of landings change (but not spatial patterns)
Albacore engagement analysis	Only some southern communities engaged in harvesting likely to be affected by projected albacore range shifts	How communities and ports respond to shifts in albacore
Albacore participation network	Albacore supports diverse harvest portfolios; the success of small-boat operations appears contingent on their ability to opportunistically target albacore in coastal waters	How fishers respond to potential management changes

5.1. Physical and biogeochemical change

Results from the ROMS-ESM downscaled projections indicate some common changes of the CCS properties across ESMs. These include an intensification of upwelling-favorable wind stress in the northern CCS, an overall surface warming and increased stratification, and subsurface nitrate enrichment and deoxygenation (Fig. 3). However, there are clear differences in future properties among ESMs, especially in coastal regions for variables such as NO_3, O_2, and chlorophyll (Fig. 3). Here we highlight some of the key results from the ROMS-ESM projections, with a more comprehensive analysis provided in Pozo Buil et al. (2021).

5.1.1. Future changes in physical properties

All three downscaled projections show an overall intensification of the meridional wind stress (i.e., proxy for upwelling favorable winds) in the northern CCS, with ROMS-IPSL showing the weakest intensification and ROMS-GFDL the strongest. In contrast, projected changes in the southern CCS differ between models (Fig. 3). Surface warming is consistent across all models, though its magnitude is region- and model-dependent. By the end of the century, ROMS-GFDL projects the weakest increase in SST (~2°C), with weaker warming in the northern CCS, while ROMS-IPSL and ROMS-HAD project stronger increases in SST (~4°C and ~ 4.5 °C, respectively). These temperature trends in the downscaled projections closely follow those of their parent ESMs (Fig. 3). Warming in the CCS is surface intensified, leading to enhanced stratification (Pozo Buil et al., 2021; Cordero-Quirós et al., in review). This has further implications for the physical ocean environment: first, a projected reduction in mixed layer depth is evident in all three models (Bograd et al., 2023); second, a more stratified ocean drives a more energetic mesoscale field, and all three projections show enhanced eddy kinetic energy (EKE) with values at the end of the 21st century that are up to five times those from the 1980–2010 historical period (Cordero-Quirós et al., in review).

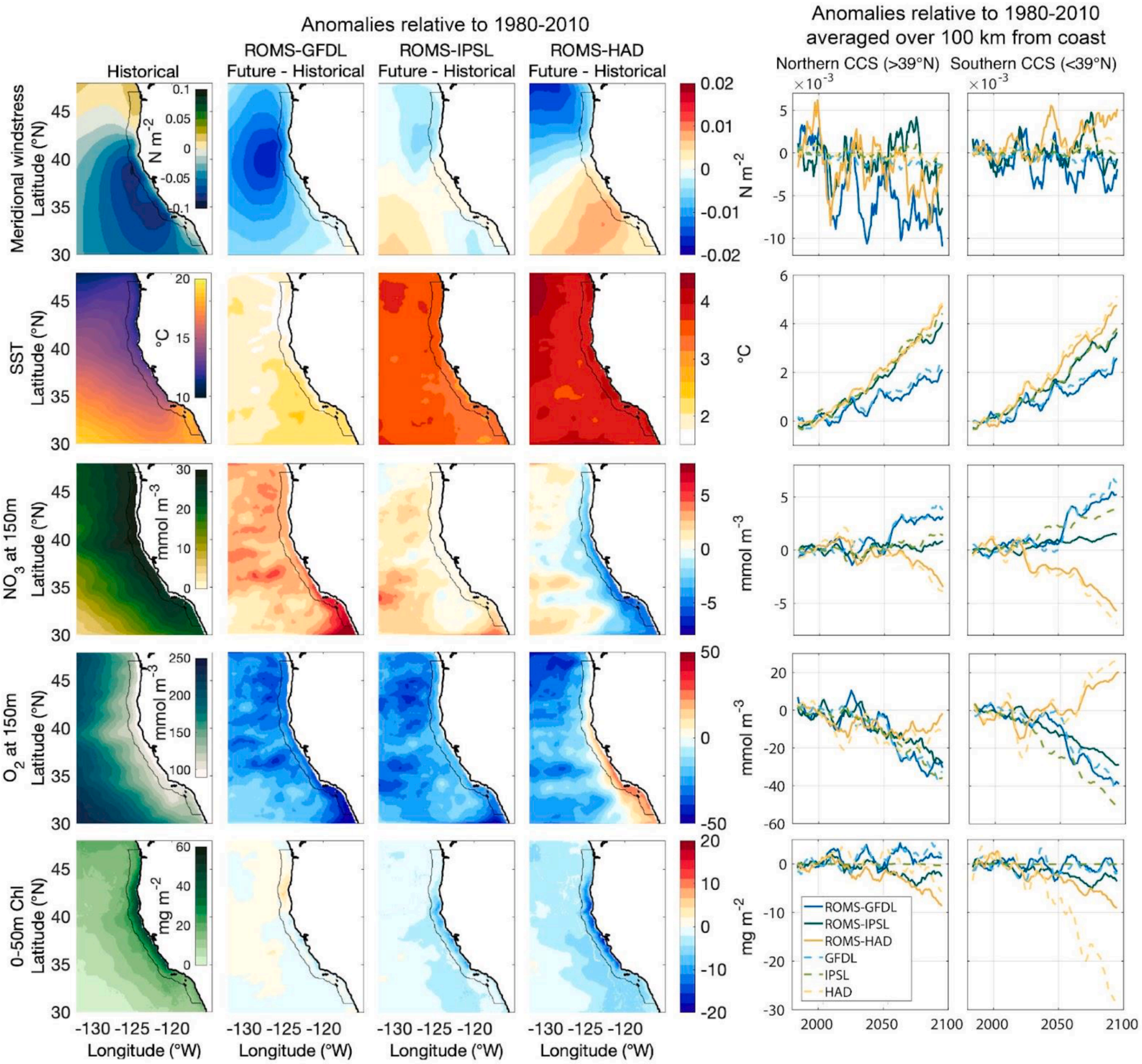

Fig. 3. Trends in five example physical and biogeochemical variables from the three downscaled projections; the rows from top to bottom: meridional wind stress, sea surface temperature (SST), nitrate concentration (NO_3) at 150 m, dissolved oxygen (O_2) concentration at 150 m, and 0–50 m vertically integrated chlorophyll concentration. *Left panels*: maps of mean absolute values from the historical control run (1980–2010; first column), and mean anomalies for a future period (2070–2100, relative to historical). Negative values of wind stress represent an increase in equatorward wind stress. Black contour marks indicate 100 km from shore. *Right panels*: time series of yearly averaged anomalies (relative to historical), averaged from the coast to 100 km offshore for the same five variables, and averaged for the northern (>39°N, left column) and southern CCS (<39°N, right column). Results from downscaled and global model resolutions are compared (e.g. ROMS-GFDL vs GFDL).

5.1.2. *Future changes in biogeochemical properties*

In the coastal regions, ROMS-GFDL and ROMS-IPSL project similar biogeochemical responses of ~ 30–40 % average increase (decrease) in subsurface nitrate (dissolved oxygen) by end of century. ROMS-HAD projects an opposite response featuring a decrease (~20 %) of subsurface nitrate along the coast and an increase (~30 %) of subsurface dissolved oxygen in the southern and central coastal waters. The evolution of these anomalies in ROMS-IPSL diverge in magnitude from those in the IPSL ESM, especially in the southern coastal region (Fig. 3). The most pronounced projected changes in chlorophyll occur in a coastal band between 35 and 45°N, the most productive portion of the CCS. ROMS-GFDL projects a weak increase of upper ocean (top 50 m) chlorophyll in the northern coastal region (~3 mg m^{-2}), whereas ROMS-IPSL and ROMS-HAD project moderate (−0.5 mg m^{-2}) and strong (−10 mg m^{-2}) declines, respectively, by the end of the century. Chlorophyll concentrations in the downscaled projections qualitatively track those of their parent ESMs, but the magnitude of change can be amplified (ROMS-IPSL) or reduced (ROMS-HAD) in the downscaled models. (Fig. 3).

5.1.3. *Emergence of novel climates*

A climate envelope analysis measures change in a multivariate space define by numerous climate variables, and novel (future) climates occur when climate conditions exceed the bounds statistically defined for a comparison (historical) climate (Williams et al., 2007; Mahony et al., 2017; Smith et al., 2022). Rather than focusing on change in single variables (e.g. SST), a climate envelope analysis examines multiple variables simultaneously, recognizing the importance of novel combinations of variables. Climate novelty can: 1) reveal novel environmental conditions otherwise difficult to identify, and 2) provide a general indication of environmental stress for a broad range of species. When considering the envelope defined by key drivers of fisheries habitat (i.e., SST, dissolved oxygen, mixed layer depth, and eddy kinetic energy), we find that (compared to the 1980–2009 period, and under RCP8.5) consistent novelty in the CCS climate envelope appears first in ~ 2040 in small patches off Southern California and the PNW, but by 2060 about 50 % of the CCS could experience a novel climate and almost all the CCS could experience a novel climate by the end of the century (Smith et al., 2022; Fig. 4). This is for mean monthly conditions, which represents a more persistent level of novelty than short-term heatwaves. The main driver of climate novelty is ocean warming, but weaker contributions also come from lower dissolved oxygen (especially inshore) and shallower mixed layer depth (especially offshore). There is great potential in exploring species- and model-specific projections of novelty using climate envelope analysis, with the primary focus being on substituting or adding other variables (e.g. bottom temperature, pH, nutrients) to reflect different aspects of an ecosystem (Smith et al., 2022).

5.2. *Ecological and fishery change*

5.2.1. *Sardine*

The preferred habitat of the northern subpopulation of sardine is projected by an SDM to shift northwards, with offshore areas becoming generally more unsuitable (Smith et al., 2021a). The IBM and population dynamics model show a similar trend, with the IBM estimating a poleward shift of 500–800 km during the 21st century, depending on the rate of warming (Fiechter et al., 2021). However, there is evidence that sardine have non-stationarity in their habitat associations, which was particularly evident during recent marine heatwaves (Muhling et al., 2020). This non-stationarity might be due to a mismatch between environmental conditions and spatial–temporal cues (such as migration or spawning), and suggests that projections based purely on correlative SDMs should be interpreted cautiously.

Projections from the IBM showed substantial low-frequency variability in sardine population biomass, with a decrease in 2020–2040 and strong increase beginning in the 2070s (Fiechter et al., 2021). In the age-structured population dynamics projections, sardine abundance moderately increases over time, with significant fluctuations caused by underlying environmental variability. Under ROMS-GFDL the population dynamics model shows an interim period of low sardine biomass in the middle of the projection due to low planktonic food availability in combination with a temporary warming hiatus (which may indicate a period of low ecological productivity), while the high temperatures reached towards the end of the century under ROMS-HAD and ROMS-IPSL drives a population increase to historical peak levels, but also high ecological uncertainty (i.e. divergence among model ensemble configurations). Both the IBM and population dynamics models show that spawning areas shift far northward in the CCS towards the end of the century, while feeding areas shift only moderately northward. This discrepancy could lead to a change in sardine migration patterns, which would reduce the impacts of surface ocean warming on the sardine stock and on accessibility to fisheries.

Across the three ESMs, the SDM-based simulation projects a decline in sardine landings of 20–50 % at Southern California ports by 2080, and an increase of 0–50 % at PNW ports (Smith et al., 2021a; Fig. 5). The seasonality of the fishery was also projected to change, with the duration of the fishing season generally lengthening, but constrained by landings

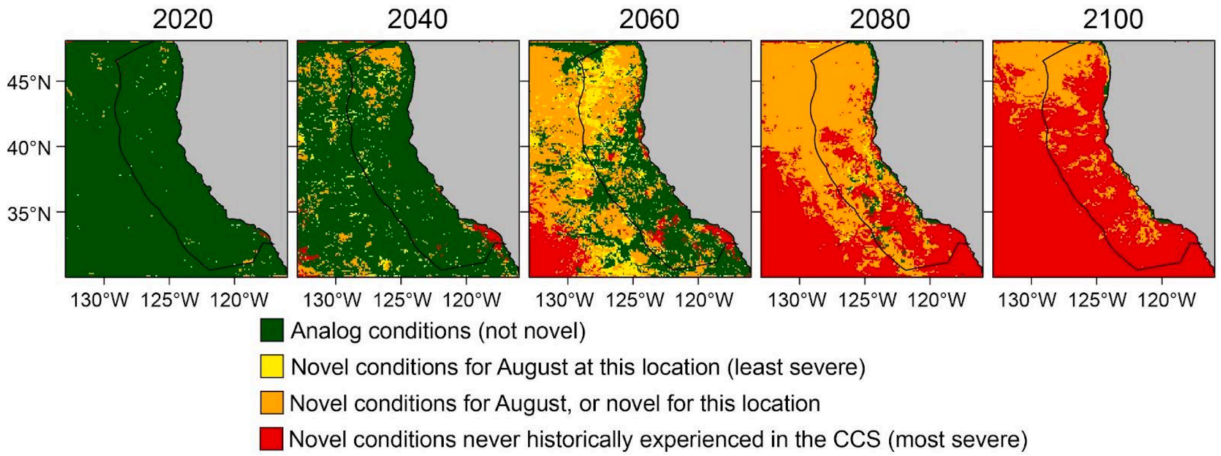

Fig. 4. Maps of locations in the CCS with novel or analog projected climates. Maps are shown for August at the end of five decades, under ROMS-IPSL. Colors represent an analog climate (green), or three scales of climate novelty (yellow, orange, red). The maps show each grid cell's majority classification over a 5-year period ending in the specified year (e.g. 2016–2020). Novelty was calculated using the hypervolume method, based on a climate envelope of SST, dissolved oxygen, mixed layer depth, and eddy kinetic energy (Smithet al., 2022). The black line is the exclusive economic zone (EEZ). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

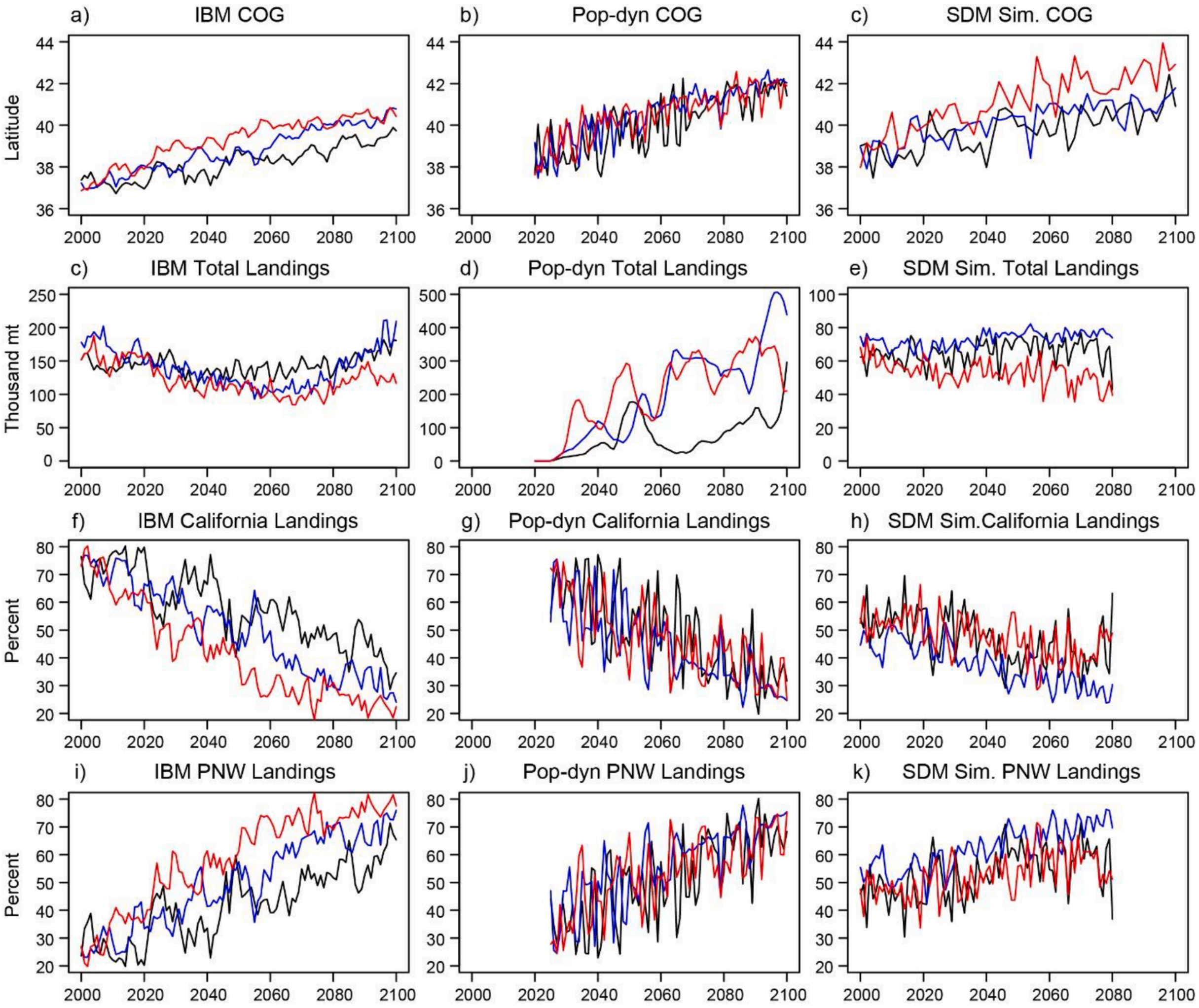

Fig. 5. Projected values for sardine latitudinal center of gravity (COG, a–c) and sardine annual landings (c–e) for the three models (IBM, age-structured population dynamics [Pop-dyn], SDM simulation) and three ESM projections (black is ROMS-GFDL, blue is ROMS-IPSL, red is ROMS-HAD). Landings are also shown as percentage of total landings in the California and Pacific Northwest (PNW) areas (f–k). In the IBM and SDM simulation landings were aggregated by summing port-level landings. For the population dynamics model, the mean of nine ensemble model configurations is shown, and the modeled period begins during a state of fishery closure (below 150,000 tons; d). Because the three models differ in how (or if) they model effort, sardine biomass, subpopulation structure, and fishery closures, COG (a–c) and the relative change in California and PNW landings (f–k) are the most robust results to compare across models. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

of other species and the seasonality of the quota allocation. The IBM projects change in catches due to changes in both sardine distribution and abundance. Catch is projected to increase by 50–70 % in the northern CCS and decrease by 30–70 % in the southern and central CCS. The late-century increase in sardine abundance in the northern CCS exhibited a large spread across climate projections, which suggest that end-of-century results bear a substantial level of uncertainty. The population dynamics modeling differs by beginning the projection period in a state of fishery closure, representing the current state of the actual fishery. After the modeled fishery reopens, the ensemble indicates a moderate increase in total sardine landings in the long term, while interannual and interdecadal variability remains high. Landings in the PNW increase in significance in comparison to California in the middle and end of the century (Fig. 5).

The three modeling approaches agree on the general future trends in sardine spatial distribution (a ~ 4°latitude shift northward by 2100) and its impact on landings, with the California fleet most vulnerable to a shifting distribution (Fig. 5). However, the uncertainty within models and among ESMs was high, and similar to the uncertainty in relative change among the three modeling approaches. To develop effective adaptation strategies for sardine, it will thus be important to assess performance of current and alternative harvest controls, quota allocation schemes, and monitoring systems given the projected shift in distribution and climate and ecological uncertainty. While an MSE was not attempted for sardine in the first phase of the Future Seas project (but see Section 6, Future directions), the SDM-based simulation did investigate how the current management strategy might constrain future landings given a future range shift (Smith et al., 2021a). This simulation shows that a seasonal quota allocation can limit landings when the availability of the species shifts temporally; i.e. to maximize adaptation to the projected range shift, the future seasonal allocation should be sensitive to a changing fishing season phenology. The simulation also indicated the importance of considering the futures of other CPS and fisheries impacts from a CPS guild perspective, as the timing of other CPS landings constrained sardine landings even when sardine presence was high. Finally, this work stresses the importance of monitoring and modeling the distribution of the southern sardine subpopulation, which may increasingly migrate into U.S. waters and potentially ease projected negative impacts on the California CPS fleet.

5.2.2. *Swordfish*

Swordfish habitat in the CCS is broad but sensitive to SST in particular, and projections show a poleward and offshore redistribution of habitat, with an average 52 % increase in total habitat suitability (Fig. 6). The magnitude of the COG shift from the historical distribution range (1985–2015) to the future distribution range (2070–2100) is an average of 198 km northwards and slightly offshore, with only small variation among ESMs. Habitat suitability decreases only in nearshore areas (Fig. 6).

Models of catch rate show the strong influence of SST and MLD, which can mean a strong seasonality of (and potential for long-term change in) the inshore-offshore distribution of swordfish, which may also change coincident with Northeast Pacific climate regimes (Smith et al., 2020). The analysis of the timescales of predictability of swordfish shows that a monthly climatology is sufficient to explain much of the swordfish distribution at these scales, and the addition of low frequency (interannual) environmental variability provides most of the capacity to predict anomalous distribution and catch, whereas high frequency variability adds only minor improvement (Brodie et al., 2021). This result indicates that catches of swordfish in the DGN fishery are more predictable at broader spatial and temporal scales, with uncertain association with finer scale ephemeral ocean features. This gives confidence in distribution projections for highly migratory species, as broad-scale distribution patterns are primarily driven by low frequency climate variability – a timescale that is better captured in ESMs compared to fine scale variability.

Given the likely redistribution of many species in the CCS, including swordfish, the spatial management of bycatch in the swordfish DGN fishery will benefit from increased dynamism (Pons et al., 2022), i.e. closures that can change in time or space. Even without a climate trend, interannual variation in ocean environment and species' distribution can have a large proportional impact on a static closure's impact (Smith et al., 2020). When this historical analysis is extended to project 'lost opportunity' out to 2050, we see evidence that a redistribution of swordfish leads to changes in fishing opportunity (the proportion of the profitable fishing area outside closures), but that there is likely no change, or even an increase, in future fishing opportunity (Fig. 7). In other words, the economic impact of the existing static closures on the DGN fishery is unlikely to increase due to any climate-driven changes in the spatial distribution of swordfish; where 'economic impact' here relates to the severity of changes to effort or fisher behavior that will occur due to a closure's enactment (Smith et al., 2020). However, opportunity is just one metric for evaluating spatial closures. Our MSE highlights that the key to the continued success of DGN spatial closures for bycatch reduction will be following the future distribution of sea turtles, and the evaluation of more dynamic closures (alongside other bycatch mitigation tools) that match the dynamism of the species' distribution (Smith et al., 2021b; Kaplan et al., 2021). New gear types that are being tested to catch swordfish with lower bycatch rates may provide an opportunity as swordfish change in distribution and abundance in the future. Dynamic closures can achieve similar or better reduction of bycatch compared to static closures (Pons et al., 2022), while allowing higher target species catch and fisher profit (Appendix G).

5.2.3. *Albacore*

Projected COGs from the albacore SDM move generally inshore and northward in the future (Fig. 8a). In the CCS, predicted CPUE decrease in the southern and offshore study region, but increase closer to shore north of Point Conception (Fig. 8b). These shifts are due to SSTs becoming warmer in the offshore CCS than those historically linked to albacore fishing grounds, but becoming more favorable in the nearshore upwelling zone. Historically, albacore catches have been low in the high-chlorophyll region close to shore, but a combination of warming and reductions in surface chlorophyll nearshore – projected by the ROMS-IPSL and ROMS-HAD models – increase the favorability of this area for albacore in the future. However, the ability of albacore to make use of this increasingly nearshore suitable habitat may also depend on continued availability of a suitable migration corridor to reach the CCS.

The distribution of albacore fishery landings and effort has been highly variable across space and time (Frawley et al., 2021). The community engagement analysis shows that numerous communities along the West Coast are currently engaged in the albacore fishery, with location-based processing engagement centered in the PNW, and harvesting engagement more uniform along the coast (Fig. 9a). Most communities have very low engagement in the fishery, with a handful dominating both types of engagement, but especially processing. A community is considered highly engaged when engagement score is considerably higher than the mean score for all involved communities (see Appendix F). Vessel size influences engagement, with the most communities engaged for small vessel harvesting or processing, and the least for large vessels. Processing engagement otherwise shows little difference among vessel sizes, while for harvesting engagement communities in Central California show more engagement with small vessels, and Southern California with large vessels. Albacore has become an increasingly important component of the harvest portfolios of small-boat fishermen (Frawley et al., 2021), many of whom lost access to other traditionally important species assemblages due to environmental change and regulatory reform. While large high-volume vessels based in Southern California have been able to accommodate significant spatial shifts in the fishery, the success of range-restricted and capacity-limited

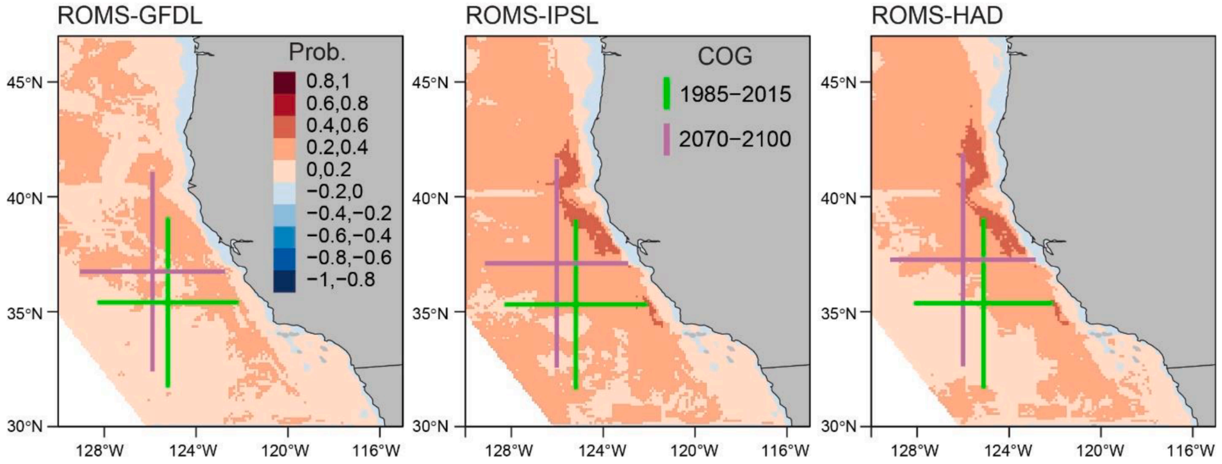

Fig. 6. (a) Maps of change in the habitat suitability of swordfish and their center of gravity (COG), for the three ROMS-ESMs. Color represents change in the probability of presence between historical (1985–2015) and future (2070–2100) periods (red an increase, blue a decrease). Change in bivariate COG is represented by historical (green) and future (purple) bars. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

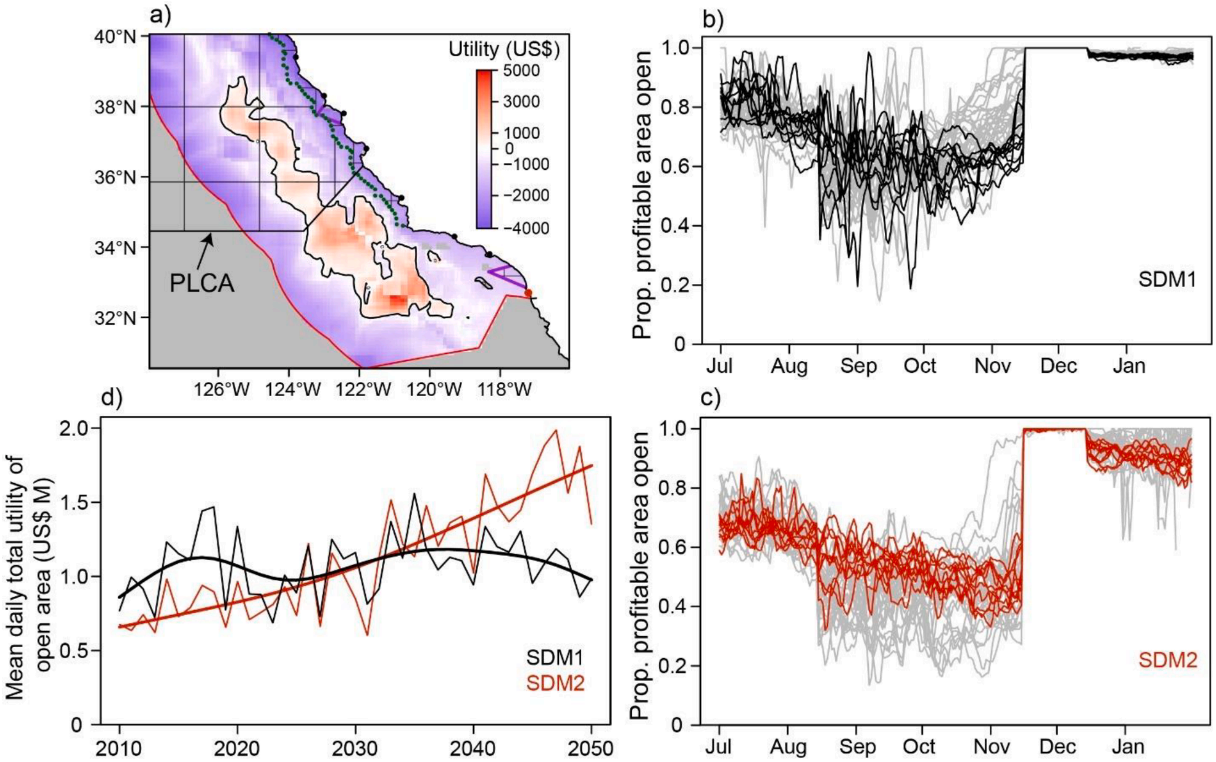

Fig. 7. Results of the 2010–2050 projection of fishing opportunity in the DGN. (a) An example date (30-Sep-2030) of estimated utility (the difference between swordfish revenue and fishing costs) given swordfish catch-*per*-unit effort on this day predicted by an SDM. The red areas are those with profitability (positive utility) for a vessel leaving San Diego (red dot) on a 3-day fishing trip and landing at the nearest port (see Smithet al., 2020). There are seven closures active on this date (five possible in this extent; hashed areas and purple lines) including the large Pacific Leatherback Conservation Area (PLCA). (b–c) The fishing opportunity (proportion of profitable area outside closures) is shown for every year from 2010 to 2050 for the extent of the fishing season (Jul-Jan), with the last 10 years (2041–2050) shown as black lines (SDM1) or red lines (SDM2). Two plausible SDMs (SDM1 and SDM2; based on those in Smith et al. (2020)), were used to account for structural uncertainty. (d) The changes in opportunity (b–c) can be summarized as the mean for each fishing season of daily total profitability (the sum of the positive utility in open areas). We see that SDM1 (black lines) indicates fishing opportunity will be stable to 2050, while SDM2 (red lines) indicates fishing opportunity will increase. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

small-boat operations appears contingent on their ability to opportunistically target albacore in coastal waters and to maximize catch value as part of a diverse harvest portfolio.

The albacore landings projection demonstrates that different fisher groups have different strategies for adapting to changes in albacore distributions, and that communities in southern California are likely to be negatively impacted by future change, while communities in the PNW may benefit. Larger vessels are projected to be more responsive to changes in albacore distribution, employing a ‘follow the fish’ adaptation strategy, and switching landing ports more quickly if it becomes economically beneficial. Small vessels, which have more limited mobility, are more likely to keep landing in the same community. As the COG of albacore distribution moves northward (Fig. 8a), projected landings from large and medium vessels in 2041–2070 and 2070–2100 show a 25–100 % increase in landings in PNW communities and a 5–60 % decrease in San Diego and Long Beach relative to average landings in 1995–2018 (Fig. 9b). Small and medium vessels rely on a more diverse portfolio (Frawley et al., 2021), and, unlike for large vessels, projected changes in landings depend on biomass trends of other species and estimated albacore availability within 60 miles (small vessels) or 120 miles (medium vessels) from port. Variability in considerable among ESMs (Fig. 9b) due to the variability in nearshore habitat suitability, with ROMS-HAD showing higher suitability than ROMS-IPSL or ROMS-GFDL (Fig. 8b). Our results are consistent with those of Phillips et al. (2014), who found a positive but spatially variable effect of SST on historical albacore catch rates and hypothesized that climate change would negatively affect southern albacore-reliant communities, while northern communities would be positively impacted.

Our social-ecological investigation of the albacore fishery suggests that the fishery is composed of diverse participants who may be differentially impacted by projected changes to the CCS. While some ports, processors, and vessels classes have demonstrated the capacity to negotiate large-scale shifts in distribution and abundance, the negative impacts upon others are likely to be significant. This may be particularly true for processing communities in Southern California that are heavily dependent on North Pacific albacore. Given albacore’s role in helping to support diverse harvest portfolios and promoting operational flexibility, changes impacting the albacore fishery may have cascading impacts upon the effort allocated to other linked fisheries (i.e. salmon and Dungeness crab). More broadly, our analysis of divergent impacts and responses across albacore fishery user groups suggests the limitations of a management strategy that applies equally to all fishery participants. The design of equitable and effective interventions may necessitate explicit accounting of the distinct response capacities and vulnerabilities of different user groups. This consideration is important in light of recent interest by regional fisheries management organizations to establish a harvest control rule for North Pacific albacore and the recent MSE (ISC Albacore Working Group, 2021). Our landings model adds to the performance metrics used in the MSE by providing a framework with which to test impacts of different HCRs on metrics reflective of the heterogeneous nature of fishery participants. The model also highlights factors affecting the catchability of the U.S. albacore fleet, which can inform development of climate-driven implementation error scenarios for this fleet. Finally, projected albacore fishing effort more often straddles the U.S./Canada border by 2100 (Fig. 8a), highlighting the need for continued coordination of fishing access across national jurisdictions via

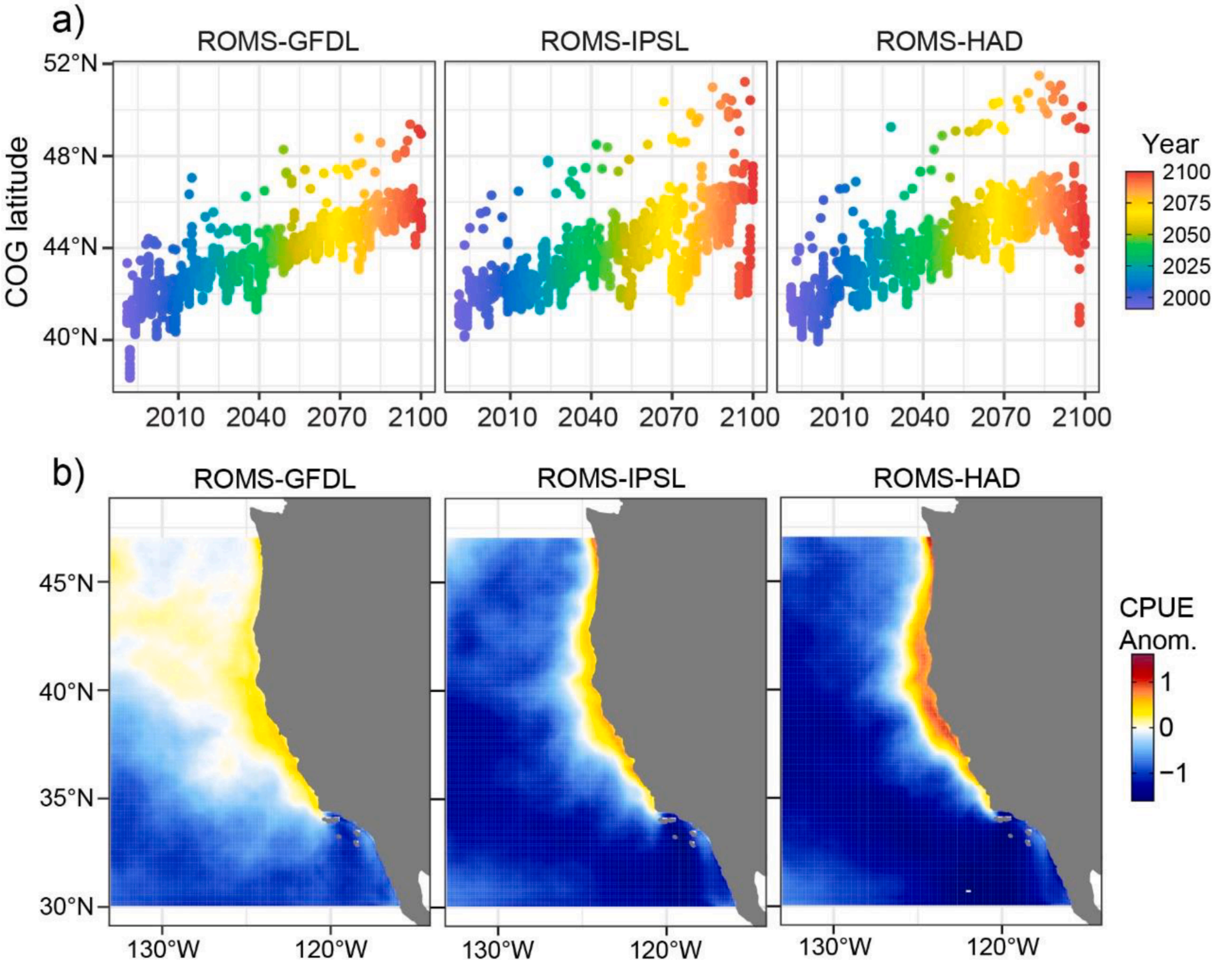

Fig. 8. (a) Projected latitudinal center of gravity (COG) of fishing effort for North Pacific albacore in the Eastern Pacific Ocean for the three ROMS-ESMs. Points represent multiple iterations of each year based on resampling of historical fishing locations. Points are also colored by year. (b) Maps of projected mean albacore habitat suitability in 2080–2100 shown as change in CPUE [log10(x + 1) fish/vessel/day] relative to 1990–2020 (i.e. an anomaly) from the albacore SDM for the three ROMS-ESM projections (red is better habitat, blue is poorer habitat). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

the existing United States-Canada albacore treaty.

6. Future directions

The first phase of the Future Seas project has focused on highlighting patterns of future change and potential impacts to fisheries social-ecological systems, and informing strategic decision making for fisheries management. This information can be used in scenario planning, by providing a range of potential environmental change as well as plausible future fish distributions and fishing grounds. Our results can also help prioritize tactical research; for example, we identified the sensitivity of the sardine fishery quota allocation strategy to sardine redistribution, which indicates the value of an MSE exploring specific alternatives. Likewise, our swordfish MSE provides further evidence that dynamic spatial closures are valuable for bycatch mitigation, but that managing very rare species comes with high uncertainty. This result could spur development of an MSE for specific closure types in the DGN (rather than the generic DGN-like fishery described herein), including hybrid strategies (e.g. incorporating hard caps) that can help manage the increased level of bycatch uncertainty. Our long-term projections, and evaluation of current and historical fishery structure and engagement, can also feed into NOAA's Integrated Ecosystem Assessment program (Harvey et al., 2017) by contributing to risk assessment of fisheries and species, and quantitative scenario analysis in the CCS (Holsman et al., 2017; Samhouri et al., 2019). By focusing in detail on specific fisheries, our community engagement analyses complement the broader suite of metrics available in NOAA's Community Social Vulnerability Indicators Toolbox (Jepson and Colburn, 2013), which identify fishing communities susceptible to the adverse impacts from a range of stressors (Kasperski et al., 2021).

The second phase of Future Seas is underway, and aims to develop and improve our modeling framework. To date, Future Seas has used predominantly-one-way coupling between ecological and social components, i.e. the environment and species were not affected by the social system (Kasperski et al., 2021). In general, the social components of our models are less well developed than the environment and ecological components. Thus, our goals for the future include: enhanced two-way coupling, including feedbacks between fishing and species' abundances and distributions; more tactical environment-informed MSE models testing harvest control rules; improved integration of the environment into biological models (for example, via recruitment in population dynamics models); and more comprehensive social system components. Enhanced dynamic feedback between social and ecological components of the system can enable quantification of climate adaptation effectiveness as well as residual risk (remaining risk after adaptation) to ecosystems and fisheries. Some of our ongoing CCS research focuses on specific species groups (i.e. forage species) but with better integration of model components. Models in development include: a

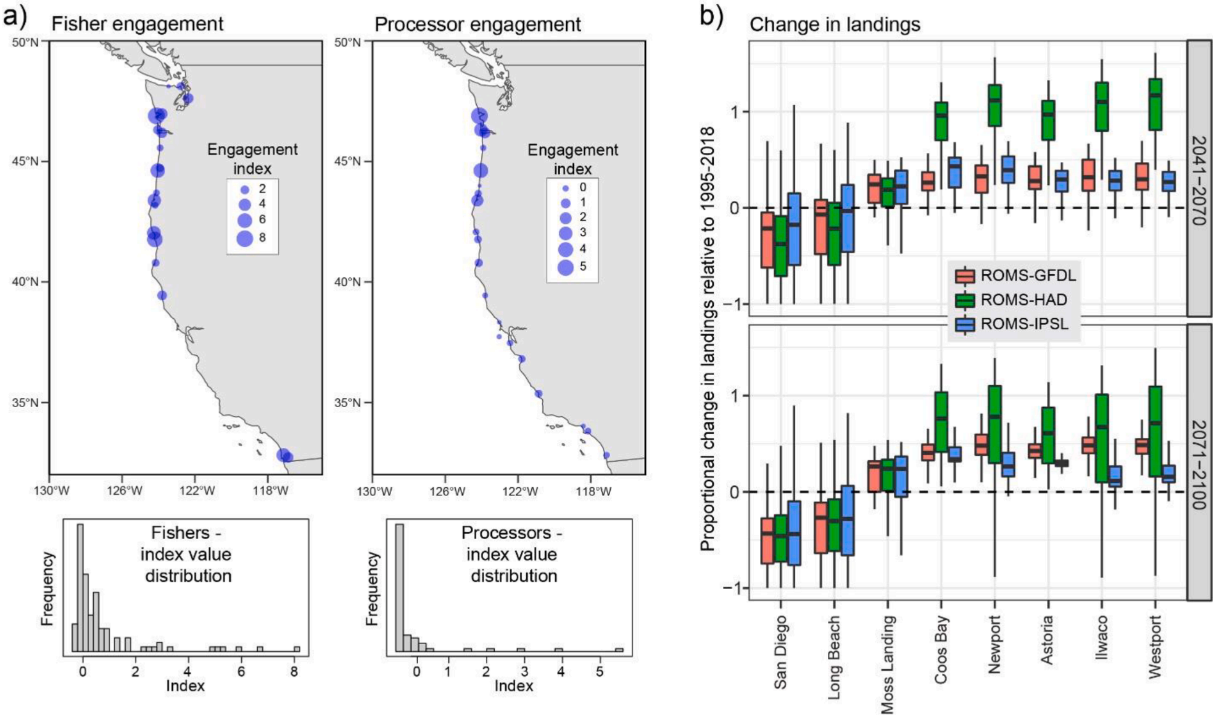

Fig. 9. (a) Maps of indices for historical (1995–2018) harvesting and processor engagement in the albacore fishery, for medium sized vessels (45–60 ft). Each unit of the index represents one standard deviation, meaning that a value of 8 represents extreme engagement compared to the mean level of engagement. The histograms under each map show the distribution of index values for the most engaged 100 communities (harvesting index) or all 67 engaged communities (processor index). (b) Projected proportional change in port-level albacore landings for medium vessels for two future periods compared to the 1995–2018 historical period, for the three ROMS-ESMs.

California Current Atlantis spatial ecosystem model (Kaplan et al., 2017) with dynamic, climate-responsive spatial distribution of key species or functional groups informed by SDMs; an ensemble of sardine operating models for more tactical MSEs; improved bioeconomic modeling for projections of impacts on the CPS fishery; and a spatial population dynamics model for sardine including environment-driven movement.

We are also exploring how changes in forage fish will propagate through the CCS food web, based not only on ecosystem modeling (and the planned Atlantis modeling incorporating species distributions) but also trait-based modeling. Trait-based ecology focuses on the role of organism traits in mediating organism abundance and distribution, and how these traits can be used to predict unobserved responses (beyond using only abiotic variables). Body size, habitat associations, and life history traits are commonly used when investigating climate change effects (Green et al., 2022), but interactions between species and their impacts to species productivity and distributions are an often-overlooked biotic filtering step. By assessing predator diets based on traits of forage species that synthesize trophic interactions, we can generate future predictions of predator distributions given trophic filtering processes such as prey switching. These approaches will be applied to research on albacore, which exhibit dynamic prey switching behavior in response to varying forage availability, and we aim to evaluate whether trait-based models, and measurements of prey energy content, can improve projections of albacore distributions and potentially abundance.

The coupled ocean-biogeochemical model projections developed as part of Future Seas have provided a foundation for the wide array of ecological and socio-economic analyses described herein, as well as in a number of other CCS research projects. Nonetheless, there are a number of avenues for enhancements and improvements to these projections. Modifications to the model domain could improve the utility of the projections; e.g. a larger domain would enable better coverage of species ranges and connectivity, and higher spatial resolution could improve representation of fine scale processes and bathymetry, particularly over the continental shelf. Inclusion of river inputs in future versions of the model projections would improve their fidelity especially in the northern part of the domain, and would widen the scope of applications to include species that are dependent on estuarine or freshwater sources at the land-sea interface. Lastly, as is typical of regional ocean simulations, the size of our projection ensemble (three ESMs, one RCP) was limited by computational resources. Including more ESMs in the projection ensemble, as well as forcing from multiple scenarios, would allow for improved characterization of the range of potential ocean futures. This is a key goal for regional climate projections intended for marine resource applications, but one that often competes with efforts to enhance resolution (Drenkard et al., 2021). Our experiences in Future Seas lead us to prioritize greater domain size and more ensemble members over further increases to ocean model resolution.

The CCS is a well-studied system, and there are numerous studies using climate projections to investigate the physical, ecological and socio-economic future of the CCS (e.g. Ainsworth et al., 2011; Woodworth-Jefcoats et al., 2013; Cheung et al., 2015; Marshall et al., 2017; Morley et al., 2018; Haltuch et al., 2019; Howard et al., 2020). There are also ongoing efforts beyond our own to develop projections for the CCS, for nearby regions, and globally, which are relevant to our results and project structure and to the development of integrated projection analyses in general. Important foci for these modeling efforts include: evaluation of relative climate risk to coastal communities and fisheries (Payne et al., 2021); integrated, iterative, and multi-model frameworks (e.g. the Alaska Climate Integrated Modeling project; Hollowed et al., 2020), which can develop projections while robustly estimating uncertainty (Reum et al., 2020; Whitehouse et al., 2021); developing projections for species complexes in the CCS, including groundfish, and highly migratory species (e.g. the Fisheries and Climate Toolkit Project, https://fisheriesclimatetoolkit.sdsu.edu); and development of accessible and standardized ensembles of climate-fishery models, to encourage consistent and comparable projections and uncertainty (i.e. Fisheries and Marine Ecosystem Model Intercomparison Project; Tittensor et al., 2018, Tittensor et al., 2021). Marine ecosystems are complex, and there are many issues and processes to explore in projection studies (and beyond what is currently considered in Future Seas), including food web changes and the balance of nutrients, vitamins (e.g. thiamine; Sutherland et al., 2018; Mantua et al., 2021), and predator–prey dynamics (Ohlberger et al., 2019). Multi-model frameworks are likely the best way to evaluate these complex systems, by balancing narrower focused models for tactical projection analysis alongside generalized and ecosystem model for strategic projection analysis.

7. Recommendations

7.1. Consider the physical, ecological, and socio-economic context

The general methodological approach of Future Seas – linking climate models to oceanographic, ecological, and socioeconomic models – can be employed in a wide range of applications and regions. However, in each case the details of the modeling framework should be tailored to the specific context; outlining key elements of that context, including stakeholder priorities, is thus an important early step in such a project design. For Future Seas, the physical, ecological, and socio-economic context is outlined in Section 3, and many of the elements described here will be applicable to other projects. Examples include the spatiotemporal scales of dominant atmospheric and oceanographic processes, prominence of anthropogenic signals relative to natural variability, population dynamics of focal species (e.g., boom-bust vs more stable), bottom-up vs top-down control of ecological change, regulatory environment and management concerns (e.g., harvest guidelines, spatial management, species interactions or human-wildlife conflict), and socio-economic considerations (e.g., cultural and economic value, large vs small-scale fisheries). Of course, other projects will likely have similar considerations as well as different or additional ones. In any case, an effort to thoroughly understand the context of a project at its outset will help to ensure that methods, analyses, and products are ultimately responsive to, and able to address, stakeholder concerns.

7.2. Develop a modeling and analysis framework guided by the context and constraints

With a thorough understanding of the context in which the project is being carried out, an appropriate analytical framework can then be developed. We have found that a thoughtful and intentional approach to this process can be aided by some guiding questions: Which models should be used? How will environmental information be incorporated? Which management modeling framework is best suited to addressing stakeholder concerns? What are the relevant metrics of change produced by the models? We provide details of these considerations for Future Seas in Section 4 as a case study. In brief, some examples include (i) matching oceanographic projections to population dynamics of focal species (e.g., projecting continuous ocean change, as opposed to just past and future slices, is appropriate for species such as sardine whose populations exhibit dramatic low-frequency variability), (ii) matching ecological model type to the characteristics of focal species (e.g., we included population dynamics models for sardine, which spawn in the CCS, but focused on distribution models for swordfish, which spawn outside the CCS), and (iii) matching management strategies to stakeholder concerns (e.g., alternative harvest guidelines for sardine, alternative spatiotemporal closures for swordfish).

7.3. Fit and project ecological models with appropriate environmental information

When making ecological projections based on environmental data, it is necessary to reconcile historical data used to develop ecological models with the model output used for long-term projection. Future climate projections are typically derived from ESMs that are global in scope, and include coupled atmosphere, land and ocean components that are freely evolving in response to greenhouse gases and aerosols. In these simulations, the statistics (i.e. mean and variability) of quantities of interest under historical greenhouse gas levels (e.g. the 1980–2020 period of a 1980–2100 projection) should match observations, but projection output from specific years in this historical period would not match the historical observations (Stock et al., 2011; Drenkard et al., 2021; Table 1). For example, the historical portion of a climate model simulation will have El Niño events, but their timing will not match those in the historical record. While this fact is not a shortcoming of the models, it does severely limit the use of the historical period of the projection for ecological model fitting.

As a result, historical ocean state estimates used to fit ecological models often come from either in situ observations, a model hindcast, or a reanalysis (Table 1). Each of these data sources has advantages and disadvantages in the context of developing ecological projections. reanalyses combine the strengths of observations and hindcasts to give ocean state estimates that have complete spatiotemporal coverage and are more accurate than those from a hindcast. However, they are typically physics-only, are much more time and computationally intensive to create, and perform best for regions, times, and variables that are well constrained by observations. The inclusion of biogeochemical dynamics is much more common in ocean hindcasts, but the absence of data assimilation is, however, likely to degrade the ocean state estimate to some degree.

A recommended workflow for model fitting-projection would be: (1) fit ecological models based on historical environmental data (observations, hindcast, or reanalysis, depending on their availability and suitability); (2) project the fitted model, using ocean model output forced by ESMs, including historical and future periods (e.g., 1980–2100); (3) check that the mean/variability in the projections of the ecological/economic quantity of interest over the historical period is comparable to the one obtained when predicting with realistic historical data; and (4) reference future changes to the historical period of the ESM-driven projection. If step 3 shows that future changes are referenced to a historical model simulation that is biased relative to reality, it is more appropriate to interpret changes (e.g. fishing catch) in relative rather than absolute terms.

7.4. Capture uncertainty and use ensembles

When models are used to predict the real world, it is important that outputs include estimates of uncertainty and error in predictions. Uncertainty and error will always exist and arise from imperfect understanding, representation, or observation of the system being modeled. There are numerous schemes for classifying and distinguishing uncertainty and error, and these will often be idiosyncratic to the modeling approach and study. Some effort has been made to unify the schemes for climate and ecological models, by using four main classifications: structural (or model) uncertainty, parametric uncertainty, scenario uncertainty, and internal (and sometimes initialization) uncertainty (Cheung et al., 2016; Payne et al., 2016). Fisheries science, and often for MSEs, typically uses some combination of six classifications: process, observation, parameter, structural (or model), estimation (or assessment), and implementation uncertainty (Francis and Shotton, 1997; Punt et al., 2016).

In Table 3 we specify these main sources of variation - attempting to align the two classification schemes above - and how they were, or could be, represented in our project. Accounting for every source of uncertainty in any projection is probably not feasible due to computational and statistical limitations, and attempting to do so could increase the potential to overestimate joint uncertainty, conceal important signals, and challenge the ability to provide climate and management advice. Instead, a reasonable goal is to identify the most important

Table 3
Types of uncertainty and how they were, or could be, incorporated in our projections. These broad classifications are often divided into more specific classifications. For example, SDM uncertainty can be estimated separately from ESM uncertainty (Morleyet al., 2020) even though both are types of model uncertainty. [1]Francis and Shotton (1997), [2]Hill et al. (2007), [3]Payne et al. (2016).

Type of uncertainty	Domain relevance	Description	Representation in Future Seas	Example methods to estimate/incorporate
Scenario	Physical, socio-economic	Uncertainty arising from forcing processes, typically future emissions and aerosols arising from future socio-economic patterns; could also include 'implementation uncertainty'[1], if scenarios were used to model variable uptake of management actions	Climate: not evaluated (used single RCP) Other: alternate spatial closure responses evaluated in swordfish models	Evaluate multiple RCPs or SSPs (shared socio-economic pathways); develop fishing industry and management scenarios
Model / Structural	Physical, ecological, socio-economic	Uncertainty arising from differences in model design, configuration, or structure	Climate: three ESMs usedOther: multiple SDMs used (swordfish), multiple model types used (sardine) and multiple configurations (sardine pop. dynamics model)	Multiple models or 'ensembles'; model weights can also be explored[2]
Parametric / Parameter	Physical, ecological, socio-economic	Arising from variation in model parameters; compared to model uncertainty (which is about evaluating various plausible structures), parameter uncertainty focuses on how well a model explains data (e.g., uncertainty due to extrapolation of SDMs)	Climate: implicit in use of three ESMs Other: multiple iterations of the swordfish MSE, varying key parameters and sampling posterior distributions	Run models multiple times with resampling of parameter estimates[2]; report mean and spread of model outputs; model extrapolation can also be measured as a surrogate of statistical measures of parameter (and prediction) uncertainty
Internal variability / process uncertainty	Physical, ecological, socio-economic	Natural variations that contribute to 'random' variability in projections (e.g. stochasticity in population dynamics); can also include 'initialization uncertainty'[3], which is both an observation and parameter problem; internal variability could be considered to be estimated by model residuals, although they maay be unrealistically large in poorly specified models; true internal variability is considered 'irreducible uncertainty'[1]	Climate: implicit in three ESMs with different internal variabilityOther: in the albacore projection, future fishing locations were randomly assigned, constrained by historical distances offshore and effort within an SST-chlorophyll envelope; in the swordfish MSE, catches were sampled randomly from an empirical distribution, representing irreducible fishing catch success (i.e. they caught the mean catch only in the long run)	Multiple iterations of climate projections from the same scenario and model; allow for and estimate with error terms (e.g. recruitment deviations in stock assessment models); run models multiple times[2]
Observation	Physical, ecological, socio-economic	Uncertainty associated with imperfect measurement and sampling of the system; more often explored in ecological models	Evaluated in the swordfish MSE by random variation in the simulated observer program, and by ensuring simulated observations were as accurate of the simulated truth as real observations are in reality	Incorporate through iteration; specify observer error in estimation model of MSE; estimate using hierarchical modeling where appropriate; reduce by increasing amount and coverage of observations; evaluate and communicate observation biases

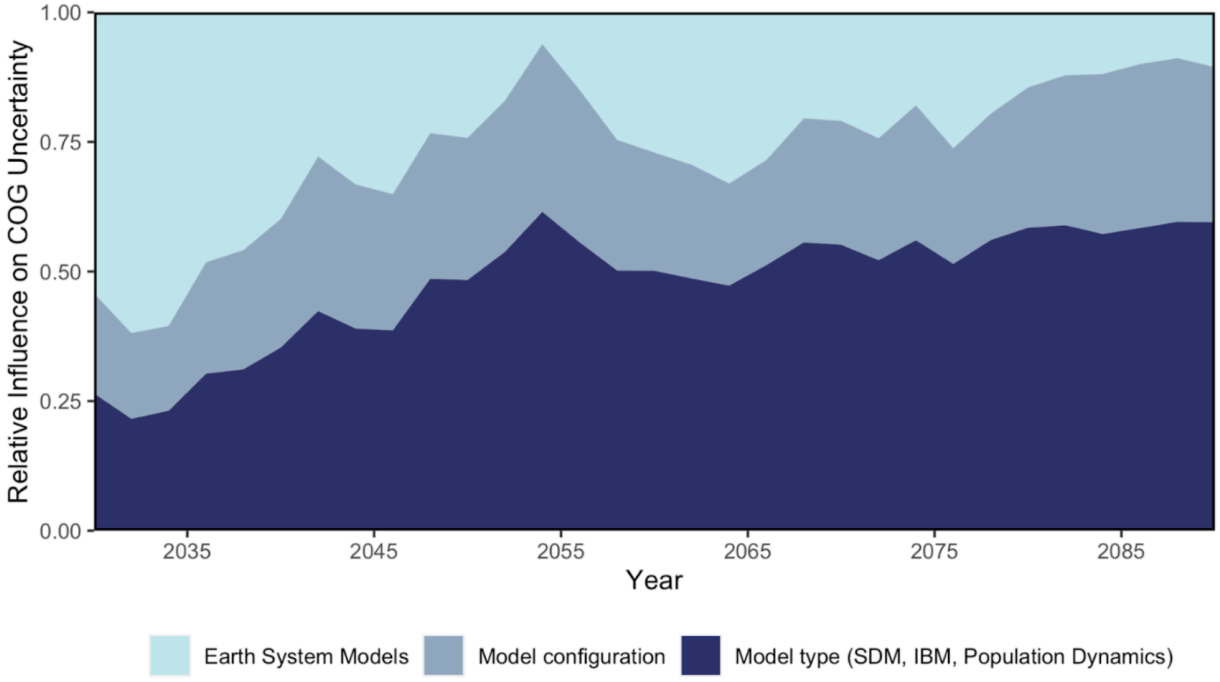

Fig. 10. Relative uncertainty in center of gravity (COG) predictions for the Pacific sardine population in the CCS, partitioned across earth systems models, model configuration (for the population dynamics model), and model type. COGs are smoothed over 10 years. Analysis was completed using the *dominanceAnalysis* function in the 'dominanceanalysis' R package (Navarrete and Soares 2020), with model configuration nested within model type.

uncertainties, propagate them through the projections, and ensure the interpretation of results acknowledges the variation and uncertainty that remains unmodeled. Our most thorough evaluation of uncertainty was for sardine, specifically the center of gravity (COG) projections (Fig. 5), for which we can partition the relative contributions of: uncertainty associated with the ESMs; uncertainty associated with ecological model type (SDM, IBM, population dynamics); and uncertainty associated with multiple configurations of a single model type (the population dynamics model). We found that the relative contribution of uncertainty associated with ecological model type increased as the projection horizon increased, while the relative ESM uncertainty decreased (Fig. 10). Our results for Pacific sardine agree in part with those of Brodie et al. (2022) and Reum et al. (2020), who found that ecological model uncertainty increased over time, although Reum et al. (2020) also found a similar increase in ESM uncertainty for some species groups.

Based on analyses to date and subsequent exploration of uncertainty (Table 3, Fig. 10), we report the following findings and recommendations:

- Our projections would benefit from additional emission scenarios (or Shared Socio-economic Pathways; Section 7.5); however, these may not be the dominant source of uncertainty, especially for shorter projection horizons (Frölicher et al., 2016), because our suite of models for the CCS under RCP8.5 captured much of the range in projected physical and biogeochemical change exhibited in lower RCPs (Pozo Buil et al., 2021).
- Our project, and likely others, would benefit from developing and integrating scenarios for processes other than just emissions, such as socio-economic trajectories that might influence factors such as seafood price or fishing effort and efficiency (see Section 7.5).
- Our projections would benefit from additional ESMs. While the three we selected bound the range of potential futures well, we are unable to quantify the likelihood of different trajectories within that range. Ensembles of models are useful, although care should be taken when determining model inclusion, as not all models are equally reasonable (Overland et al., 2011; Muhling et al., 2018). Deciding whether to report mean results from an ensemble, or results from each member of an ensemble, is an important consideration; model weighting (Hill et al., 2007) may be appropriate when presenting ensemble mean results, but can be challenging to implement objectively.
- Ecological model uncertainty is a large source of uncertainty, potentially equal to or greater than climate model uncertainty in long projections (Fig. 10, Thuiller et al., 2019; Morley et al., 2020), highlighting the value of developing multiple ecological model configurations and parameterizations (Smith et al., 2021b, Koenigstein et al. in review), and potentially different model types that are diverse in fundamental structure (Fig. 5).
- The uncertainty of correlative SDM projections will be underestimated by assuming stationarity of habitat associations (e.g. ignoring acclimation or adaptation). Although this uncertainty can be identified with careful cross-validation (Muhling et al., 2020), how this uncertainty can be propagated into projection results is unclear. Building multiple SDMs may (inadvertently) help to account for this uncertainty. A future research focus could be a better representation of non-stationarity in SDMs, perhaps with hybrid modeling approaches that incorporate dynamic processes in correlative models (e.g. Bush et al., 2016).
- Extrapolation is a key aspect of projection, and is a key issue for correlative SDMs, especially given the emergence rate of climate novelty (Smith et al., 2022; Brodie et al., 2022; Fig. 4). Poor extrapolation is a parameterization problem, but it is unclear how this uncertainty can be represented in model results. Mapping where and when extrapolation occurs (Zurell et al., 2012) can identify where models may be less accurate, even if the magnitude of that inaccuracy is uncertain. Quantifying biological rates (e.g. migration capacity, stage-specific survival, consumption and growth, or predation rates) in process-based models could help to validate or constrain extrapolations.
- When future uncertainty is high, constructing and interpreting future scenarios can be simplified by projecting change in only some variables while keeping others constant. For example, in our SDM-based sardine landings simulation only the environmentally-driven sardine distributions are projected, and our interpretation is restricted to the impacts of environmental change on a representative but largely independent fishing industry. An alternative to this could be carefully controlled scenarios, especially in terms of socio-economics, which we discuss in the next section.
- More and better data should always be a priority, and benefits modeling in a number of ways. including: reducing (and quantifying) uncertainty in data such as the locations of fishing catches; better constraining and evaluation of ocean models; and improving empirical associations between species and their environment.

7.5. *Consider scenarios and socio-economic futures*

Socio-economic variables are some of the most difficult to characterize and project (Fulton et al., 2011). In Future Seas to date, we typically assumed constant: fishing effort and behavior, port capacity, gear efficiency, fish price, etc; and used this realistic background to isolate environmentally-driven change. This was also the case in the engagement analyses of the albacore fishery, because it was unreasonable to attempt to project engagement (given projected albacore changes) without information on how vessel ownership, port infrastructure, or albacore ex-vessel value might change or respond to these albacore changes. In short, our projection results are fundamentally based on a static socio-economic future, when adaptation and innovation will likely be key for reducing potential environmental impacts, and the future ecosystem state will depend on feedbacks from a changed human system.

A valuable alternative to attempting to model these extremely complex processes is to use socio-economic scenarios. A key development of the research community is ‘shared socio-economic pathways’ (Riahi et al., 2017) - which have been applied to aquatic systems in similar integrated climate and fisheries projects (Pinnegar et al., 2020) - and the adapted ‘oceanic system pathways’ (Maury et al., 2017). SSPs are one component of scenarios integrating future changes in climate (including emissions) and society, and encompass five core narratives and associated quantitative descriptions encompassing future change in human demographics, development, economy, institutions, technology, and environment (O’Neill et al., 2017). A similar effort was made for the U.S. West Coast as part of the PFMC’s Climate and Communities Initiative (PFMC, 2020): experts derived four narratives predicting potential changes to 2040, distinguishable primarily along two axes representing changes in climate and species abundance. These global, ocean, and West Coast scenarios currently serve as signposts for potential physical and socio-economic futures to help bound projections, but progress is needed before these scenarios can be linked directly to climate, ecological, and social projections, namely by defining realistic (and hopefully generalizable) quantitative variables and values associated with each scenario (Maury et al., 2017; Boschetti et al., 2020).

An alternative to strictly quantitative modeling, but also offering strategic advice, is the Climate Vulnerability Assessment framework, which is designed to systematically identify potential climate change impacts on fisheries social-ecological systems (Hare et al., 2016). This framework has been demonstrated prospectively for the U.S. West Coast albacore fishery, given projected climate changes (Dudley et al., 2021). That study did not develop socio-economic scenarios, but rather used characteristics of current ecological and social subsystems to identify areas of the socio-economic system most sensitive to future change, where the greatest uncertainties lie, and (in the case of albacore) anticipate potential interjurisdictional conflicts.

8. Conclusion

Our downscaled climate projections show that, without strong curbing of emissions, the CCS will undergo significant change this century, including 2–4 °C warming of SST and an almost ubiquitous shift to novel conditions (Pozo Buil et al., 2021; Smith et al., 2022). However, there is a considerable difference in patterns of change among ESMs, which highlights the value of model ensembles. Our case studies highlight that issues of species redistribution will be paramount, which will impact spatial closures, quota allocations, fleet and port accessibility, and community engagement. Biomass will also be influenced, but we are only beginning to understand, and represent in models, the relationship between biomass and climate change. It seems likely that engagement of U.S. West Coast communities with specific species and fisheries will change in the coming decades, and flexibility in both fishing grounds and catch portfolios will be important processes for community resilience. The value of such long-term projection information is related to understanding the potential extent of change and impacts which necessarily determines the resilience of our natural and human systems, and to decadal-scale decision making such as long-term investments in infrastructure and industry. The NOAA Fisheries Climate Science Strategy was developed to aid the preparation and response to climate-related impacts on U.S. living marine resources and resource-dependent communities (Busch et al., 2016), and some key objectives of this strategy are identifying future states of ecosystems and communities, and building science infrastructure. We hope that Future Seas has contributed, and will continue to contribute, to meeting both these objectives by developing and sharing long-term projections of the CCS and important fisheries. Coordination across integrated climate analyses and consistent delivery of climate-informed fisheries advice, like that from Future Seas, is the foundation of effective adaptation and climate ready fisheries (Bell et al., 2020; IPCC, 2022). Our estimates of long-term changes and impacts complement more tactical scales (i.e. real-time monitoring and modeling, and near-term forecasts) to contribute to a comprehensive view of the future CCS. This supporting role of long-term projection helps provide as much information as possible to stakeholders and decision makers, including helping to identify the more vulnerable - and more resilient - species, fisheries, management strategies, and communities.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: EC and RRR serve as editors for Progress in Oceanography.

Data availability

Data availability is reported in Appendix C. Some remains confidential and cannot be made public.

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Author contributions

MGJ, MA, EC, RRR, AHC, SJB, JF, ELH, SS, DT, BM, AH and CAS initiated the Future Seas project, and MGJ led project administration. All authors contributed to project development and various aspects of the analyses. Ocean projections were led by MPB and MGJ, sardine analyses by JAS, BM, JF and SK, swordfish analyses by JAS, SB, SS, NLO and HW, and albacore analyses by BM, DT, TF and AMC. JAS and MGJ led the writing, and all authors contributed to the original draft and its revision.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.pocean.2023.102973.

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