**Title:** Marine heat waves provide a signature of future climate change impacts on west coast fisheries

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**Introduction**

Impacts of climate change are global [1, 2, 3, 4], diverse [5, 6], and accelerating [7, 8]. Scientific consensus on existence and causes of climate change is virtually universal [9, 10, 11, 12, 13), and warming trends will continue [14, 15, 16, 17]. Climate change litigation has been initiated in at least 28 countries to date, with governments acting as defendants in over 80% of cases globally [18], yet socio-political acceptance still lags behind [19, 20]. This disconnect between science, policy, and public awareness and opinion fosters a landscape of fear [21] and creates barriers [22] in which progress is inhibited [23], science and management funding are insufficient [24], both problems and solutions are ignored [25], and even denial movements are organized [26, 27, 28]. Scientific uncertainty, while expected and documented, can also be misinterpreted or even weaponized [e.g., 29], particularly in socio-political arguments about solutions to climate change.

In the oceans, scientific uncertainty is often quite high due to difficulties with and expense of measuring patterns and processes in the marine environment. The oceans act as a buffer from impacts associated with climate change, absorbing significant amounts of anthropogenically produced heat and CO2, which means biological, industrial, and even socioeconomic impacts can have significant lags [30]. Anomalous fisheries impacts related to climate have mostly only recently begun to emerge [e.g., 31, 32, 33, 34]. As a result, public awareness of the role of the oceans in climate change is limited [35], policy often lags behind impacts [30, 36, 37, 38], and fisheries management actions are thus reactive rather than proactive [e.g., 39]. This creates a landscape in which future problems that could be anticipated are not, timely information that could reduce impacts is lacking, and response costs are significantly greater than if proactive approaches were adopted [39, 40]. Both reactive and proactive management strategies are currently being implemented on the west coast of the United States following a recent extreme and unprecedented large-scale marine heat wave [41, 42, 43], yet despite broad support for adaptive ecosystem-based management approaches (e.g., Marine Protected Area networks), fisheries impacts and solutions are still being addressed principally in fishery- or stock-specific contexts.

Warming events have become increasingly common globally [44, 45, 46], and warming trends have significantly impacted marine fisheries production in several regions around the world [47]. Climate change is expected to bring even more frequent, extensive, and intense warming events [17], and ocean biomass is predicted to decline by 5% with every degree C of warming [48]. Anomalous marine heat waves in the present may thus provide a snapshot of the future ‘normal’ scenarios as warming trends continue [49]. In the northeast Pacific, anomalous climatic and oceanographic events occurred during a 5-year period from 2013-2018, which initiated with the development of the ‘ridiculously resilient ridge’ of geopotential height [50, 51]. This led to an unprecedented multi-year drought and a sustained marine heat wave that was a product of the combined effects of the warm ‘blob’ from 2013-2015 [41, 42, 43], an El Niño from 2015-2016 [52], and a sustained warming period afterwards from 2017-2018 [53, 54, 55, 56].

Oceanographic impacts from this unprecedented marine heat wave were severe, spanning physical, chemical, and biological processes that disrupted the California Current ecosystem [32, 41, 42, 57]. These impacts included record-breaking sea surface temperatures [52, 58], shoaling of low-oxygen depth zones [59], increased ocean acidification [60, 61], fewer oceanic fronts [62], reduced coastal upwelling and increased downwelling [63], reduced regional carbon export [64], anomalous changes in phytoplankton biomass [65, 66, 67], regional-scale Harmful Algal Blooms (HABs) [68, 69, 70], decreased primary production and nutrient transport [71, 72, 73], and changes in zooplankton species composition and biomass [74, 75]. This warming event even created the enabling conditions for hurricane intensification, yielding the second most active hurricane season on record in the northeast Pacific in 2015, which included the strongest hurricane ever recorded in the world making landfall just south of Puerto Vallarta, Mexico [76, 77].

Cascading effects of these climatic and oceanographic anomalies on the west coast of North America included changes in species distribution and productivity among marine taxa ranging from microbes to baleen whales. During the last five years, scientists have documented mass mortality events of marine mammals and seabirds [78, 79, 80, 81, 82], regional loss of kelp forests [83, 84, 85, 86, 87], broad-scale changes in species distributions [32, 88, 89, 90], changes in fish spawning locations and timing [91], marine invertebrate disease outbreaks spanning the entire west coast [92], increased toxicity of harmful algal blooms [93], declines in ichthyoplankton abundance [94], and impacts of ocean acidification on larval physiology [95]. These ocean impacts have also translated into critical threats to fishing communities and coastal economies, ranging from Mexico to Alaska [e.g., 85, 96, 97], which provide food, jobs, and recreation for millions of people. Impacts to fisheries included economic losses from fishing season closures and delays [32, 67, 98], human health risks from animal toxicity [99], negative fishery interactions with threatened and endangered species [100, 101, 102, 103], significantly altered fishing grounds [104] creating permitting and other social challenges, and increased bycatch of non-target species and marine mammals. These effects were pervasive in the northeast Pacific, and similar or worse anomalous warming events are expected to occur more frequently in the future [17, 43]. There were also signals that a second warm ‘blob’ reappeared in the northeast Pacific in 2019 [105], which could have had severe impacts given that this marine ecosystem is still recovering from the previous marine heat wave. Clearly, there is significant evidence and momentum supporting the integration of climate dynamics into fisheries management models. Such adaptive management frameworks have been proposed, but integrating proactive and adaptive fisheries management models with conventionally reactive frameworks requires funding and capacity that are limited, even in the face of severe climate-related impacts, in both state and federal fisheries management agencies.

Here, we provide a current and comprehensive picture of west coast fisheries impacts from an anomalous and large-scale marine heat wave, which may provide a snapshot of the future of west coast fisheries as warming trends continue. Widely documented impacts can broadly be classified into three categories: changes in both species and fishery distribution, changes in both species and fishery production, and resulting direct or indirect changes to or closures of the fisheries themselves. In multiple cases, these fisheries impacts have even led to formally declared federal fisheries disasters on a significant economic scale. As a potential pathway forward, we address the concept of climate-ready fisheries management [106] as a new adaptive model that may be better suited for achieving both economic and conservation goals than traditionally slow and reactive fisheries management models.

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