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# Future marine ecosystem drivers, biodiversity, and fisheries maximum catch potential in Pacific Island countries and territories under climate change

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## ABSTRACT

The increase in anthropogenic $CO_2$ emissions over the last century has modified oceanic conditions, affecting marine ecosystems and the goods and services that they provide to society. Pacific Island countries and territories are highly vulnerable to these changes because of their strong dependence on ocean resources, high level of exposure to climate effects, and low adaptive capacity. Projections of mid-to-late 21st century changes in sea surface temperature (SST), dissolved oxygen, pH, and net primary productivity (NPP) were synthesized across the tropical Western Pacific under strong climate mitigation and business-as-usual scenarios. These projections were used to model impacts on marine biodiversity and potential fisheries catches. Results were consistent across three climate models, indicating that SST will rise by $\geq 3\,^{\circ}C$, surface dissolved oxygen will decline by $\geq 0.01\ ml\ L^{-1}$, pH will drop by $\geq 0.3$, and NPP will decrease by $0.5\ g\ m^{-2}\ d^{-1}$ across much of the region by 2100 under the business-as-usual scenario. These changes were associated with rates of local species extinction of > 50% in many regions as fishes and invertebrates decreased in abundance or migrated to regions with conditions more suitable to their bio-climate envelope. Maximum potential catch (MCP) was projected to decrease by > 50% across many areas, with the largest impacts in the western Pacific warm pool. Climate change scenarios that included strong mitigation resulted in substantial reductions of MCP losses, with the area where MCP losses exceeded 50% reduced from 74.4% of the region under business-as-usual to 36.0% of the region under the strong mitigation scenario.

## 1. Introduction

Global climate change driven largely by greenhouse gas emissions from anthropogenic activities has modified the physical and chemical properties of the oceans [69]. Growing evidence has shown significant anomalies in temporal fluctuations and spatial distributions of key environmental parameters in both open-oceans and coastal areas [43,50]. Since the 1950s, the global ocean has experienced increases in sea surface temperature (SST), decreases in pH, an expansion of oxygen minimum zones, and a rise in sea level. These oceanographic changes are projected to continue and amplify in the 21st century with an unprecedented rate of change and reaching $CO_2$ concentrations that have not been experienced since geologic times [35].

These changes in ocean conditions are affecting living marine resources at a global scale. Most fishes and invertebrates are particularly sensitive to changes in ocean conditions because their body temperature and biological performance varies with the environment [60]. Warming temperatures affect ectothermic fishes by accelerating a range of metabolic processes that influence life stage duration, growth rates, energetic demand, and other vital rates [61]. In addition to changing temperatures, ocean acidification, decreasing oxygen concentration, and declining primary productivity also have the capacity to negatively impact fishes and fisheries. Primary productivity is important for sustainable fisheries because phytoplankton is the base of the ocean food web and ultimately provides energy for most organisms in higher trophic levels. Primary productivity is projected to decline in low latitude regions of the ocean due to the fact that warming surface temperatures will increase stratification preventing nutrients at depth from making their way to the surface where they are needed for photosynthesis [13]. Decreases in oxygen concentration can limit the depths that can be occupied by fishes leading to habitat compression. Such changes in the depth distribution of fishes can affect interactions between predators and prey, as well as interactions between fisheries and their target species [62,56]. Ocean acidification negatively affects fishes and fisheries through three mechanisms. First, ocean acidification can alter the sensory perception and behavior of fishes in ways that

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make them increasingly vulnerable to predation [27,54,55]. Second, due to ocean acidification's impact on coral reef calcification, these changes in pH will decrease the amount of habitat available to reef-associated fishes [39,70]. Third, ocean acidification is projected to alter marine food webs through its effects on the calcification, growth, mortality rates, and reproductive success of a variety of marine organisms that serve as prey, predators, and competitors of fishes [45]. In the tropical Pacific, direct effects of ocean acidification and food web impacts are expected to have larger effects on coastal fishes than open-ocean species, such as tuna [15,48].

Overall, marine fishes and invertebrates respond to these changes through shifts in distribution towards higher latitude, deeper water, or generally, toward areas with closer to optimal environmental conditions for the population to survive [44,58,59], and the alteration of their seasonal cycles, such as spawning and migration timing [2,36,37]. Consequently, these biological responses affect biodiversity and important ecosystem services (*e.g.*, fisheries), with changing species composition (*i.e.*, species gains and local extinction resulting from distribution shifts) and regional decreases in fisheries catch potential anticipated as the climate warms [23].

Tropical Pacific areas have been identified as one of the most vulnerable regions in the world's oceans to climate change impacts [8,23]. Biologically adapted to a seasonally more stable environment relative to other parts of the ocean, tropical marine species generally have a narrower tolerance range for temperature [20,60]. This renders tropical species more sensitive to warming and other oceanographic changes [18]. In addition, coral reefs, a critical habitat for many tropical species and fisheries resources, are highly sensitive to small changes in temperature resulting in coral bleaching during heat waves, physical damage from storms, and reduced calcification from ocean acidification [26,39,40].

Socially and economically, most countries in the tropical Pacific are strongly dependent on fisheries for food and livelihoods [4,6,19,33]. Across most countries in this region, fishes contribute > 20% of the animal protein that sustains the human population [32], with this contribution well exceeding 50% on some islands [19]. From an economic perspective, this region's tuna fisheries are especially lucrative, with tuna fishing licenses sold to other countries contributing up to 60% of tax revenues for some Pacific Island countries and territories (PICTs) [9]. Climate fluctuations in this region can also have economic impacts through their effect on the tourism industry, which is strongly related to iconic marine species. Overall, travel and tourism contributed 12% of the GDP and 13% of the employment in Oceania in 2016, making tourism a key sector of the regional economy [74]. The socio-economic vulnerability of the region to marine climate change impacts is also underscored by the fact that the capacity of Small Island Developing States (SIDS) in the tropical Pacific to adapt to or mitigate climate change impacts may be lower than that of developed countries [10,46].

This paper aims to provide an overview of long-term projections of changes in ocean conditions, biodiversity and fisheries that are important to the sustainability of coastal communities in PICTs during the 21st century under climate change. This information is used to highlight the potential level of exposure and sensitivity of these countries to climate change. The paper then discusses the potential impacts of climate change on important biological and social-ecological systems for PICTs.

## 2. Materials and methods

### 2.1. Physical and biogeochemical oceanic variables

SST, surface pH, surface oxygen concentration, and vertically integrated (0–100 m) net primary production (NPP) were selected as indicators of changes in ocean physics and biogeochemistry. These variables were selected because changes in these variables are likely to have large impacts on marine species through either direct effects on physiology or alterations of the trophodynamics of marine ecosystems.

Information on these variables was derived from the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory's Earth System Model (GFDL ESM2G; [28,29], the Institute Pierre Simon Laplace model (IPSL-CM5A-MR; [3], and the Max-Planck Institutes Earth System Model (MPI-ESM-MR; [42]. These three climate models were selected since they were developed independently, include all ocean biogeochemical variables of interest, and represent the full spectrum of equilibrium climate sensitivities among models included in the latest Intergovernmental Panel on Climate Change (IPCC) assessment report [1]. GFDL ESM2G has a nominal 1° latitudinal/longitudinal ocean resolution and 63 depth layers. This earth system model uses the TOPAZ2.0 biogeochemical submodel to examine dynamical changes in pH, $O_2$, and NPP. The IPSL model has a latitudinal/longitudinal ocean resolution that varies between 0.5–2.0° and contains 31 depth layers. It uses the PISCES submodel to track the dynamics of the biogeochemical variables reported upon herein. The MPI model has a latitudinal/longitudinal ocean resolution of 0.4° with 40 depth layers. Ocean biogeochemistry is tracked in MPI using the HAMOCC5.2 submodel. To account for variability between different climate models, our analysis averaged data from these three models together to create a composite projection of future changes.

Data from these models were extracted for three time periods: a baseline period (1980–2000), a mid-century period (2040–2060), and an end-of-century period (2080–2100). Data for twenty-year periods were extracted to minimize the likelihood that a climate change signal would be masked by naturally occurring interannual or decadal climate variability (*e.g.*, El Niño-Southern Oscillation, Pacific Decadal Oscillation). Two climate change emissions scenarios were considered: Representative Concentration Pathways (RCP) 2.6 and 8.5. RCP 8.5 is a high emissions scenario where anthropogenic greenhouse gas and aerosol emissions induce an 8.5 $\mathrm{W\,m^{-2}}$ change in radiative forcing by the year 2100. Under the RCP 2.6 scenario, considerable climate mitigation efforts result in a lower 2.6 $\mathrm{W\,m^{-2}}$ change in radiative forcing by 2100.

### 2.2. Ocean biodiversity

The projected effects of climate change on species richness were mapped in tropical Pacific regions using an approach similar to Jones and Cheung [44]. Current and future distributions of marine fishes and invertebrates were projected using species distribution models. To identify the environmental niche of 1091 selected species occurring in the tropical Pacific, records of species occurrence were collated from the following publicly accessible databases: the Ocean Biogeographic Information System (OBIS – www.iobis.org), the Intergovernmental Oceanographic Commission (IOC – ioc-unesco.org), the Global Biodiversity Information Facility (GBIF – www.gbif.org), Fishbase (www.fishbase.org), and the International Union for the Conservation of Nature (IUCN – http://www.iucnredlist.org/technical-documents/spatial-data). Species in these databases were selected for inclusion in our analysis if there were at least 10 occurrences of them between 40°S and 40°N in the Pacific. Most species far exceeded this minimum threshold of records for inclusion (*i.e.,* median number of records per species = 1205). The common and scientific names of these species, as well as the number of species records, are listed in Supplementary Table 1. Records were removed from the dataset if there were null values, the spatial location was marked as “not assigned”, or when records were replicated among multiple databases. An environmental dataset based on the outputs of the three earth system models (IPSL-CM5A, GFDL ESM2G, and MPI-ESM-MR) was assembled for the RCP 2.6 and 8.5 scenarios. This environmental dataset was comprised of information on ocean temperature, salinity, oxygen, pH and NPP from the seafloor and the surface layer (0–100 m). Each environmental variable was interpolated spatially onto a 0.5° × 0.5° latitudinal/longitudinal