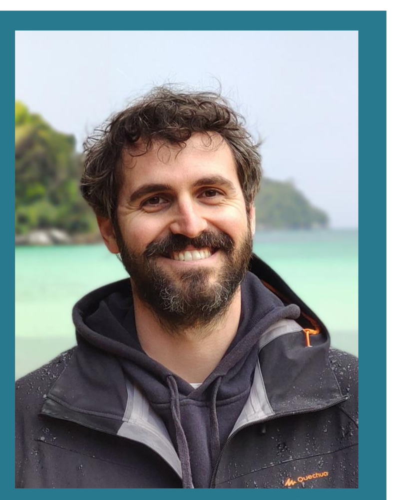
Exploring the ecosystem-level effects of the 2013-2016 marine heatwave in the Gulf of Alaska with an Atlantis ecosystem model

Alberto Rovellini[1], Isaac Kaplan[2], André E. Punt[1], Kerim Aydin[3], Meaghan Bryan[3], Gemma Carroll[4], Bridget Ferriss[3], Elizabeth Fulton[5], Adam Hayes[1], Albert J. Hermann[6], Elizabeth McHuron[6], Szymon Surma[7], and Martin Dorn[3]

[1]School of Aquatic and Fishery Sciences, University of Washington, USA; [2]Northwest Fisheries Science Center, National Oceanic and Atmospheric Administration, USA; [3]Alaska Fisheries Science Center, National Oceanic and Atmospheric Administration, USA; [4]Environmental Defense Fund, USA; [5]CSIRO Oceans & Atmosphere, Hobart, TAS, Australia; [6]Cooperative Institute for Climate, Ocean and Ecosystem Studies, University of Washington, USA ; [7]Institute for the Oceans and Fisheries, University of British Columbia, Canada.



arovel@uw.edu

Background: The Gulf of Alaska (GOA) is a large temperate marine ecosystem in the northeast Pacific that supports valuable and diverse marine fisheries. The GOA in the past has exhibited strong fluctuations in productivity driven by climate events, like the 2013-2016 northeast Pacific marine heatwave. The heatwave caused abrupt changes in biomass and community composition across trophic levels on the GOA shelf (Suryan et al. 2021), including declines in diatoms and shifts in copepod species composition, with cold-water species becoming less abundant (Batten et al. 2022). Such plankton community reorganization caused trophic disruption at the level of forage fish (Arimitsu et al. 2021). In addition, high temperatures caused recruitment failure for some groundfish, including cod (Barbeaux et al. 2020). The ecosystem-level effects of the heatwave remain largely unexplored to date. We used a spatially-explicit end-to-end ecosystem model of the GOA shelf to explore the ecological effects of heatwave conditions similar to those experienced by the GOA marine ecosystem during the 2013-2016 event.

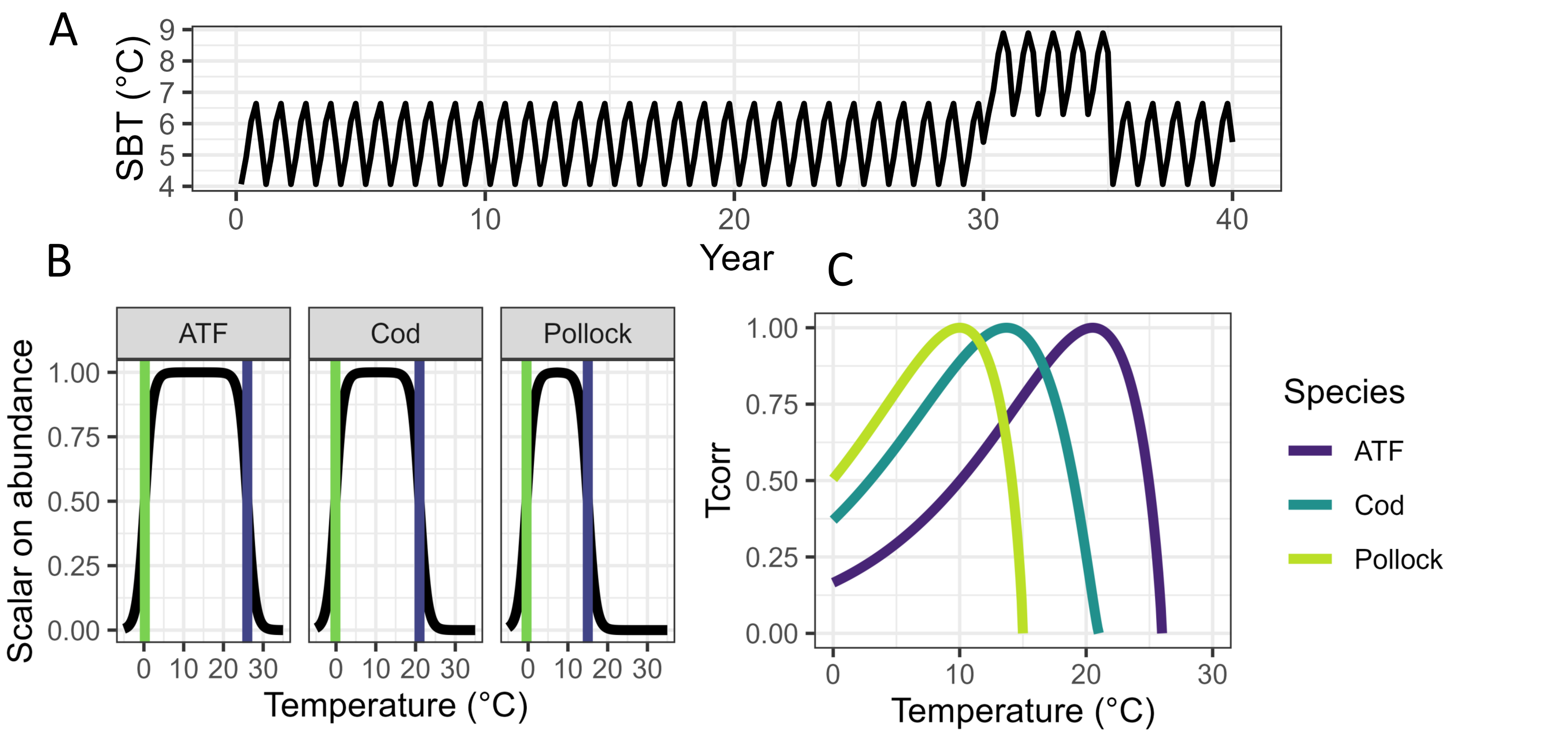


Figure 1. Implementation of a simplified heatwave scenario in Atlantis GOA. A: mean bottom temperature across the model domain, with physical forcings for a pre-heatwave year (1999) looped for 30 simulated years, and forcings for a heatwave year (2014) looped for 5 years followed by a 5-year recovery period. B: Species thermal niches used to scale abundance when water temperature falls below a minimum (green) or overshoots a maximum (blue) value (niches applied to all species in the model, examples for 3 groundfish species are plotted; ATF = arrowtooth flounder). C: Temperature-dependent bioenergetic correction scalar applied to consumption and mortality of selected species (Holsman & Aydin 2015).

Methods: We developed and applied an Atlantis model for the GOA (Fulton et al. 2011). The model resolves physics (temperature, salinity, transport), plankton production, and the GOA food web. We ran the model for 40 years simulating a 5-year heatwave (2014 conditions) after 30 years of pre-heatwave conditions (1999, Fig. 1A). Temperature affects species in the model by: (i) scaling abundance based on species thermal niches; (ii) limiting spawning success (e.g., Laurel & Rogers 2020); and affecting consumption and mortality of selected species (Fig. 1B,C). We also decreased diatom and copepod productivity to 25% during the heatwave runs to approximate the heatwave regime (Batten et al. 2022). We compared heatwave runs with 40-year runs of pre-heatwave forcings only.

Results and discussion: Effects of a simulated heatwave on the GOA food web were complex. Here, we focus on the effects on weight at age and numbers at age of three forage fish species (capelin, sand lance, and Pacifc herring) and three groundfish species (arrowtooth flounder, walleye pollock, and Pacific cod). We examined effects from applying temperature and plankton forcings combined (Fig. 2) and separately (results not shown). Compared to a run without heatwave forcings:

Increased temperature caused:

- Increased weight at age mediated by higher consumption at higher temperature, especially for groundfish (Fig. 2A).
- Increased mortality (Fig 2B).
- Recruitment failures for cod (Fig 2B).
- Increased recruitment for species other than cod (deriving from increased weight at age, Fig 2B).
- Some model areas became suboptimal or unviable, especially for cod and arrowtooth flounder (Fig 3).

Decreased plankton production caused:

- Decreased weight at age of forage fish (Fig. 2A, especially when the beneficial effects of warmer water on metabolism subside).
- Consequently, decreased recruitment for forage fish after the heatwave (Fig. 2B).

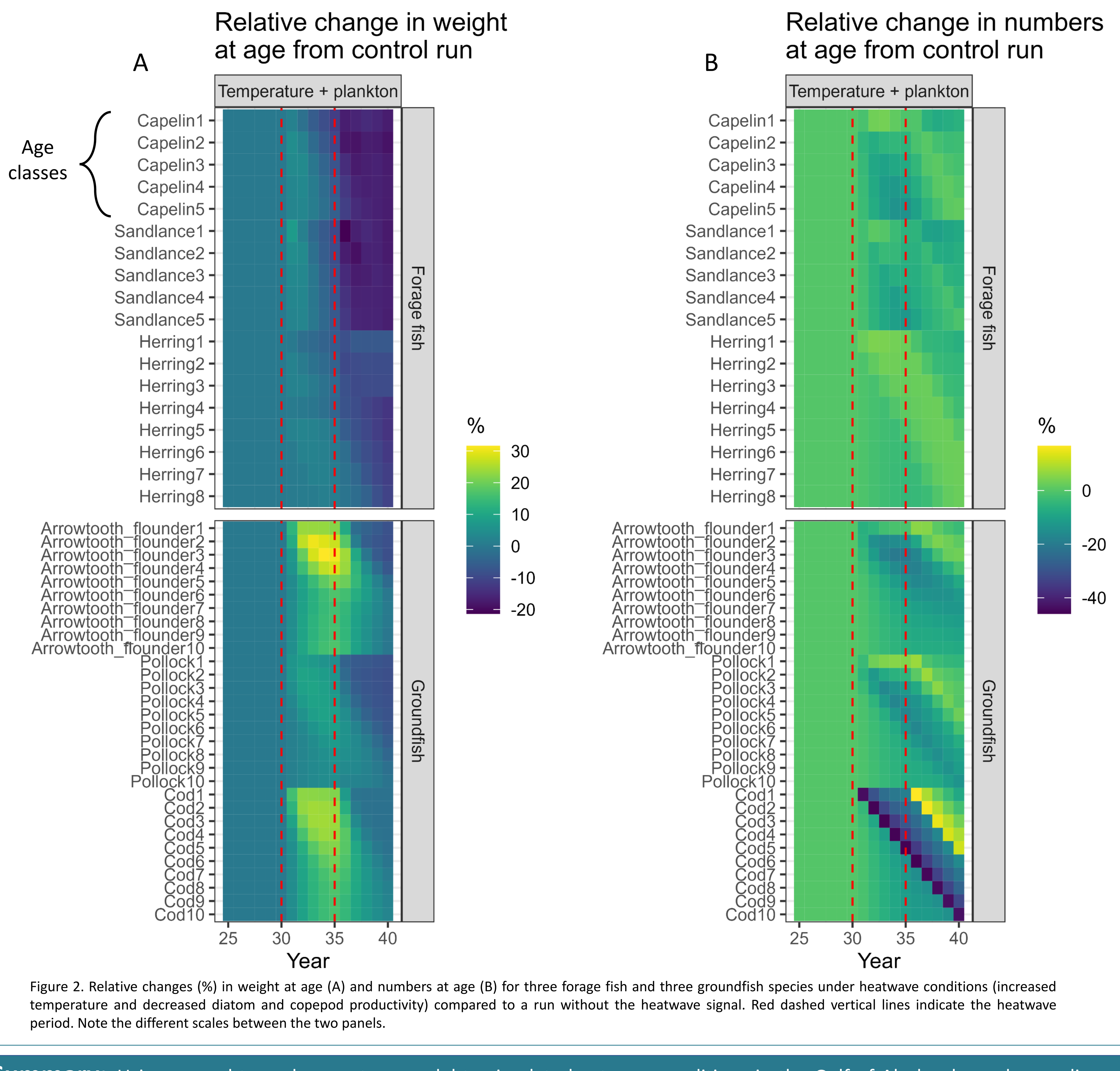


Figure 2. Relative changes (%) in weight at age (A) and numbers at age (B) for three forage fish and three groundfish species under heatwave conditions (increased temperature and decreased diatom and copepod productivity) compared to a run without the heatwave signal. Red dashed vertical lines indicate the heatwave period. Note the different scales between the two panels.

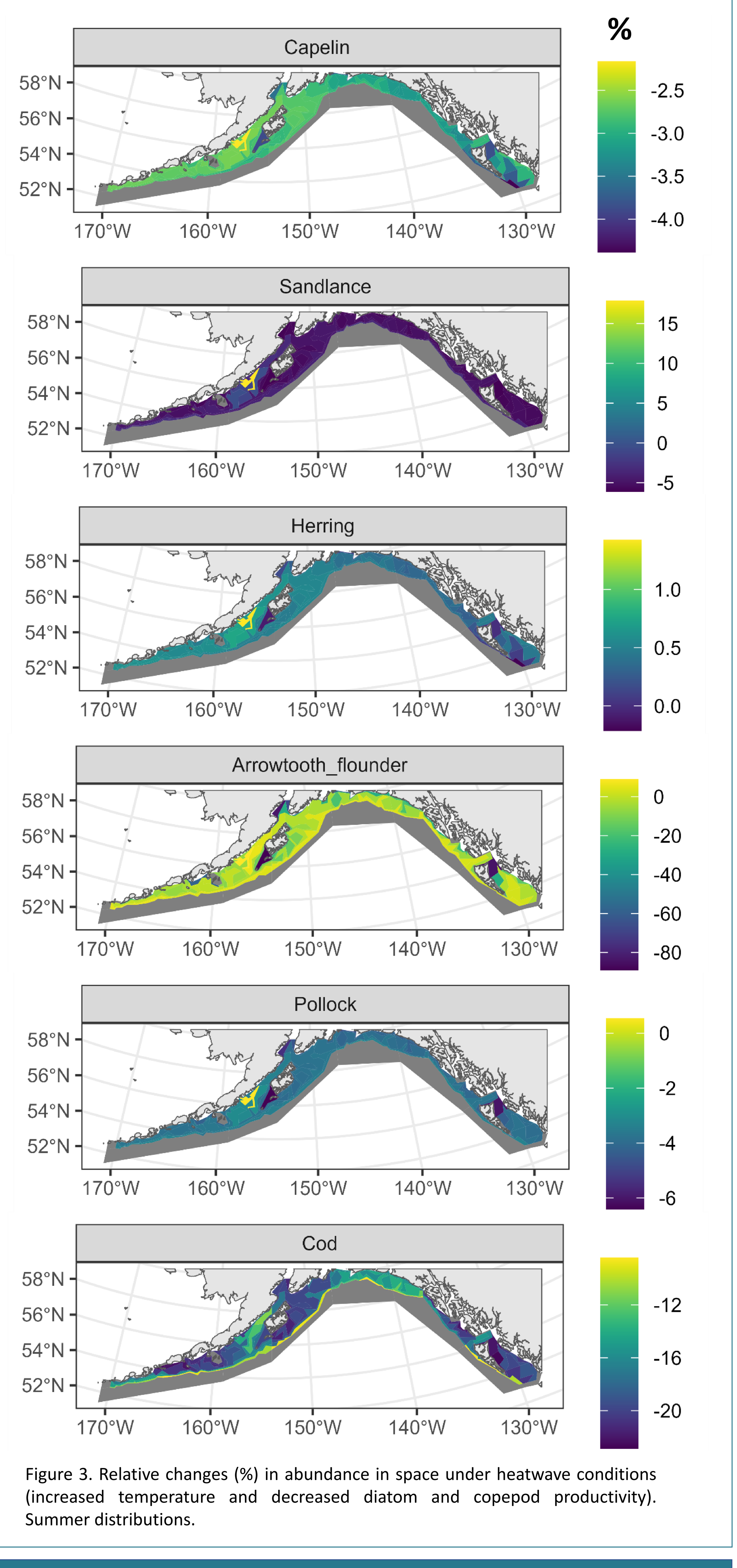


Figure 3. Relative changes (%) in abundance in space under heatwave conditions (increased temperature and decreased diatom and copepod productivity). Summer distributions.

Summary: Using an end-to-end ecosystem model to simulate heatwave conditions in the Gulf of Alaska showed cascading effects on forage fish and upper trophic levels. The model was able to capture different mechanisms of propagation of the heatwave signal. Higher temperature caused increased weight at age of groundfish mediated by increased consumption, but also caused mortality, recruitment failures, and local depletions. Decreased plankton production had cascading effects by reducing weight at age of forage fish that propagated to groundfish and upper trophic levels.

References: Arimitsu et al. (2021). Heatwave-induced synchrony within forage fish portfolio disrupts energy flow to top pelagic predators. Global Change Biology, 27(9). Barbeaux et al. (2020). Marine heatwave stress test of Ecosystem-Based Fisheries Management in the Gulf of Alaska Pacific cod fishery. Frontiers in Marine Science, 7(703). Batten et al. (2022). Responses of Gulf of Alaska plankton communities to a marine heat wave. Deep-Sea Research Part II: Topical Studies in Oceanography, 195(105002). Fulton et al. (2011). Lessons in modelling and management of marine ecosystems: The Atlantis experience. Fish and Fisheries, 12(2). Holsman & Aydin (2015). Comparative methods for evaluating climate change impacts on the foraging ecology of Alaskan groundfish. Marine Ecology Progress Series, 521. Laurel & Rogers (2020). Loss of spawning habitat and prerecruits of pacific cod during a gulf of alaska heatwave. Canadian Journal of Fisheries and Aquatic Sciences, 77(4). Suryan et al. (2021). Ecosystem response persists after a prolonged marine heatwave. Scientific Reports, 11(6253).