Supplemental Information

This paper compiles several datasets to illustrate impacts of the 2014-16 marine heatwave on fisheries of the U.S. and Canada West Coast. We describe the compilation of these datasets below.

Sea surface temperature data (Figure 1)

The sea surface temperature data were obtained from the COBE Sea Surface Temperature (SST) dataset (Ishii et al., 2005), which provides monthly SST data on a globally complete 1°x1° grid from 1850-present based on an interpolation of in-situ and satellite-derived SST observations.

Federal fisheries disaster data (Figure 2)

The federal fisheries disaster data were obtained from Bellquist et al. (2021). These data describe information on every U.S. federal fisheries disaster declaration occurring from 1989-2020, including information on the fishery impacted, the cause of the disaster, the amount of relief money requested and awarded, and other relevant information.

Commercial revenues data (Figures 3 & S1)

We used annual statewide fisheries revenue data to evaluate impacts of the heatwave on commercial fisheries. To create this dataset, we combined data from a few sources. We used annual revenue data from the PacFIN database for the U.S. West Coast (California, Oregon, and Washington) and data provided directly from NOAA for the Gulf of Alaska. We were unable to use the AKFIN database (i.e., the equivalent of PacFIN for Alaska) for Alaska because the AKFIN database only includes crabs and groundfish (i.e., it is less comprehensive), is not species-specific (i.e., it is more generic), and does not separate the Gulf of Alaska from the Bering Sea and Aleutian Islands regions. We focus on the Gulf of Alaska region because this was the region impacted by the 2014-16 marine heatwave. We used annual revenue data provided directly by Fisheries and Oceans Canada (DFO) for British Columbia.

Recreational landings data (Figures 4 & S2)

We used estimates of annual statewide fisheries landings (i.e., number of retained fish) to evaluate impacts of the heatwave on recreational fisheries. To create this dataset, we combined data from a few sources. We used estimates of annual landings from the RecFIN database for the U.S. West Coast (California, Oregon, and Washington) and from the ADFG website for the Gulf of Alaska. However, the RecFIN data does not include catches of highly migratory species in California's for-hire (Commercial Passenger Fishing Vessel or CPFV) fleet. Thus, we used data from the CDFW Landings Reports for these species. We used the ADFG database for Alaska because the AKFIN database does not include recreational landings estimates. Although the NOAA FOSS database includes estimates of recreational landings by state, these estimates have been transformed into biomass (pounds) and are thus less representative of the original data. Furthermore, they do not include recreational landings estimates for Alaska.

Case study time series data

Dungeness crab management history (Figure 6A)

We obtained the spatial-temporal history of the Dungeness crab fishery from (Free, Moore, et al., 2022). These data describe the location and duration of every closure (or evisceration order) in the West Coast Dungeness crab fishery from 2014-2021.

GOA Pacific cod revenues data (Figure 6B)

We obtained time series of commercial Gulf of Alaska (GOA) Pacific cod fisheries revenues by gear and subarea from the AKFIN database.

Red abalone landings data (Figure 6C)

We obtained time series of recreational red abalone landings estimates by county from a CDFW report (CDFW, 2015). CDFW estimated these values using abalone "report cards" (i.e. creel survey) and telephone surveys (Kalvass & Geibel, 2006).

Klamath River Fall Chinook escapement forecasts and observations (Figure 6D)

We obtained time series of Klamath River Fall Chinook salmon pre-season escapement forecasts and post-season escapement observations from the 2022 pre-season report (PFMC, 2022). Escapement represents the number of salmon that escaped fishing and returned upriver.

Pacific sardine revenues data (Figure 6E)

We obtained time series of commercial Pacific sardine fisheries revenues by state from the PacFIN database (PSMFC, 2021), as compiled in the CALFISH database (Free, Vargas Poulsen, et al., 2022).

Pacific bluefin tuna landings data (Figure 7A)

We obtained time series of Pacific bluefin tuna landings by source waters (U.S. or Mexico) by California's recreational for-hire fleet from the California Marine Logbook System (MLS). The data query was submitted and processed by a co-author who is a CDFW employee.

Market squid revenues data (Figure 7B)

We obtained time series of commercial market squid fisheries revenues by port complex from the PacFIN database (PSMFC, 2021), as compiled in the CALFISH database (Free, Vargas Poulsen, et al., 2022).

Bocaccio recruitment estimates (Figure 7D)

We obtained time series of Bocaccio rockfish recruitment estimates from the first author of the most recent bocaccio rockfish stock assessment (DFO, 2021).

Shortbelly rockfish bycatch data (Figure 7E)

We obtained time series of shortbelly rockfish landings and discard estimates from the Groundfish Expanded Mortality Multiyear (GEMM) (Somers et al., 2020, 2021).

Northern anchovy index of abundance data (Figure S3)

Larval anchovy time series is from the CalCOFI spring survey. Young of the year time series is from the Rockfish Recruitment and Ecosystem Assessment Survey (RREAS) in southern California (Thompson, Bjorkstedt, et al., 2022).

Pacific bluefin tuna trophy size fish data (Figure S4)

We obtained time series of trophy size Pacific bluefin tuna reported in the "Whoppers of the Week" section of Western Outdoor News from 1968-2019 from (Bellquist et al., 2016).

Table S1. Lessons for improving monitoring, management, and adaptive capacity.

	Principle	Example
For improved monitoring		
1	Strategically enhance the spatial-temporal scale of monitoring to promote dynamic management that reduces tradeoffs among competing objectives	Increased spatial-temporal monitoring of harmful algal blooms and biotoxin contamination can protect public health while minimizing impacts on fishing opportunities
2	Target monitoring to understand drivers of sudden shifts in productivity/distribution that have occurred during past heatwaves and use this knowledge to better prepare for future heatwaves	Targeted monitoring is needed to resolve (a) the relationship between local HMS availability and stockwide abundance, (b) reversals in long-believed relationships between the environment and CPS fisheries productivity, and (c) earlier detection of heatwave-driven shifts in abundance/distribution.
3	Develop tools for rapidly processing, visualizing, and disseminating raw monitoring data to democratize and accelerate the rate at which “unknown unknowns” and other surprises are detected and responded to	The standardized summaries of available fisheries-dependent and fisheries-independent data for Canadian Pacific groundfish (Anderson et al., 2019) provide a useful template for such tools.
4	Use technology that makes monitoring cheaper or partnerships that make monitoring more efficient to reduce or maintain costs	Citizen/community science programs can integrate new tools to achieve cheaper data collection at scale
For improved management		
1	Broaden co-management systems that leverage stakeholder knowledge, lower monitoring/management costs, and empower diverse voices	The inclusion of fishers in the management of whale entanglement risk in the CA Dungeness crab fishery assisted in identifying/implementing feasible, equitable, and effective management actions.
2	Increase the agility and flexibility of fisheries management institutions and procedures to expedite effective responses to surprises	This could involve establishing (a) alternative procedures for updating bycatch quotas in response to unexpectedly high recruitment events or (b) plans for evaluating and managing rapidly emerging fisheries that introduce novel conflicts between fisheries or between economic/conservation goals.
3	Enhance the adaptiveness or robustness of fisheries management to the impacts of heatwaves and climate change	This could involve (a) accounting for shifting productivity by incorporating climate variables into stock assessments and/or (b) designing harvest control rules that are robust to climate change.
4	Use climate-linked management strategy evaluation to compare the performance of alternative management strategies under climate change to quantitatively inform management decisions	Apply marine heatwave scenarios, particularly for short-lived species (e.g., CPS), species that experience critical life history bottlenecks (e.g., aggregating or diadromous species), or uniquely vulnerable species (e.g., red abalone).
For improved adaptive capacity		
1	Broaden co-management systems that leverage stakeholder knowledge, lower monitoring/management costs, and empower diverse voices *(note: this is also a lesson for improved monitoring and management)*	NOAA-funded research conducted with the recreational fishing industry facilitated the development of descending devices that reduce rockfish discard mortality. Led by the recreational fishing industry, these devices are now mandated in recreational fisheries coastwide (voluntary in California).
2	Bolster policies that promote livelihood diversification to buffer fishing communities against negative climate impacts	Easing access to fishing permits can promote target species diversification and buffer revenues against heatwaves, climate change, and other market shocks.
3	Enhance permit programs that allow experimentation to accelerate innovation in climate-ready strategies	Exempted Fishing Permits with good experimental design could, for example, be leveraged to stimulate an expanded purple sea urchin fishery that enhances kelp reforestation, design whale-safe fishing gear or practices that jointly prevent entanglements and fishery closures, or develop new fisheries-dependent data streams that enhance adaptive management.
4	Enhance programs that provide economic relief in response to negative environmental impacts to improve the resilience of fishing communities to climate change	This could involve (a) reforming disaster relief programs to be more timely, accurate, and equitable in their assessment and distribution of disaster relief and/or (b) developing fisheries insurance programs that smooth risk, mitigate losses, and/or incentivize climate-resilient actions.

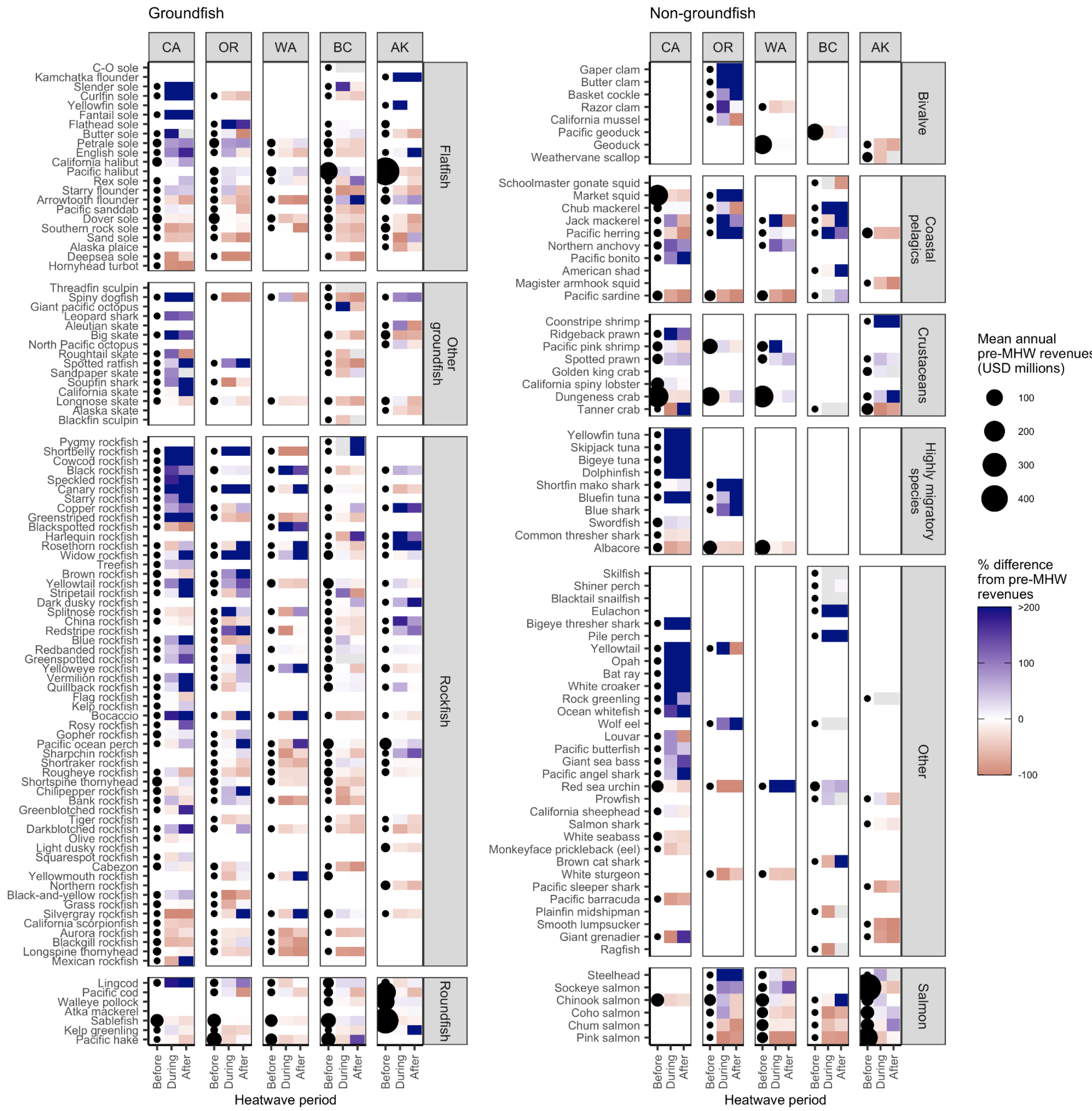

Figure S1. Commercial fisheries revenues before the 2014-16 marine heatwave and the percent change in revenues during and after the heatwave by state, management group, and species. Species (rows) are grouped by management group and are vertically ordered from greatest losses (bottom) to the greatest gains (top) in revenues during the heatwave averaged across states. The size of the points plotted in the “before” column indicate mean annual revenues during the years before the heatwave and the colors plotted in the “during” and “after” columns indicate the percent change in revenues relative to the years before the heatwave.

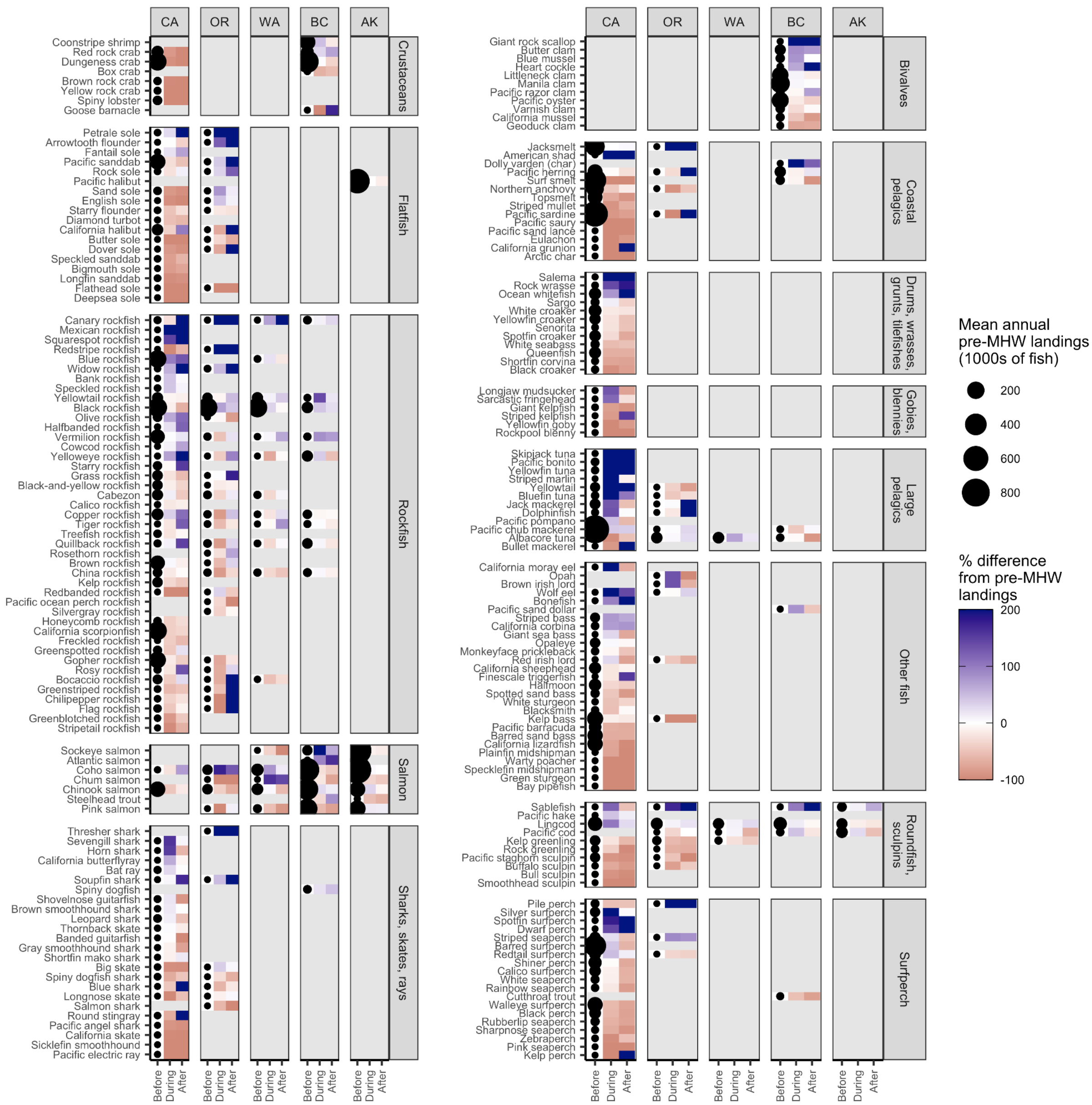

Figure S2. Recreational fisheries landings (number of retained individuals) before the 2014-16 marine heatwave and the percent change in landings during and after the heatwave by state, management group, and species based on multiple recreational landings databases. Species (rows) are grouped by taxonomic group and are vertically ordered from greatest losses (bottom) to the greatest gains (top) in landings during the heatwave averaged across states. The size of the points plotted in the "before" column indicate mean annual landings during the years before the heatwave and the colors plotted in the "during" and "after" columns indicate the percent change in revenues relative to the years before the heatwave.

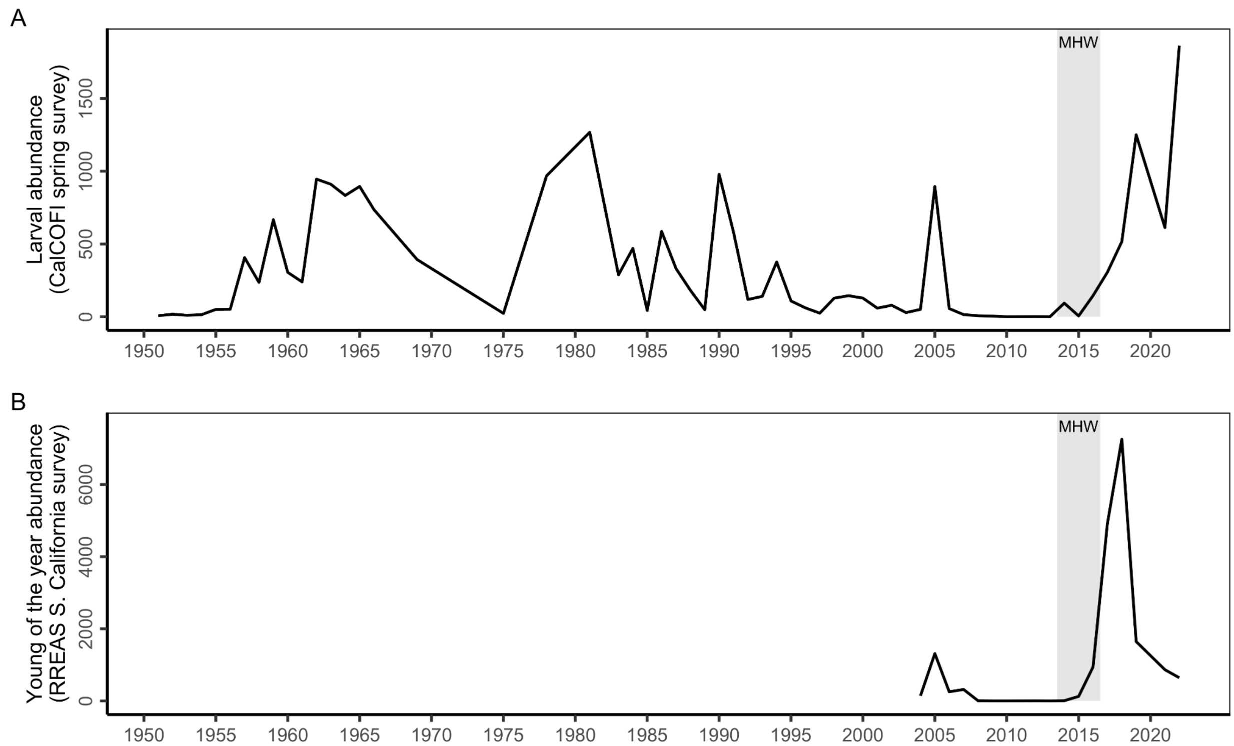

Figure S3. The mean abundance of Northern anchovy **(A)** larvae (number under 10 m^2) and **(B)** young-of-the-year in southern California (number per catch) . Larval anchovy time series is from the CalCOFI bongo net spring survey. Young of the year time series is from the summer midwater trawlRockfish Recruitment and Ecosystem Assessment Survey (RREAS) in southern California.

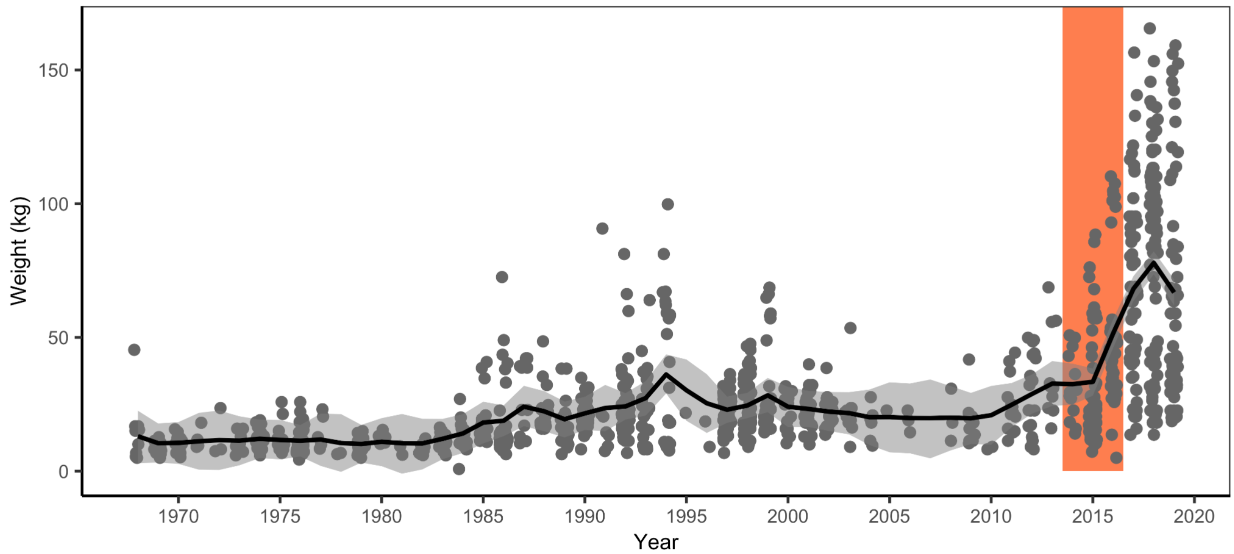

Figure S4. Time series of trophy size Pacific bluefin tuna reported in the "Whoppers of the Week" section of Western Outdoor News from 1968-2019. The vertical orange rectangle illustrates the 2014-16 marine heatwave. The black line and shading indicate the median and 95% confidence interval of a state-space model fit to the data. The data and modeling framework are an extension of that published in (Bellquist et al., 2016).