8. THE HIGH LATITUDE MARINE HEAT WAVE OF 2016 AND ITS IMPACTS ON ALASKA

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The 2016 Alaska marine heat wave was unprecedented in terms of sea surface temperatures and ocean heat content, and CMIP5 data suggest human-induced climate change has greatly increased the risk of such anomalies.

Earth System Observations. The Gulf of Alaska (GOA) and Bering Sea have been anomalously warm for several years with the warmth peaking in 2016. As a consequence of the high marine heat content (HC) and SSTs, coastal areas of Alaska had their warmest winter–spring of record in 2016 (Walsh et al. 2017) and earliest river ice breakup for multiple Alaska rivers (www.weather.gov/aprfc/breakupDB). Observed marine warmth, impacts on the marine ecosystem, and an attribution analysis using CMIP5 models are presented here.

The marine heat wave was first noted over deep waters of the northeastern Pacific Ocean in January 2014 (Freeland 2014; Bond et al. 2015); anomalous temperatures at coastal GOA stations arrived variously between January and June. Warm temperature anomalies were confined to the top 100 meters until late 2014, after which they penetrated to depths of 300 meters and reached strengths greater than 2 standard deviations (Roemmich and Gilson 2009).

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The consensus of previous studies is that atmospheric circulation anomalies played a key role in initiating and maintaining the North Pacific "blob" of warm water (Bond et al. 2015). Unusually high pressure south of the Gulf of Alaska reduced heat loss to the atmosphere and also reduced cold advection over the region. Forcing of the atmospheric anomalies has been linked to SST anomalies in the western tropical Pacific Ocean (Seager et al. 2015) and to decadal-scale modes of North Pacific Ocean variability (Di Lorenzo and Mantua 2016). Lee et al. (2015) have argued that sea ice anomalies also contributed to the atmospheric circulation anomalies in 2013/14. By contrast, the winter of 2015/16 was characterized by negative sea level pressure anomalies of more than 12 hPa centered in the eastern Bering Sea (Fig. ES8.1d). The associated northward airflow evident throughout the depth of the atmosphere (Fig. ES8.1b) likely drove lingering heat from the blob into the GOA and Bering Sea regions. An unusually deep Aleutian low is a typical feature of the El Niño conditions that characterized early 2016 (Walsh et al. 2017).

The positive HC anomalies (Fig. 8.1a) reached an extreme in 2016 for the GOA and Bering Sea (Figs. 8.1d,e), with most of the region ranking in the top five warmest HCs of record (Fig. ES8.2a). Oceanic temperatures are from GODAS (Saha et al. 2006), NCEP's high-resolution ocean analysis. HC was calculated by integrating ocean temperature (°C) from the surface to 300 meters or the bottom of each model water column. This value was then divided by the depth of its respective water column, the 1981–2010 mean was removed, and the quantity was normalized to allow comparison between the Bering Sea (51°–64.5°N, 180°–160°W) and GOA (50°–60°N, 150°–130°W) regions (Figs. 8.1d,e).

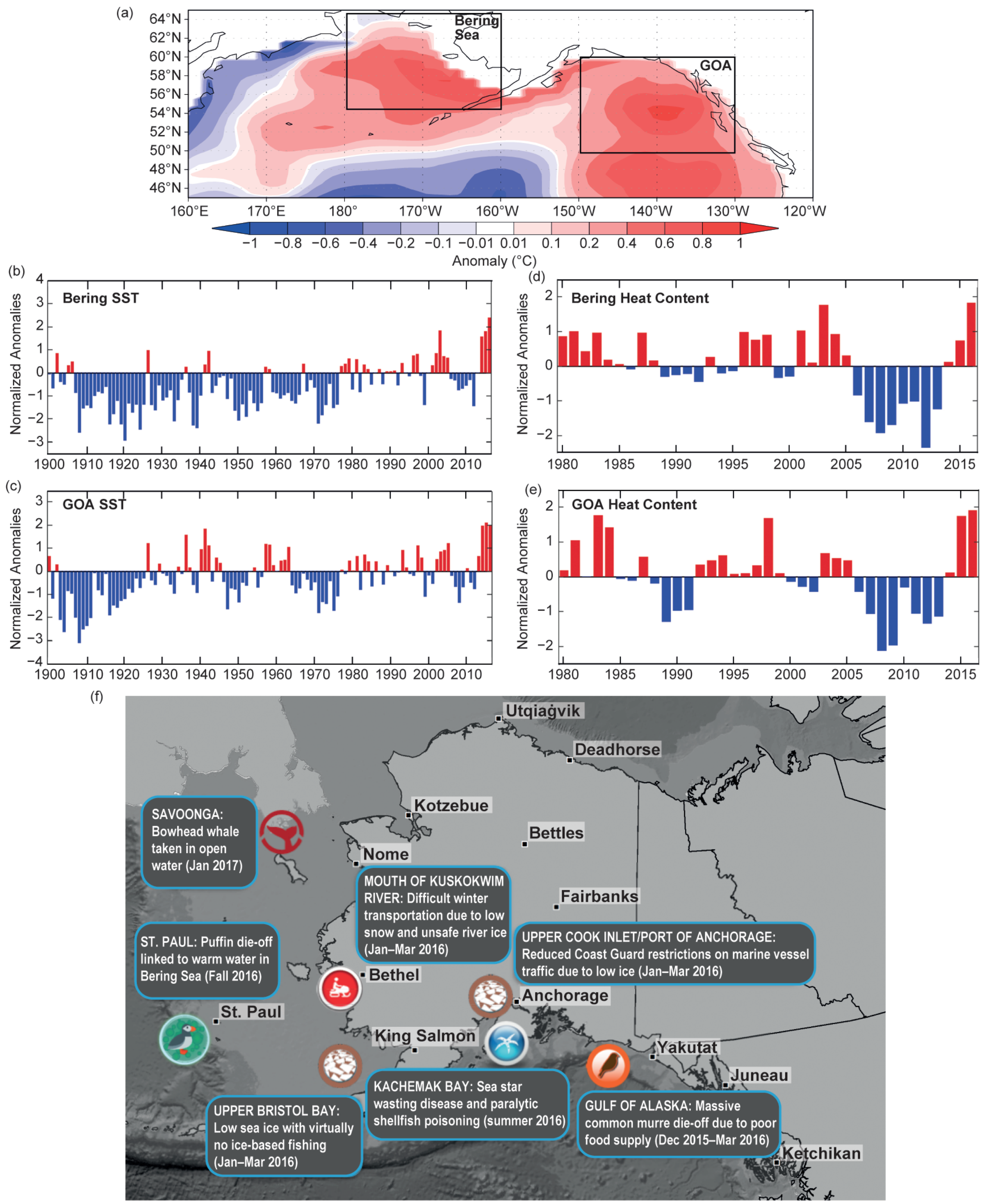

Fig. 8.1. (a) Jan–Dec 2016 ocean heat content anomaly (°C) from the surface to 300 m or bottom of ocean column. Boxes outline GOA and Bering Sea regions. Normalized area-weighted SST anomalies for (b) Bering Sea and (c) GOA. Normalized area-weighted heat content anomalies for (d) Bering Sea and (e) GOA. (f) Select impacts of 2016 marine heat in Alaska waters.

Normalized SST anomalies from 1900 provide context for the anomalies. The 2016 SSTs were the warmest on record for the Bering Sea and the second warmest in the GOA (Figs. 8.1b,c) where 2015 was warmest. SSTs were anomalously warm starting in 2012 (Weller et al. 2015), and most of the GOA and

Bering Sea ranked in the top five SSTs of record (Fig. ES8.2b). SST data are from NOAA's Extended Reconstructed Sea Surface Temperature dataset, version 4 (Huang et al. 2014), and anomalies use the 1981–2010 mean. Negative anomalies greater than 2 sigma are evident in both regions from 2006–13.

The warming was primarily confined to the inner GOA shelf in September 2014, suggesting that heat was advected along-shore within the Alaska Coastal Current. By spring 2015 the shelf was uniformly warm and water remained 1°–2°C warmer than normal through September 2016. This heat was accompanied by surface mixed layer shoaling and a strengthening of the near-surface stratification, impacting nutrient availability and the ecosystem.

Impacts. Ecological and societal impacts of the 2016 marine heat wave are complex but unequivocal. Some marine ecological impacts resulted from the multiyear nature of the marine heat wave, so cannot be attributed solely to the 2016 event.

The consequences of this persistent warming were felt through the entire marine food web. The warm conditions favored some phytoplankton species, and one of the largest harmful algal blooms on record reached the Alaska coast in 2015 (Peterson et al. 2016a). Kachemak Bay had uncommon paralytic shellfish poisoning events and oyster farm closures in 2015 and 2016. Copepods, the crustaceans that form the cornerstone of the open ocean food web, had a higher abundance of smaller species, which provide less nutritious food source to higher trophic levels, including forage fish. The occurrence of more southern copepod species in the GOA likely resulted from the anomalous warmth (Kintisch 2015; Peterson et al. 2016b).

The dramatic mortality events in seabird species such as common murres (*Uria aalge*) in 2015/16 (tens of thousands of dead birds counted) were attributed to starvation and presumed to be a result of warming-induced effects on food supply (H. Renner 2017, U.S. Fish and Wildlife Service, personal communication). Increased occurrences of diseases were also observed, including sea star wasting disease, first recognized in Kachemak Bay in 2015. (K. Iken 2017, personal observations; Fig. 8.1f).

Over 100 observations of impacts on communities across Alaska were posted to the Local Environmental Observer (LEO) network (http://leonetwork.org) between October 2013 and December 2016. These impacts relate to changes in the acquisition, preservation, quality, and quantity of wild foods. Local observers noted changes in seasonality, weather, ocean conditions, plants, and wildlife, which challenge people engaged in subsistence and commercial activities with increased variability and uncertainty. The lack of winter sea ice in western Alaska delayed or prevented ice-based harvesting of fish, crab, seal, and whale. For shellfish harvests, the warm waters translated into persistent high levels of harmful algae across the GOA and North Pacific as far west as the Aleutian Islands, with concerns about food safety extending to the Bering Strait.

Attribution. The role of anthropogenic climate change in the marine heat wave of 2016 was assessed through an evaluation of CMIP5 model output. Attribution was estimated by comparing SSTs and HC in 60-year segments (to resolve relevant decadal variability such as the Pacific decadal oscillation; PDO) from present and preindustrial climate simulations. Five CMIP5 models were selected (see online supplement material; Walsh et al. 2017b, manuscript submitted to *Environ. Modell. Software*): CCSM4, GFDL-CM3, GISS-E2-R, IPSL-CM5A-LR, and MRI-CGCM3. The models' trends of SST over the 1900–2005 historical simulations ranged from 0.27° to 0.52°C century^{-1} (mean = 0.41°C) for the Bering Sea and 0.22° to 0.90°C century^{-1} (mean = 0.46°C) for the GOA. The corresponding observational values from Figs. 8.1b,c are 0.70° and 0.84°C century^{-1} for the Bering Sea and GOA. If the models' century-scale trends represent the anthropogenic forcing signal, then one may argue that the larger values of the observed trends are partially attributable to internal variability.

For the attribution analysis, the present climate period is centered on 2016 and incorporates the historical simulation (1987–2005) and RCP8.5 (2006–46), which is the current trajectory of climate forcing, while the preindustrial climate incorporates a random 60-year period from each model. Monthly HC was calculated using ocean potential temperatures with a procedure similar to that used for GODAS. The SSTs and HCs were then interpolated to the GODAS grid, annual averages were computed, and area-weighted averages were extracted over the Bering Sea and GOA. This yielded 60-year time series for each region, model, and variable (present and preindustrial).

Annual values of SST and HC are warmer in GOA than the Bering Sea. Normalized anomalies using a 1987–2016 base period were used to account for differences in means. For SST and HC the present climate has increasing trends while the preindustrial does not (Figs. 8.2a,b). In all cases the preindustrial climate is

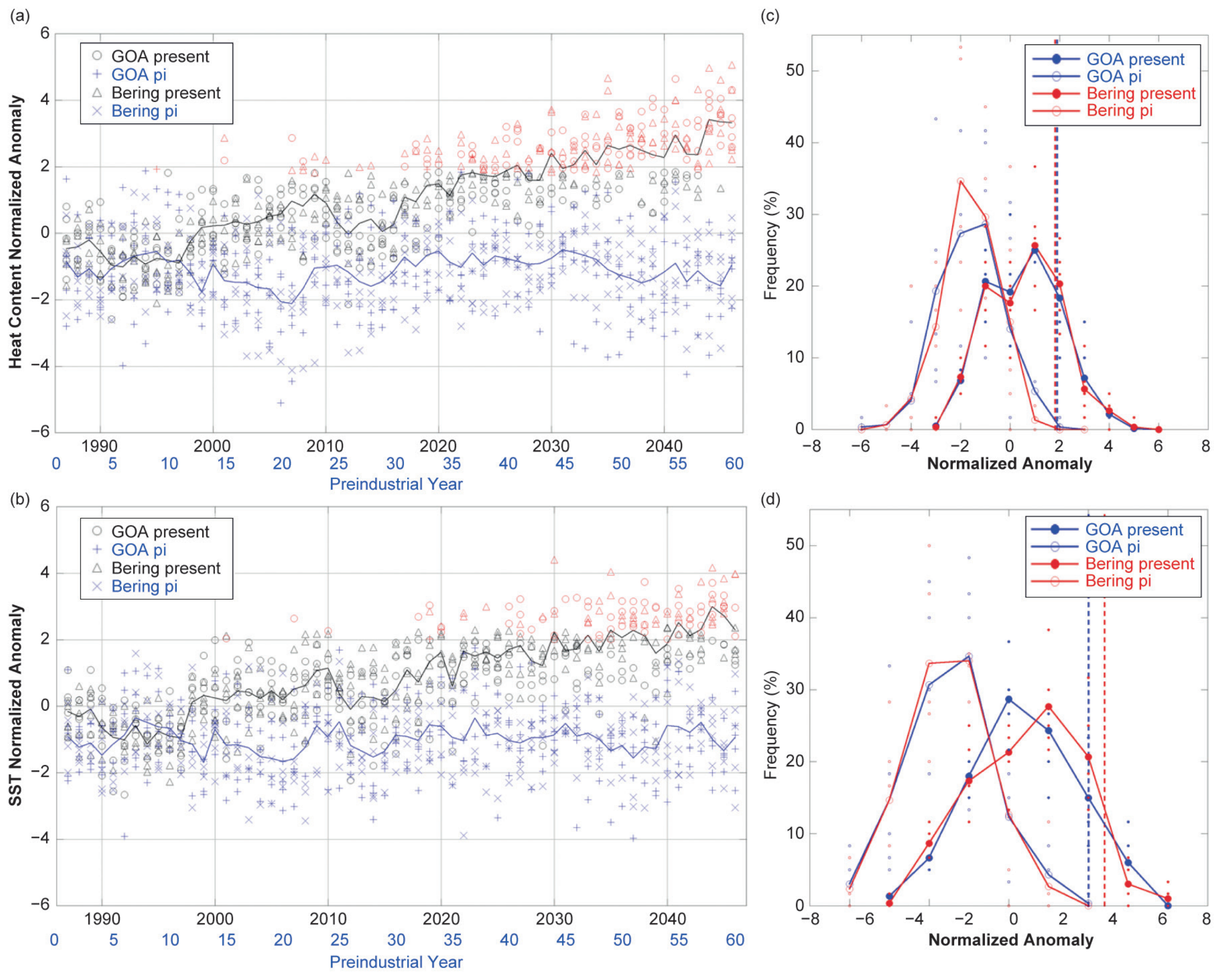

FIG. 8.2. Normalized anomalies of (a) heat content and (b) SSTs for the present (black) and preindustrial (blue) climate of the GOA (circle and plus) and Bering Sea (triangle and x) regions from the five model ensembles. Anomalies exceeding 2016 value are in red (shapes as indicated), and the ensemble/region means are shown by the solid lines. Mean probability distributions (%) of (c) heat content and (d) SSTs from the model ensembles; solid (open) circles indicate present (preindustrial) climate for the GOA (blue) and Bering Sea (red). Spread of individual models is shown by the smaller, corresponding open/closed circles. Dashed vertical lines show the 2016 anomalies: GOA (blue), Bering Sea (red).

generally cooler with no extreme positive anomalies comparable to the present climate (Figs. 8.2c,d).

Each model/variable/region was compared with its corresponding 2016 observed normalized anomaly value (see red coloring in Figs. 8.2a,b and vertical dashed lines in Figs. 8.2c,d). The preindustrial period had few cases meeting or exceeding the 2016 anomaly for any region or variable, while the present climate had many more, especially later in the period. For HC the number of years each model exceeded the 2016 anomaly ranged from 11 to 20 (0–2) cases in the present (preindustrial) climate for GOA and 16–24 (0) for Bering Sea. Fewer cases reached 2016 values in SSTs, with 5–18 (0–1) for GOA and 4–11 (0) for Bering Sea. For both variables the Bering Sea region's preindustrial climate never reached the 2016 observed magnitude.

In this analysis the fraction of attributable risk (FAR; Stott et al. 2004; NASEM 2016) was computed as FAR = 1 − $\text{Prob}_{\text{preindustrial}}/\text{Prob}_{\text{present}}$ with the probability being the exceedance of the observed 2016 normalized anomaly. Bering Sea SSTs had FAR = 1 for all cases, while the GOA's FARs were 0.88–1 for SST and 0.82–1 for HC (but most models had FAR = 1, i.e., no instances of 2016-like anomalies in the preindustrial climate).

Conclusion. The warmth of the Bering Sea in 2016 was unprecedented in the historical record, and the warmth of the GOA nearly so. The FAR values based on an ensemble of five global climate models indicate that the 2016 warm ocean anomalies cannot be explained without anthropogenic climate warming, although the region's large internal variability was also a contributing factor (Fig. 8.1 and online supplement material). A strong El Niño with a positive PDO (warm) phase, together with preconditioning of the waters during 2014/15 and the anomalous atmospheric circulation of early 2016, made for a "perfect storm" of marine heating around Alaska. Both anthropogenic forcing and internal variability were necessary for the extreme warmth of the subarctic seas. Our conclusions are consistent with and extend previous findings concerning the 2014 warm SST anomalies in the northeast Pacific (Weller et al. 2015). Additionally, the trajectory of the present climate with RCP8.5 indicates that SST and HC extreme anomalies like 2016 will become common in the coming decades. Given the many impacts of the 2016 anomaly, the future climate projected here will result in a profound shift for people, systems, and species when such warm ocean temperatures become common and not extreme in the GOA and Bering regions.

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