THE RECORD LOW BERING SEA ICE EXTENT IN 2018: CONTEXT, IMPACTS, AND AN ASSESSMENT OF THE ROLE OF ANTHROPOGENIC CLIMATE CHANGE

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Record low Bering Sea sea ice in 2018 had profound regional impacts. According to climate models, human-caused warming was an overwhelmingly likely contributor, and such low levels will likely be typical by the 2040s.

During the 2017/18 Northern Hemisphere cold season, sea ice extent in the Bering Sea was less than any winter in the observed or reconstructed past. The eastern and northern Bering Sea covers a shallow and expansive continental shelf that has historically exhibited 40%–100% ice cover at its annual winter maximum. This sea ice provides many important ocean climate and ecosystem services. For example, winter ice insulates warmer ocean waters from extreme cold in the atmosphere. During spring, algae growth on the undersurface of sea ice initiates the annual onset of biological productivity (Szymanski and Gradinger 2016). The seasonal ice cover is critical to the regional climate, marine ecosystems, societal expectations, and economics through maintenance of a thermal barrier that separates two distinct temperature-adapted marine ecosystems in the northern and southern portions of the Bering Sea shelf (Schumacher et al. 1983; Mueter and Litzow 2008). We utilized remote sensing derived ice extent products for ice context; governmental and academic investigations, media, and public reports for impacts; and the Community Earth System Model's Large Ensemble Project (CESM-LENS) for assessment of the relative likelihoods of current low ice extent.

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OBSERVATIONS AND HISTORICAL CONTEXT. *Sea ice cover.* Mean Bering Sea ice extent (SIE) for January through April for the 40-yr satellite-derived passive microwave record in the National Snow and Ice Data Center's Sea Ice Index version 3 (Fetterer et al. 2017) shows that 2018 was the lowest of record (Fig. 1a), with the greatest anomalies compared to a 1981–2010 baseline north and west of St. Matthew Island (Fig. 1b). Analysis of late winter Bering Sea ice extent 1956–80 (Pease et al. 1982) and reconstructed monthly Arctic-wide ice extent since 1850 (Walsh et al. 2017) also supports the unprecedented nature of the 2018 ice extent. The maximum daily Bering Sea SIE was reached in early February and was the lowest on record (~411,500 km^2), only 47% of the 1979–2016 mean seasonal maximum extent. The SIE then dropped ~215,000 km^2 (Perovich et al. 2018).

Ocean. Bering Sea sea surface temperatures (SSTs) and upper ocean heat content overall were both above the 1981–2010 mean during late summer and autumn 2017 (Timmermans et al. 2017) and this persisted

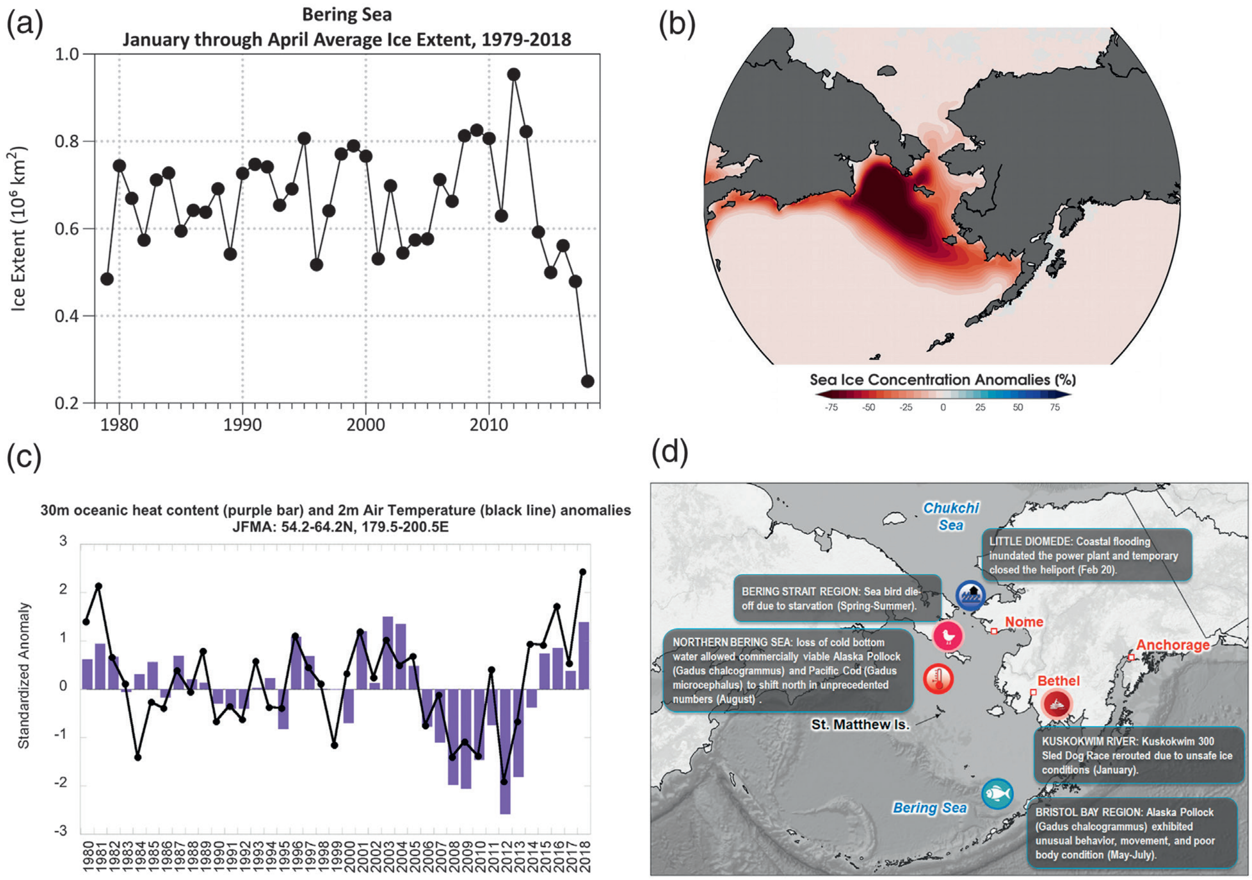

Fig. 1. (a) Annual time series of mean January–April Bering Sea ice extent since 1979 from the Sea Ice Index (Fetterer et al. 2017) (b) Mean January–April 2018 sea ice concentration anomalies calculated from a 1981–2010 climate baseline from NOAA/NSIDC climate data record of passive microwave sea ice concentration, version 3 (Meier et al. 2017). (c) Time series of normalized January–April upper 30-m Bering Sea heat content calculated from a 1981–2010 climate baseline from Global Ocean Data Assimilation System (Behringer 2007) and 2-m mean air temperature from ERA-Interim reanalysis. (d) Selected impacts of the low ice extent.

into early 2018 (Fig. 1c). Chukchi Sea SSTs were also above normal and delayed freeze-up north of Bering Strait, which possibly triggered atmosphere–ocean feedbacks that contributed to this winter's southerly airflow (Tachibana et al. 2019).

Atmosphere. The winter of 2017/18 was persistently stormy over the Bering Sea. The mean sea level pressure anomaly fields for both autumn (September–November) and winter (December–February) were characterized by negative anomalies over Chukotka and positive departures (>5 hPa) south of the Aleutians. The departures from normal air temperature (at 925 hPa) were positive throughout autumn and winter, with the largest positive anomalies in the January to March season, when the western Bering Sea was more than 5°C above normal (Overland et al. 2018a) and the eastern Bering Sea had the highest mean January–April 2-m air temperature of record (Fig. 1c). Stabeno and Bell (2019) highlight the particular importance of episodic but recurring southerly winds during this winter that advected relatively warm air over the Bering Sea and the relationship to the extremely low ice extent.

IMPACTS OF LOW ICE. Impacts of record low sea ice extent in the Bering Sea beyond the climate system were widespread and profound, and included unprecedented weather events, marine wildlife die-offs, and sightings of animals outside of their normal range, such as the ecosystem impacts discussed in Duffy-Anderson et al. (2019). The Local Environmental Observer (LEO) Network (https://www.leonetwork.org/bering-sea-ice-2018) received more than 50 reports of notable events in western Alaska through August 2018. Persistently warm weather contributed to poor ice conditions resulting in a fatal accident on the Kuskokwim River ice road (Alaska

Dispatch News 2018). In the Bering Strait, retreating and fractured sea ice during a late February storm allowed a coastal sea ice–laden flooding event that caused a power outage and infrastructure damage at Little Diomede, Alaska (Walsh 2018). Historically in February, stable landfast ice at Little Diomede Island provided an ice airstrip for primary transportation. In the Bering Strait region, the limited duration, poor quality, and unseasonable retreat of the sea ice was coincident with the loss or impairment of maritime subsistence activities for coastal communities. Ecologically, changes in the northern Bering Sea marine ecosystem included the first documented mass strandings of ice-associated seals in the Bering Strait region (Sheffield 2018), redistribution of thermally sensitive fish species, and a multi-species seabird die-off attributed to starvation (Siddon and Zador 2018).

ATTRIBUTION. To evaluate the role of anthropogenic climate change in the 2018 Bering Sea ice extreme anomaly, we employed monthly gridded sea ice concentration data from the CESM Large Ensemble (CESM-LENS). CESM-LENS features fully coupled simulations with 40 ensemble members reflecting historical (1850/1920–2005) and projected (2005–2100; RCP8.5) climate forcing and a pre-industrial control simulation (1,800 yr) reflecting climate forcing from 1850 (Kay et al. 2015). Arctic sea ice extent (Jahn et al. 2016) and sea ice thickness (Labe et al. 2018) in the CESM-LENS have been shown to be realistic when compared to satellite observations post-1978. The Bering Sea region grid points were masked and monthly SIE was derived by summing the area of the grid cells with concentrations greater than or equal to 15% annually for the January to April period. There is a weak (not statistically significant) negative trend in the observed January to April mean SEI (though a significant trend is found in other aspects of Bering Sea ice extent; see Fig. ES1 in the online supplemental material), although some sub-intervals (e.g., 1979–2012) show an increasing trend. This is expected since the subdecadal-scale variability of Bering SIE is known to be driven by internal atmospheric variability (e.g., Pease et al. 1982; Overland et al. 2018b). The CESM-LENS ensembles averages display declining trends over 1980–2018 that are mostly (35 of 40 members) greater in magnitude than the observed trend (and one member exceeds the 1979–2012 observed trend) while similar 39-yr subsets of the pre-industrial simulation have mixed increasing and decreasing trends (see Fig. ES2). The variances of the model ensembles are generally higher than the observations although the standard deviation decreases by about 50% between 2010 and 2080. The Bering SIE observations from 1980 to 2018 (Fetterer et al. 2017) were quantile-mapped to fit the CESM-LENS distribution (Fig. 2a). The SIE for each ensemble member during this period was sorted by increasing value and each quantile was then averaged over all ensemble members and matched to the corresponding quantile from the observations. The resulting distribution (see blue line in Fig. 2a) gives an model-adjusted observed 2018 SIE minimum of 406,332 km^2, which is used to assess the role of anthropogenic climate change. This is done by calculating the fraction of attributable risk (FAR; Stott et al. 2004; National Academies of Sciences, Engineering, and Medicine 2016) where FAR = 1 − $\text{Prob}_{\text{pre-Industrial}}/\text{Prob}_{\text{present}}$, and the probability is the likelihood of exceeding (i.e., being lower than) the 2018 SIE. Figure 2b shows the pre-industrial simulation of the January–April ice extent, together with the adjusted (blue) and unadjusted (red) values for 2018. There were two exceedances during the 1,800-yr pre-industrial simulation and a total of 117 from the 40 CESM-LENS ensemble members from the 2003–33 "present" climate, resulting in a FAR of 0.99. Individual LENS members ranged from 0 to 7 occurrences from 2003 to 2033. However, if the present climate were defined as the 1980–2018 historical period, there would have been only 29 exceedances of 2018 in the 40 ensemble members, making the FAR correspondingly smaller (0.94). Finally, Fig. 2c shows the probability, over all 40 CESM-LENS simulations, that the 2018 minimum will be exceeded in each decade. The probability is essentially zero through the 1990s, after which it increases to 0.06 in the 2010s, 0.14 in the 2020s, 0.29 in the 2030s, 0.52 in the 2040s, and 0.94 by the 2060s. Thus CESM-LENS indicates that 2018 extreme ice extent in the Bering Sea may become the mean extent by the 2040s and essentially an upper bound (with only a 6% probability of greater extent) by the 2060s.

CONCLUSIONS. The 2018 January through April sea ice extent in the Bering Sea was far lower than any previous winter in the reconstructed or observed past (since 1850). This had ramifications for the weather and climate system, economic impacts, and long-lasting ecosystem impacts. Ocean warmth, late ice development, and frequent atmospheric storminess were important factors. Using CESM-LENS, we find that the observed 2018 January through April mean sea ice extent to be extremely rare in the pre-industrial control simulation (2 out of 1,800) but becomes much more frequent in the current era. The FAR exceeds 0.9 using either the current era (2003–33) or recent

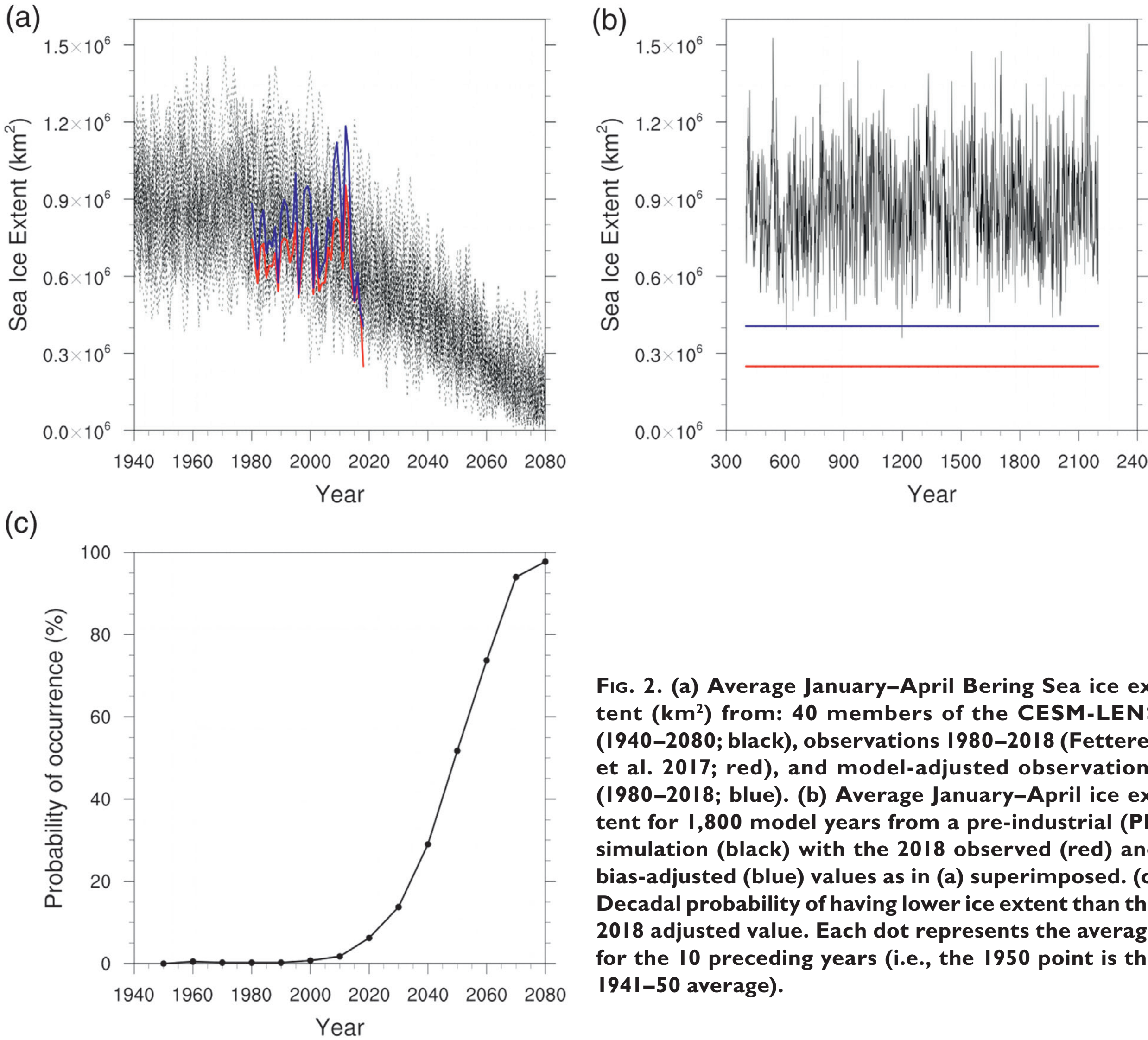

Fig. 2. (a) Average January–April Bering Sea ice extent (km²) from: 40 members of the CESM-LENS (1940–2080; black), observations 1980–2018 (Fetterer et al. 2017; red), and model-adjusted observations (1980–2018; blue). (b) Average January–April ice extent for 1,800 model years from a pre-industrial (PI) simulation (black) with the 2018 observed (red) and bias-adjusted (blue) values as in (a) superimposed. (c) Decadal probability of having lower ice extent than the 2018 adjusted value. Each dot represents the average for the 10 preceding years (i.e., the 1950 point is the 1941–50 average).

past (1980–2018) simulations and that with ongoing Earth system warming the 2018 extent and could potentially be typical by the 2040s and represent an upper bound within 50 years.

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REFERENCES

Alaska Dispatch News, 2018. Father dies, 5 people rescued after family falls through river ice near Bethel. 1 January 2018, *Alaska Dispatch News*, https://www.ktuu.com/content/news/Body-of-man-who-fell-through-ice-found-467631083.html.

Behringer, D. W., 2007: The Global Ocean Data Assimilation System (GODAS) at NCEP. *11th Symp. on Integrated Observing and Assimilation Systems for the Atmosphere, Oceans, and Land Surface.* San Antonio, TX, Amer. Meteor. Soc., 3.3, https://ams.confex.com/ams/87ANNUAL/webprogram/Paper119541.html.

Dee, D. P., and Coauthors, 2011: The ERA-Interim reanalysis: Configuration and performance of the data assimilation system. *Quart. J. Roy. Meteor. Soc.*, **137**, 553–597, https://doi.org/10.1002/qj.828.

Duffy-Anderson, J. T., and Coauthors, 2019: Responses of the northern Bering Sea and southeastern Bering Sea pelagic ecosystems following record-breaking low winter sea ice. *Geophys. Res. Lett.*, **46**, 9833–9842, https://doi.org/10.1029/2019GL083396.

Fetterer, F., K. Knowles, W. N. Meier, M. Savoie, and A. K. Windnagel, 2017 (updated daily): Sea Ice Index, Version 3. Regional Daily Data. National Snow and Ice Data Center, accessed April and August 2019, https://doi.org/10.7265/N5K072F8.

Jahn, A., J. E. Kay, M. M. Holland, and D. M. Hall, 2016: How predictable is the timing of a summer ice-free Arctic? *Geophys. Res. Lett.*, **43**, 9113–9120, https://doi.org/10.1002/2016GL070067.

Kay, J. E., and Coauthors, 2015: The Community Earth System Model (CESM) Large Ensemble Project: A community resource for studying climate change in the presence of internal climate variability. *Bull. Amer. Meteor. Soc.*, **96**, 1333–1349, https://doi.org/10.1175/BAMS-D-13-00255.1.

Labe, Z., G. Magnusdottir, and H. Stern, 2018: Variability of Arctic sea ice thickness using PIOMAS and the CESM Large Ensemble. *J. Climate*, **31**, 3233–3247, https://doi.org/10.1175/JCLI-D-17-0436.1.

Meier, W. N., F. Fetterer, M. Savoie, S. Mallory, R. Duerr, and J. Stroeve. 2017: NOAA/NSIDC Climate Data Record of Passive Microwave Sea Ice Concentration, Version 3. National Snow and Ice Data Center, accessed August 2019, https://doi.org/10.7265/N59P2ZTG.

Mueter, F. J., and M. A. Litzow, 2008: Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecol. Appl.*, **18**, 309–320, https://doi.org/10.1890/07-0564.1.

National Academies of Sciences, Engineering, and Medicine, 2016: *Attribution of Extreme Weather Events in the Context of Climate Change*. National Academies Press, 186 pp., https://doi.org/10.17226/21852.

National Ice Center and National Snow and Ice Data Center, 2010 (updated daily): Multisensor Analyzed Sea Ice Extent–Northern Hemisphere (MASIE-NH), version 1. NSIDC, accessed 6 August 2019, https://doi.org/10.7265/N5GT5K3K.

Overland, J. E., E. Hanna, I. Hanssen-Bauer, S. J. Kim, J. E. Walsh, M. Wang, U. S. Bhatt, and R. L. Thoman, 2018a: Surface air temperature [in "Arctic Report Card 2018"]. NOAA, https://arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/783/Surface-Air-Temperature.

Overland, J. E., M. Wang, and T. J. Ballinger, 2018b: Recent increased warming of the Alaskan marine Arctic due to midlatitude linkages. *Adv. Atmos. Sci.*, **35**, 75–84, https://doi.org/10.1007/s00376-017-7026-1.

Pease, C. H., S. A. Schoenberg, and J. E. Overland, 1982: A climatology of the Bering Sea and its relation to sea ice extent. NOAA Tech. Rep. ERL 419-PMEL 36, 29 pp.

Perovich, D., and Coauthors, 2018: Sea ice [in "Arctic Report Card 2018"]. NOAA, https://arctic.noaa.gov/Report-Card/Report-Card-2018/ArtMID/7878/ArticleID/780/SeanbspIce.

Schumacher, J. D., K. Aagaard, C. H. Pease, and R. B. Tripp, 1983: Effects of a shelf polynya on flow and water properties in the northern Bering Sea. *J. Geophys. Res.*, **88**, 2723–2732, https://doi.org/10.1029/JC088iC05p02723.

Sheffield, G., 2018: Response to reported mass seal stranding at Wales, Alaska–June 2018. Trip Report to Alaska Marine Mammal Stranding Network, Juneau, Alaska, 8 pp.

Siddon, E., and S. Zador, 2018: Ecosystem Status Report 2018: Eastern Bering Sea. NOAA Fisheries, accessed 9 May 2019, https://www.fisheries.noaa.gov/resource/data/2018-status-eastern-bering-sea-ecosystem.

Stabeno, P. J., and S. W. Bell, 2019: Extreme conditions in the Bering Sea (2017–2018): Record-breaking low sea-ice extent. *Geophys. Res. Lett.*, **46**, 8952–8959, https://doi.org/10.1029/2019GL083816.

Stott, P., D. Stone, and M. Allen, 2004: Human contribution to the European heatwave of 2003. *Nature*, **432**, 610–614, https://doi.org/10.1038/nature03089.

Szymanski, A., and R. Gradinger, 2016: The diversity, abundance and fate of ice algae and phytoplankton in the Bering Sea. *Polar Biol.*, **39**, 309–325, https://doi.org/10.1007/s00300-015-1783-z.

Tachibana, Y., K. K. Komatsu, V. A. Alexeev, L. Cai, and Y. Ando, 2019: Warm hole in Pacific Arctic sea ice cover forced mid-latitude Northern Hemisphere cooling during winter 2017–18. *Sci. Rep.*, **9**, 5567, https://doi.org/10.1038/s41598-019-41682-4.

Timmermans, M.-L., C. Ladd, and K. Wood, 2017: Sea surface temperature [in "Arctic Report Card 2017"]. NOAA, https://arctic.noaa.gov/Report-Card/Report-Card-2017/ArtMID/7798/ArticleID/698/Sea-Surface-Temperature.

Walsh, J., 2018: Sea ice in the Alaska region: The remarkable winter of 2017–18. Alaska Climate Dispatch—A state-wide seasonal summary and outlook, 1–3, https://uaf-accap.org/wp-content/uploads/2019/10/climate_dispatch_May_2018_FINAL.pdf.

——, F. Fetterer, J. S. Stewart, and W. L. Chapman, 2017: A database for depicting Arctic sea ice variations back to 1850. *Geogr. Rev.*, 107, 89–107, https://doi.org/10.1111/j.1931-0846.2016.12195.x.