AGU100 ADVANCING EARTH AND SPACE SCIENCE

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL078971

Special Section:
Midlatitude Marine Heatwaves: Forcing and Impacts

Key Points:

- Subsurface water in the Northeast Pacific Ocean is still anomalously warm
- This warmth extends across Queen Charlotte Sound to Rivers Inlet, a BC fjord
- The prolonged warmth in coastal waters may have substantial ecological impacts

Supporting Information:

- Supporting Information S1

Correspondence to:
J. M. Jackson,
jennifer.jackson@hakai.org

Citation:
Jackson, J. M., Johnson, G. C., Dosser, H. V., & Ross, T. (2018). Warming from recent marine heatwave lingers in deep British Columbia fjord. *Geophysical Research Letters*, *45*, 9757–9764. https://doi.org/10.1029/2018GL078971

Received 29 MAY 2018
Accepted 31 AUG 2018
Accepted article online 4 SEP 2018
Published online 22 SEP 2018

Warming From Recent Marine Heatwave Lingers in Deep British Columbia Fjord

Jennifer M. Jackson[1], Gregory C. Johnson[2], Hayley V. Dosser[1,3], and Tetjana Ross[4]

[1]Hakai Institute, Victoria, British Columbia, Canada, [2]NOAA/Pacific Marine Environmental Laboratory, Seattle, WA, USA, [3]Department of Earth, Ocean and Atmospheric Sciences, University of British Columbia, Vancouver, British Columbia, Canada, [4]Fisheries and Oceans Canada, Institute of Ocean Sciences, Sidney, British Columbia, Canada

Abstract While satellite data indicate that the surface expression of the North Pacific marine heatwave, nicknamed "The Blob," disappeared in late 2016, Argo float and ship-based conductivity-temperature-depth data show that warm conditions persisted below the surface mixed layer through at least March 2018. We trace this anomalously warm subsurface water from the open ocean through Queen Charlotte Sound to Rivers Inlet, on British Columbia's central coast. In Rivers Inlet, deep water below the sill depth continues to be 0.3° to 0.6 °C warmer than the monthly average, suggesting that impacts of this marine heatwave have persisted in coastal waters at least 4 years after its onset, with potentially substantial effects on coastal ecosystems.

Plain Language Summary The Northeast Pacific Ocean was affected by two warm water events, the first was the 2013 to 2015 marine heatwave, nicknamed The Blob, and the second was the 2015 to 2016 El Niño. Surface satellite data have shown that the warm water was gone by 2016. Using temperature data collected by ship and by autonomous robots, we find that abnormally warm water continues to exist in the open ocean below the surface, at about 140-m depth. In the coastal ocean, we find that deep waters in Rivers Inlet are still 0.3° to 0.6 °C warmer than normal, at least 4 years after The Blob was first observed. This warm water could have a big impact on the Rivers Inlet ecosystem.

1. Introduction

During the boreal winter of 2013/2014, persistent anomalously high sea level pressure over the Northeast Pacific Ocean decreased heat flux from the ocean to the atmosphere and weakened advection of cold water from the north, leading to an offshore marine heatwave, "The Blob," (Bond et al., 2015), that peaked in early 2014. Downwelling-favorable winds in the summer and autumn of 2014 advected warm anomalies from The Blob toward the North American west coast (McCabe et al., 2016). A teleconnection between the weak 2014/2015 El Niño and the North Pacific likely contributed to anomalously high sea level and reduced winds, evaporation, and thus further increased sea surface temperature through air-sea interactions (Di Lorenzo & Mantua, 2016). Then during the winter of 2015/2016, one of the strongest El Niño events on record occurred (Jacox et al., 2016). These events led to anomalously warm surface ocean temperatures impinging upon the west coast of North America from around May 2014 through September 2016 (Gentemann et al., 2017).

This strong and extended Northeast Pacific marine heatwave exerted substantial impacts on marine ecosystems. It altered phytoplankton composition (McCabe et al., 2016; Peterson et al., 2017) and abundance (Cavole et al., 2016). It contributed to the largest recorded outbreak of the neurotoxin domoic acid (McCabe et al., 2016). Off the Oregon (Peterson et al., 2017) and British Columbia (Galbraith et al., 2016) coasts, the normally dominant cold water, lipid-rich copepods were replaced with warm-water species. The loss of cold-water zooplankton species led to the starvation of thousands of Cassin's Auklets off British Columbia (Jones et al., 2018). Spawning phenology and distribution of anchovy and hake changed dramatically during the marine heatwave (Auth et al., 2017). Salmon abundance within the California Current marine ecosystem is expected to be reduced until at least 2019 due to poor ocean and stream conditions from 2014 to 2016 (Jacox et al., 2018).

North of Oregon, the Pacific coast features hundreds of fjords that support rich cold-water ecosystems. Fjords are the life-support system of early life stages of salmon (Healey, 1982; Simenstad et al., 1982). Rivers Inlet, located within Wuikinuxv Nation traditional territory, is a typical glacial-fed fjord on British Columbia's central coast (Figure 1) that is about 45 km long, 3 km wide, and 340 m deep. A 140-m (Pickard, 1961) sill at the

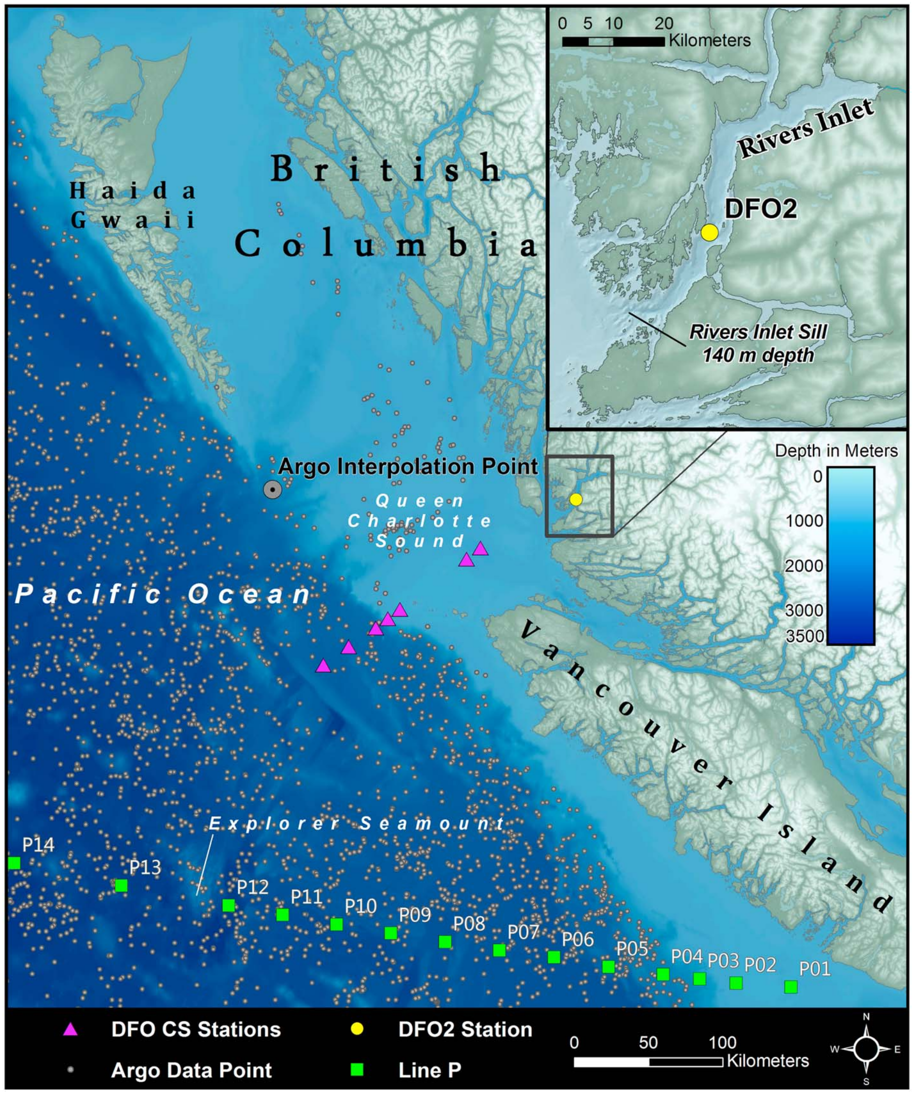

Figure 1. Bathymetric map (blue colors) of Rivers Inlet (inset), Queen Charlotte Sound, and the adjacent Northeast Pacific Ocean with locations of Argo profiles (small gray dots), Argo time series interpolation point (large gray circle), DFO CS (magenta triangles), DFO2 (yellow dot), and Line P (green squares) data (see methods).

mouth of Rivers Inlet separates the deep fjord basin from Queen Charlotte Sound and the open ocean. Deep water (defined here as water below the sill depth) in Rivers Inlet is renewed yearly when dominant winds off Queen Charlotte Sound are upwelling-favorable from about April to September (Foreman et al., 2011). Upwelling brings colder, denser subsurface water across the 150-km-wide continental shelf, which then travels from Queen Charlotte Sound to Rivers Inlet, arriving from about June to September. The denser upwelled water replaces the old bottom water, bringing colder, saltier water into the deep fjord (Farmer & Freeland, 1983; Hodal, 2010). Annual upwelling-driven deep-water renewal is typical for many fjords in the Pacific Northwest (Farmer & Freeland, 1983). Once home to the third largest sockeye salmon run in British Columbia, Rivers Inlet experienced persistent low salmon abundance during the early 1990s that led to a closure of the commercial fishery in 1996 (Mckinnell et al., 2001). It has yet to reopen.

Until at least June 2018, deep water below the sill depth in Rivers Inlet continued to be 0.3° to 0.6 °C warmer than the monthly average, almost 4 years after the onset of The Blob, and 2 years after the end of the 2015/16 El Niño. To explain the persistence of the marine heatwave in the fjord deep waters, we analyze four datasets —Argo (Jayne et al., 2017) float data from the Northeast Pacific, ship-based CTD (conductivity-temperature-depth) data from Queen Charlotte Sound, ship-based CTD data from Rivers Inlet, and ship-based CTD data from Line P. We find from offshore Argo and ship-based CTD data that the marine heatwave persisted below the surface through at least March 2018. We trace this anomalously warm subsurface water from the open ocean through Queen Charlotte Sound to Rivers Inlet, which has the longest, most frequently sampled time series of any fjord on British Columbia's central coast. We then discuss how continued warming could impact the marine ecosystem in Rivers Inlet and in the many similar fjords along the British Columbia and Washington coasts.

2. Data

Argo is a global array of autonomous CTD floats that profile year-round from the surface to 2,000 m with a global target of one profile every 10 days at 3° × 3° spacing (Jayne et al., 2017; Figure 1, gray dots). Groups contributing to the Argo program commenced deployments in 1999. Argo first achieved sparse near-global coverage in 2005 or 2006. It has over 3,800 operational units at the time of this writing. Here we analyze monthly objective maps of Argo data on a 1° × 1° grid (Roemmich & Gilson, 2009) that start in January 2004 and have been updated through March 2018 (http://sio-argo.ucsd.edu/RG_Climatology.html). These objective maps are constructed by applying appropriate decorrelation length scales to monthly anomaly values relative to a long-term climatological seasonal cycle that provides the high spatial resolution baseline.

Fisheries and Oceans Canada has collected CTD data at 11 stations along the Cape Scott (CS) line since the 1980s. This line runs from the open ocean, across Queen Charlotte Sound toward Rivers Inlet (Figure 1; magenta triangles). Between 1998 and 2017, a total of 410 temperature profiles were collected, with 210 of those at 6 stations that extend deeper than the 140-m Rivers Inlet sill. Sampling occurs on average twice per year, in the spring and the fall; however, there was more frequent sampling in both 2015 and 2016.

Temperature and salinity data have been collected at five stations in Rivers Inlet since 1951 (Figure 1; yellow circle shows the station discussed in this paper). These five stations are spaced about 5 to 10 km apart and stretch from the mouth to the head of the inlet. There is high correlation among stations (not shown) so only DFO2 was used in this study because that station has the highest frequency sampling. From 1951 to 1993, temperature was measured with reversing thermometers and salinity was measured from water collected by Niskin or Nansen bottle. Since 1998, temperature and salinity have been measured using a Seabird or RBR CTD. From 1951 to 1987 and from 2008 to 2010, the University of British Columbia collected data. From 1990 to present, Fisheries and Oceans Canada collected data. From 2013 to present, the Hakai Institute collected data. The UBC, DFO, and Hakai programs have been run independently. This is the first time that the three data sets have been brought together for analysis. To ensure consistency among data types, the Salish Sea Ambient Monitoring Exchange program (www.ssamex.org) has recently compared CTD data collected by DFO, NOAA, and Hakai. Preliminary results suggest that these data are comparable and can be used interchangeably. To date, 626 temperature profiles have been collected in Rivers Inlet at five stations, with more than 90% of the data collected since 1998.

The Line P monitoring program has collected oceanographic data at stations between southern Vancouver Island and Ocean Weather Station Papa (50°N, 145°W) since 1959 (Figure 1; green squares; Freeland, 2007). Currently, there are 27 stations that are sampled on three cruises each year (winter, spring, and summer).

3. Results

Similar to the surface warmth in the Northeast Pacific, anomalous subsurface warmth (Figure 2; here shown in red at a pressure of 140 dbar, in yellow at the surface, and in orange when anomalously warm at both pressures) was observed offshore in 2014 (Figure 2a), roughly under the location of The Blob (Bond et al., 2015). By 2015 that warmth had spread eastward, impinging upon the west coast of North America (Figure 2b). In 2016 all of the west coast of North America was anomalously warm both subsurface and at the surface (Figure 2c), owing to some combination of warmth from The Blob and the 2015/2016 El Niño influence (Jacox et al., 2018). However, unlike conditions at the surface, where the marine heatwave had largely dissipated, the subsurface warmth continued throughout 2017 (Figure 2d).

In waters just off the central British Columbia coast between Haida Gwaii and Vancouver Island (Figure 1, large gray circle), the surface marine heatwave commenced in early 2014, peaked at the start of 2015,

10.1029/2018GL078971

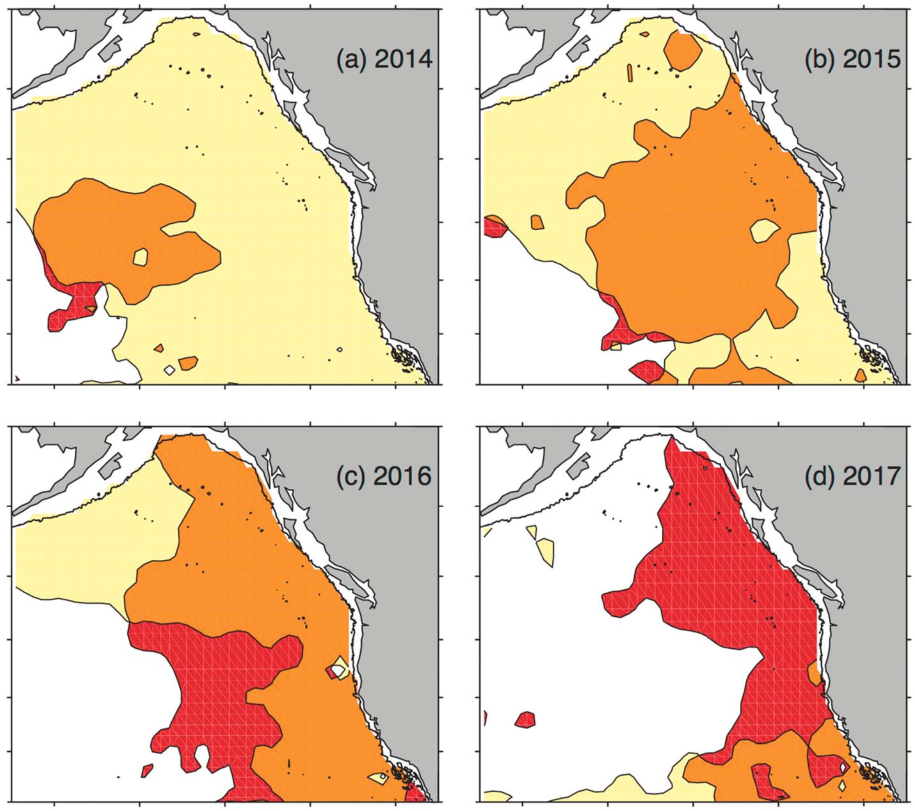

Figure 2. Regions with mean temperature anomalies exceeding the 2004–2017 monthly means by 0.25 °C at 140-dbar pressure (shaded red), the surface (shaded yellow), and at both levels (shaded orange) for (a) 2014, (b), 2015, (c) 2016, and (d) 2017. Calculated from annual averages of monthly maps of Argo data (Roemmich & Gilson, 2009).

exhibited a secondary peak in early 2016, and was gone by late 2016 (Figure 3a). However, at 140 dbar, roughly the sill depth of Rivers Inlet, warm conditions did not begin until 2015 and persisted through the end of the time series, March 2018.

The temperature-salinity relationship shifted warmer and saltier on isopycnals (e.g., became spicier) throughout the halocline. Potential temperature (θ; Figure 3b, solid line) on the isopycnal $\sigma_\theta = 26.1$ kg m^{-3} (Figure 3a, bottom thick black contour) ranged from 6.8 to 7.4 °C from 2004 until 2015 but rapidly climbed to a peak exceeding 8 °C in early 2016 and continued to oscillate near 7.7 °C until March 2018. The deviation toward warmer, saltier conditions on isopycnals (Figure 3b) was approximately coincident with the appearance of the warm subsurface anomaly on isobars (Figure 3a). These changes may be owing to some combination of surface warming and anomalously weak advection of cold fresh waters (Bond et al., 2015).

In Queen Charlotte Sound, on the shelf between Haida Gwaii and Vancouver Island (Figure 1), the anomalously warm surface water associated with the marine heatwave was first observed in the spring survey of 2015, extending down to roughly 80 dbar (Figure 3c). This surface signal persisted until September 2016. Below 80 dbar, in water with densities typically found below the sill depth in Rivers Inlet ($25.6 < \sigma_\theta < 26.1$ kg m^{-3}), θ remained 0.2–0.9 °C above the 1998 to 2014 average until at least May 2017 (the last available date in the CS line time series). On $\sigma_\theta = 26.1$ kg m^{-3} (at approximately 100 dbar) θ rose from a pre-2015 average of 7.1 °C to oscillate around 7.5 °C during 2015–2017 (Figure 3d). The magnitude and duration of the deep warm anomaly was similar for all CS stations: in the open ocean, at the shelf-break, and on the shelf across Queen Charlotte Sound.

Anomalously warm water was first observed in Rivers Inlet (Figure 1, yellow circle) in October 2014 (Figure 3e). Above the sill depth at 140 m, this warm water was observed from October 2014 to January 2017, a few months after warm surface water was observed offshore in the Argo time series. Below the 140-m sill depth, water 0.3 to 0.6 °C above the 1998 to 2018 monthly average was first observed in March

10.1029/2018GL078971

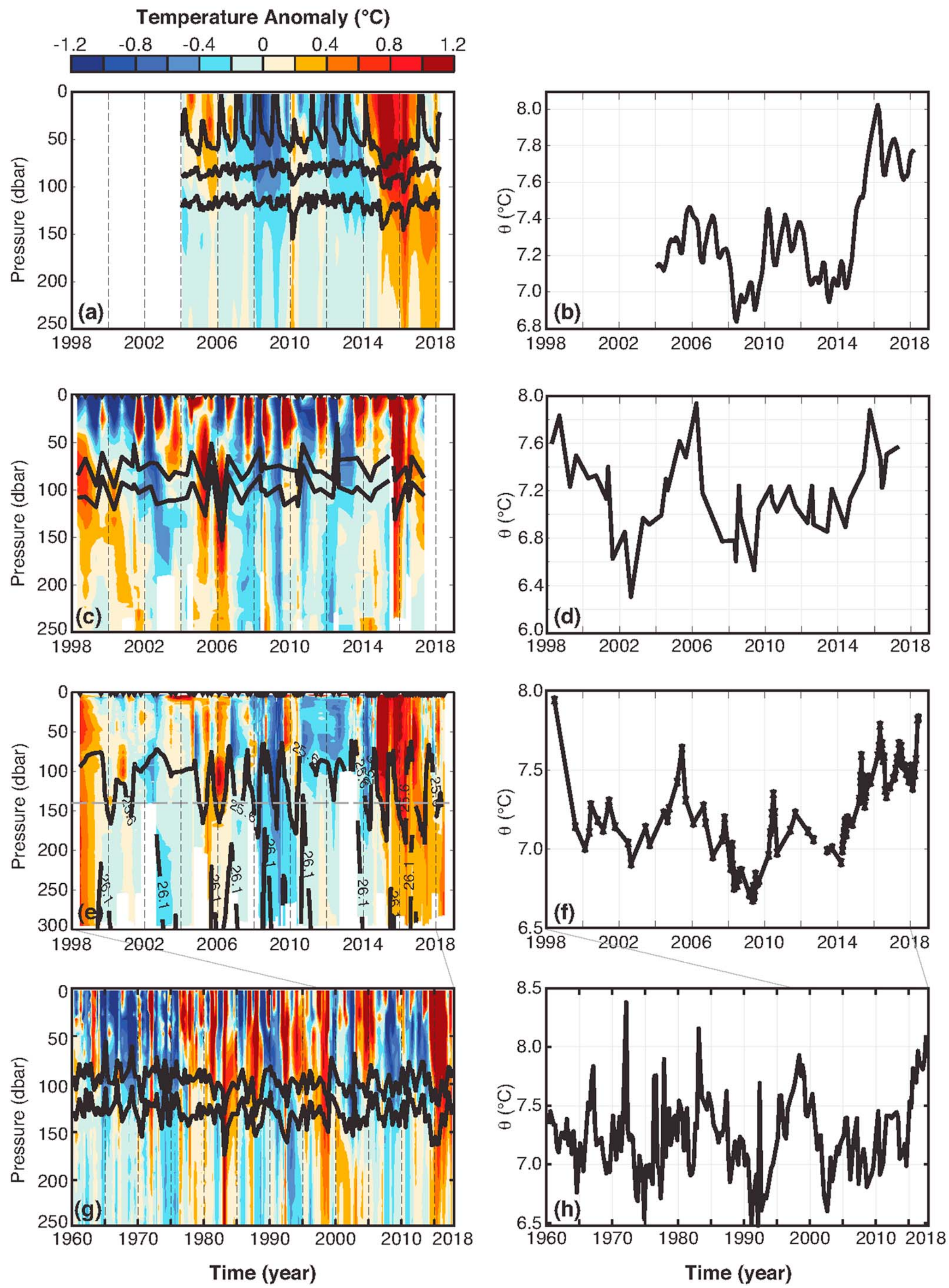

Figure 3. Potential temperature anomalies contoured versus (left-hand column) pressure and time and (right-hand column) potential temperature time series at four locations: (a and b) Argo data from the Northeast Pacific Ocean that are objectively mapped to 51.5°N, 130.5°W (Figure 1, large gray circle); (c and d) conductivity-temperature-depth (CTD) data averaged across stations crossing the shelf from Queen Charlotte Sound to the open ocean along DFO's CS line (Figure 1, magenta triangles); (e and f) CTD data collected at station DFO2 in Rivers Inlet (Figure 1, yellow circle); (g and h) CTD data averaged across stations P06 to P12 along DFO's Line P (Figure 1, green squares). The contours are at 0.2 °C intervals (color bar) with select potential isopycnals (thick black contours) overlaid: σ_θ = 25.1 kg m^{-3}(a only) to highlight seasonal outcropping, 25.6 kg m^{-3} which bounds the lightest deep waters in Rivers Inlet, and 26.1 kg m^{-3} which is a typical maximum density observed annually in Rivers Inlet. The horizontal, gray dashed line in (e) indicates the sill depth in Rivers Inlet. Potential temperature time series are for (b) σ_θ = 26.1 kg m^{-3} at 51.5°N, 130.5°W; (d) θ on σ_θ = 26.1 kg m^{-3} averaged across Queen Charlotte Sound; (f) average θ below the sill depth of 140 m in Rivers Inlet; (h) σ_θ = 26.1 kg m^{-3} averaged for stations P06 to P12 along Line P. Anomalies were calculated relative to different time periods, based on the length of the time-series: 2004 to 2018 for Argo data, 1998 to 2017 for DFO's CS line, 1998 to 2018 for Rivers Inlet, and 1960 to 2018 for Line P. The seasonal cycle was removed, either by using annual harmonics or by subtracting the monthly average, except along the CS line, where twice yearly sampling(during various months in spring and fall, plus summer sampling in 2015 and 2016) precluded its removal.

2015 and persisted through at least June 2018 (Figure 3f). Rivers Inlet deep water typically has $25.6 < \sigma_\theta < 26.1$ kg m^{-3}, which encompasses offshore isopycnals (Figure 3e, thick black contours) where the subsurface warm anomaly became evident in early 2015. The magnitude and timing of this warm anomaly in the deep water is consistent with what was observed subsurface in the adjacent open ocean and on the shelf in Queen Charlotte Sound. As is the case for other fjords in this region, upwelling likely drives the renewal of deep water by advecting denser water over the sill (Farmer & Freeland, 1983); hence, the warm anomaly was probably transported to deep Rivers Inlet via this mechanism. These results demonstrate that the subsurface marine heatwave that persists below the surface in the Northeast Pacific is still influencing coastal regions more than 4 years after the surface anomaly was first observed.

Warm deep waters have been observed before in Rivers Inlet; for example, during the strong El Niño of 1998 (Figures 3e and 3f). To assess the prevalence of anomalously warm subsurface water in the Northeast Pacific over a longer historical record, we examine the Line P time series (1959 to present, station locations shown as green squares in Figure 1) that shows warm water anomalies within the range $25.6 < \sigma_\theta < 26.1$ kg m^{-3} at the near shelf-break stations (P06–P12) in 1998 and 2015 to present (Figure 3g). In addition to 1998 and 2015 to present, both strong El Niño years, deep warm anomalies were also seen on the shelf in Queen Charlotte Sound in 2005–2006 (Figure 3d), but while there are coincident peaks in the offshore time series (Figures 3b and 3h), they were less prominent. The Line P time series shows positive subsurface anomalies of magnitude similar to the recent anomaly in 1972 and 1983 (another strong El Niño year), but both were short lived. However, starting in the mid-1990s and culminating during the 1998 El Niño, there was the only other sustained period of positive temperature anomalies in the Line P record (1959 to present), which is coincident with the collapse of sockeye salmon populations in Rivers Inlet (Mckinnell et al., 2001). Given the physical separation of Line P and Rivers Inlet, the coincidence of these time series suggests that subsurface anomalies could impact inlets up and down the coast of British Columbia.

4. Discussion

Globally averaged sea-surface temperatures have risen at a rate of 0.1 °C decade^{-1} from 1950 to 2017, with regional seasonal anomalies sometimes exceeding 2 °C even relative to a 1981–2010 climatology (Huang et al., 2018). The ocean is also taking up a substantial amount of heat, with an average warming trend from 2004 to 2017 that is largest at the surface but reaches to at least 2,000 dbar (Johnson et al., 2018) and is roughly 0.05 °C decade^{-1} at 140 dbar (near the sill depth of Rivers Inlet). That global average warming, superimposed on regional variations, is expected to continue for decades even if greenhouse gas levels are stabilized in the atmosphere (Meehl et al., 2005), likely resulting in marine heatwaves warming deep fjords to higher temperatures.

The warmth associated with marine heatwaves can persist much longer at depth than at the surface, even reemerging to affect mixed layer temperatures in late winter (Deser et al., 2003) as likely seen in 2016 (Figure 3). In the Northeast Pacific, the subsurface warming was delayed by about a year, most likely due to the time it took for the anomaly to mix down into the permanently stratified portion of the water column. The fact that the temperature warmed on isopycnals as well as on isobars supports this mixing argument, as opposed to a simple vertical motion of isopycnals and isotherms. In addition, subsurface isopycnals (Figure 3a, solid lines) did not exhibit a noticeable vertical heave concurrent with the subsurface warm anomaly.

The deep waters in fjords (waters below sill depth) are susceptible to prolonged marine heatwave conditions. First, because—as shown here—the offshore subsurface waters that renew them may retain the temperature anomalies longer than surface waters. Second, because once the warmer water fills the deep portion of the fjord the warm anomaly can only be removed by mixing with colder waters above or by colder water reentering the fjord by flowing over the sill. In Rivers Inlet, deep water entering the fjord has been anomalously warm since 2015 so any renewal occurring after that date has not cooled the bottom water.

There are approximately 53 inlets that are at least 18.5 km long in British Columbia (Pickard, 1961), and most of these have few if any observations from the past few decades. While all fjords are slightly different, the long time series in Rivers Inlet provides clues on conditions in a subset of less frequently sampled inlets.

The strong relationship between offshore properties and those observed in Rivers Inlet suggests that offshore observations collected by Argo and ship-based CTDs could be used to forecast conditions in Rivers Inlet. For example, lag correlation analyses (Figures S1 and S2 in the supporting information) suggest that it takes 1 to 3 years for 140-dbar anomalies in the center of the Gulf of Alaska to impact the Argo interpolation point (Figure 1, gray circle) and 0 to 2 months (Figure S2) for the anomaly at the Argo interpolation point to impact Rivers Inlet (Figure 1, yellow circle).With further research, it is possible that offshore ocean data could potentially predict the conditions in other deep fjords influenced by upwelling in the Pacific Northwest.

The most profound effect that these persistent temperature anomalies have on larger organisms, such as salmon, is likely through the quality of their food. Warmer ocean temperatures have been shown to favor smaller, less lipid-rich zooplankton (e.g., Galbraith et al., 2016; Mackas et al., 2007), so juvenile salmon will encounter poorer food resources both in the inlets and once they leave the inlets. This occurs primarily through a displacement of the geographic center of mass of different zooplankton populations under different temperature conditions, which may explain why warm temperatures in the Northeast Pacific are correlated with poorer years for salmon in the Pacific Northwest but better years in Alaska, as the center of mass of lipid-rich species moves further north (e.g., Mueter et al., 2002). In addition, there is evidence that temperature anomalies affect the timing of plankton growth and development in different ways (Mackas et al., 2012), which could lead to mismatches between the phenology of trophic levels, thereby negatively impacting the food web in fjords like Rivers Inlet.

Acknowledgments
We thank the scientists and crew from the University of British Columbia, Fisheries and Oceans Canada, and the Hakai Institute for collecting the ship-based CTD data between 1951 and 2018. We thank Keith Holmes and Will McInnes (Hakai Geospatial) for their help with graphics. Funding support is from the Tula Foundation (J.M.J. and H. V.D.); Mitacs Canada (H.V.D.); Fisheries and Oceans Canada (T.R.); and the Climate Observation Division, Climate Program Office, National Oceanic and Atmospheric Administration (NOAA), U. S. Department of Commerce, and NOAA Research (G.C.J.). Pacific Marine Environmental Laboratory contribution 4788. Argo data were collected and made freely available by the International Argo Program and the national observing programs that contribute to it (http://www.argo.ucsd.edu, http://argo.jcommops.org, and http://doi.org/10.17882/42182). Data collected by the Hakai Institute are available at www.hecate.hakai.org. Data collected by the University of British Columbia and Fisheries and Oceans Canada are available at www.waterproperties.ca. We would like to thank the editor and two anonymous reviewers whose thoughtful suggestions helped to improve this manuscript.

References

Auth, T. D., Daly, E. A., Brodeur, R. D., & Fisher, J. L. (2017). Phenological and distributional shifts in ichthyoplankton associated with recent warming in the Northeast Pacific Ocean. *Global Change Biology*, *24*(1), 259–272. https://doi.org/10.1111/gcb.13872

Bond, N. A., Cronin, M. F., Freeland, H., & Mantua, N. (2015). Causes and impacts of the 2014 warm anomaly in the NE Pacific. *Geophysical Research Letters*, *42*, 3414–3420. https://doi.org/10.1002/2015GL063306

Cavole, L. M., Demko, A. M., Diner, R. E., Giddings, A., Koester, I., Pagniello, C. M. L. S., et al. (2016). Biological impacts of the 2013–2015 warm-water anomaly in the Northeast Pacific: Winners, losers, and the future. *Oceanography*, *29*(2), 273–285. https://doi.org/10.5670/oceanog.2016.32

Deser, C., Alexander, M. A., & Timlin, M. S. (2003). Understanding the persistence of sea surface temperature anomalies in midlatitudes. *Journal of Climate*, *16*(1), 57–72. https://doi.org/10.1175/1520-0442(2003)016<0057:utposs>2.0.co;2

Di Lorenzo, E., & Mantua, N. (2016). Multi-year persistence of the 2014/15 North Pacific marine heatwave. *Nature Climate Change*, *6*(11), 1042–1047. https://doi.org/10.1038/NCLIMATE3082

Farmer, D. M., & Freeland, H. J. (1983). The physical oceanography of fjords. *Progress in Oceanography*, *12*(2), 147–219. https://doi.org/10.1016/0079-6611(83)90004-6

Foreman, M. G. G., Pal, B., & Merryfield, M. J. (2011). Trends in upwelling and downwelling winds along the British Columbia shelf. *Journal of Geophysical Research*, *116*, C10023. https://doi.org/10.1029/2011JC006995

Freeland, H. (2007). A short history of Ocean Station Papa and Line P. *Progress in Oceanography*, *75*(2), 120–125. https://doi.org/10.1016/j.pocean.2007.08.005

Galbraith, M., Young, K., & Perry, I. (2016). Zooplankton along the BC continental margin, 2015. In P. C. Chandler, S. A. King, & R. I. Perry (Eds.), *State of the physical, biological and selected fishery resources of Pacific Canadian Marine Ecosystems in 2015*, *Can. Tech. Rep. Fish. Aquat. Sci.* (Vol. 3179, chap. 15, pp. 64–71). Retrieved from http://dfo-mpo.gc.ca/oceans/publications/soto-rceo/2015/index-eng.html

Gentemann, C. L., Fewings, M. R., & García-entem, M. (2017). Satellite sea surface temperatures along the west coast of the United States during the 2014–2016 Northeast Pacific marine heat wave. *Geophysical Research Letters*, *44*, 312–319. https://doi.org/10.1002/2016GL071039

Healey, M. C. (1982). Juvenile Pacific salmon in estuaries: The life support system. In *Estuarine Comparisons*, (pp. 315–341). https://doi.org/10.1016/B978-0-12-404070-0.50025-9

Hodal, M. (2010). Net physical transports, residence times, and new production for Rivers Inlet, British Columbia, (MSc thesis, 71 p.) University of British Columbia. https://doi.org/10.14288/1.0053224

Huang, B., Kennedy, J., Xue, Y., & Zhang, H.-M. (2018). Sea surface temperatures [in "state of the climate in 2017"]. *Bulletin of the American Meteorological Society*, *98*(8), S196–S198. https://doi.org/10.1175/2017BAMSStateoftheClimate.1

Jacox, M. G., Alexander, M. A., Mantua, N. J., Scott, J. D., Hervieux, G., Webb, R. S., & Werner, F. E. (2018). Forcing of multiyear extreme ocean temperatures that impacted California current living marine resources in 2016. *Bulletin of the American Meteorological Society*, *99*(1), S27–S33. https://doi.org/10.1175/bams-d-17-0119.1

Jacox, M. G., Hazen, E. L., Zaba, K. D., Rudnick, D. L., Edwards, C. A., Moore, A. M., & Bograd, S. J. (2016). Impacts of the 2015–2016 El Niño on the California current system: Early assessment and comparison to past events. *Geophysical Research Letters*, *43*, 7072–7080. https://doi.org/10.1002/2016GL069716

Jayne, S. R., Roemmich, D., Zilberman, N., Riser, S. C., Johnson, K. S., Johnson, G. C., & Piotrowicz, S. R. (2017). The Argo program present and future. *Oceanography*, *30*(2), 18–28. https://doi.org/10.5670/oceanog.2017.213

Johnson, G. C., Lyman, J. M., Boyer, T., Cheng, L., Domingues, C. M., Gilson, J., et al. (2018). Ocean heat content [in "State of the climate in 2017"]. *Bulletin of the American Meteorological Society*, *98*(8), Si–S280. https://doi.org/10.1175/2017BAMSStateoftheClimate.1

Jones, T., Parrish, J. K., Peterson, W. T., Bjorkstedt, E. P., Bond, N. A., Ballance, L. T., et al. (2018). Massive mortality of a planktivorous seabird in response to a marine heatwave. *Geophysical Research Letters*, *45*, 3193–3202. https://doi.org/10.1002/2017GL076164

Mackas, D. L., Batten, S., & Trudel, M. (2007). Effects on zooplankton of a warmer ocean: Recent evidence from the Northeast Pacific. *Progress in Oceanography*, *75*(2), 223–252. https://doi.org/10.1016/j.pocean.2007.08.010

10.1029/2018GL078971

Mackas, D. L., Greve, W., Edwards, M., Chiba, S., Tadokoro, K., Eloire, D., et al. (2012). Changing zooplankton seasonality in a changing ocean: Comparing time series of zooplankton phenology. *Progress in Oceanography*, *97-100*, 31–62. https://doi.org/10.1016/j.pocean.2011.11.005

McCabe, R. M., Hickey, B. M., Kudela, R. M., Lefebvre, K. A., Adams, N. G., Bill, B. D., et al. (2016). An unprecedented coastwide toxic algal bloom linked to anomalous ocean conditions. *Geophysical Research Letters*, *43*, 10,366–10,376. https://doi.org/10.1002/2016GL070023

Mckinnell, S. M., Wood, C. C., Rutherford, D. T., Hyatt, K. D., & Welch, D. W. (2001). The demise of Owikeno Lake sockeye salmon. *North American Journal of Fisheries Management*, *21*(4), 774–791. https://doi.org/10.1577/1548-8675(2001)021<0774:TDOOLS>2.0.CO;2

Meehl, G. A., Washington, W. M., Collins, W. D., Arblaster, J. M., Hu, A., Buja, L. E., et al. (2005). How much more global warming and sea level rise? *Science*, *307*(5716), 1769–1772. https://doi.org/10.1126/science.1106663

Mueter, F. J., Peterman, R. M., & Pyper, B. J. (2002). Opposite effects of ocean temperature on survival rates of 120 stocks of Pacific salmon (Oncorhynchus spp.) in northern and southern areas. *Canadian Journal of Fisheries and Aquatic Sciences*, *59*(3), 456–463. https://doi.org/10.1139/f02-020

Peterson, W. T., Fisher, J. L., Strub, P. T., Du, X., Risien, C., Peterson, J., & Shaw, C. T. (2017). The pelagic ecosystem in the Northern California Current off Oregon during the 2014–2016 warm anomalies within the context of the past 20 years. *Journal of Geophysical Research: Oceans*, *122*, 7267–7290. https://doi.org/10.1002/2017JC012952

Pickard, G. L. (1961). Oceanographic features of inlets in the British Columbia mainland coast. *Journal of the Fisheries Research Board of Canada*, *18*(6), 907–999. https://doi.org/10.1139/f61-062

Roemmich, D., & Gilson, J. (2009). The 2004–2008 mean and annual cycle of temperature, salinity, and steric height in the global ocean from the Argo program. *Progress in Oceanography*, *82*(2), 81–100. https://doi.org/10.1016/j.pocean.2009.03.004

Simenstad, C. A., Fresh, K. L., & Salo, E. O. (1982). The role of Puget Sound and Washington coastal estuaries in the life history of Pacific salmon: An unappreciated function. In *Estuarine comparisons* (pp. 343–364). https://doi.org/10.1016/B978-0-12-404070-0.50026-0