Subsurface Evolution and Persistence of Marine Heatwaves in the Northeast Pacific

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September 02, 2020

Abstract

The reappearance of a northeast Pacific marine heatwave (MHW) sounded alarms in late summer 2019 for a warming event on par with the 2013–2016 MHW known as The Blob. Despite these two events having similar magnitudes in surface warming, differences in seasonality and salinity distinguish their evolutions. We compare and contrast the ocean's role in the evolution and persistence of the 2013–2016 and 2019–2020 MHWs using mapped temperature and salinity data from Argo floats. An unusual near-surface freshwater anomaly in the Gulf of Alaska during 2019 increased the stability of the water column, preventing the MHW from penetrating as deeply as the 2013–2016 event. This freshwater anomaly likely contributed to the intensification of the MHW by increasing the near-surface buoyancy. The gradual buildup of subsurface heat content throughout 2020 in the region suggests the potential for persistent ecological impacts.







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Key Points :

- Return of The Blob, with warming and freshening, hence more buoyancy.
- Summertime heatwaves, increase stratification, inhibit mixing.
- Wintertime mixing, warming penetrates the deep, provides memory.

1 Abstract

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3 summer 2019 for a warming event on par with the 2013–2016 MHW known as The Blob.

4 Despite these two events having similar magnitudes in surface warming, differences in

5 seasonality and salinity distinguish their evolutions. We compare and contrast the ocean's role in

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8 the Gulf of Alaska during 2019 increased the stability of the water column, preventing the MHW

9 from penetrating as deeply as the 2013–2016 event. This freshwater anomaly likely contributed

10 to the intensification of the MHW by increasing the near-surface buoyancy. The gradual buildup

11 of subsurface heat content throughout 2020 in the region suggests the potential for persistent

- 12 ecological impacts.
- 13

14 Plain Language Summary

Surface marine heatwaves (MHWs) are periods of prolonged and extremely warm regional sea
 surface temperature that can negatively impact the health and productivity of marine ecosystems.

17 Using surface and subsurface ocean observations, we compare and contrast two recent MHWs to

18 show that salinity variations play an important role in the vertical distribution of temperature

anomalies by changing the overall stability of the water column. During the 2019–2020 MHW,

20 the near-surface waters in the Gulf of Alaska were fresher than normal, preventing warm sea

21 surface temperatures from mixing as deeply into the subsurface as in the 2013–2016 MHW. The

22 freshening in 2019 likely enhanced warming in the buoyant surface layer. As warmer

23 temperatures gradually mix downward they can persist long after the surface MHW disappears,

suggesting that the ocean can provide memory for long-lived MHWs. The subsurface persistence

25 of MHWs has potential ramifications for long-lasting ecological impacts.

26

27 **1 Introduction**

28 Marine heatwaves (MHWs) have become distinguishable features of northeast (NE) Pacific

29 Ocean temperature variability that disrupt the productivity of marine ecosystems and their

30 services (Smale et al., 2019). These prolonged, discrete, and anomalously warm water events

31 (Hobday et al., 2016) are most recognizable at the sea surface and are influenced by

32 anthropogenic warming (Laufkötter, et al., 2020). The effects of long-term ocean warming have 33 led to a near-doubling in the average annual count of MHW days globally since the early 20th 34 Century (Oliver et al., 2018). Although MHWs have occurred throughout the global ocean, the 35 NE Pacific has recently emerged as a hotspot for extremely persistent and large-scale events that 36 are forced by anomalous air-sea heat flux driven by remote forcing from the tropics (Di Lorenzo 37 and Mantua, 2016; Holbrook et al., 2019), in addition to long-term warming from anthropogenic 38 greenhouse forcing (Laufkötter, et al., 2020). The most remarkable NE Pacific MHWs have 39 occurred in 2013–2016 and 2019–2020, and are colloquially referred to as The Blob (Bond et al., 40 2015) and Blob2.0 (Amaya et al., 2020) respectively (Figure 1 and Figure S1).

41

42 The magnitude of sea surface temperature (SST) anomalies associated with MHWs depends 43 critically on the seasonal evolution of the mixed-layer depth (MLD), which deepens in winter 44 and shoals in summer. If winter mixed layer MHW anomalies are present in the early spring 45 when the NE Pacific MLD shoals, they can become trapped in the subsurface during the summer 46 through detrainment. These detrained temperature anomalies are then stored in the subsurface 47 and can reemerge the following winter when the MLD deepens and re-entrains them (Alexander 48 and Deser, 1995; Alexander et al, 1999; Alexander et al., 2001). Alternatively, in the presence of 49 downward Ekman pumping from wind stress curl, for example in the North Pacific subtropical 50 gyre, detrained anomalies can subduct, where they are further isolated from the mixed layer (Qiu 51 and Huang, 1995). Here, we explore the role of detrainment and subduction in the sequestration 52 of MHW anomalies into the permanent pychocline where they can persist for years.

53

54 The evolution of the 2013–2016 NE Pacific MHW was complex and shaped by multiple drivers. 55 Warm SST anomalies first appeared in the southern Gulf of Alaska centered on 40°N and 150°W 56 and subsequently propagated towards the coast and south into the Southern California Current 57 System near 25°N. In the Gulf of Alaska, lower rates of turbulent heat loss during the winter of 58 2013–2014 from the ocean to atmosphere and a reduction in wind-generated stirring allowed the 59 winter mixed layer to remain unseasonably warm and shallow (Bond et al., 2015). The MWH 60 moved to the south owing to local positive downward shortwave radiation anomalies and a 61 positive SST-cloud feedback over the Southern California Current System that reinforced surface 62 warming near the coast in 2014 (Zaba and Rudnick, 2016; Myers et al., 2018; Schmeisser et al.,

2019). Below the mixed layer, anomalously warm and salty water was detrained to denser and
deeper isopycnals, reaching depths of 140 m beginning in 2014 (Jackson et al., 2018). These
subsurface anomalies lingered through at least 2018, long after the initial onset of atmospheric
forcing in late 2013.

67

68 A similar situation played out during the summer of 2019 when a resurgence of Blob-like surface 69 conditions intensified in the NE Pacific. Weakened surface wind speeds, driven by atmospheric 70 teleconnections associated with SST anomalies in the Tropical Pacific, resulted in reduced evaporative heat loss from the ocean to atmosphere and limited wind-driven mixing, resulting in 71 72 a MHW off the U.S. West Coast (Amaya et al., 2020). Increased shortwave radiation and a 73 positive SST-cloud feedback helped to maintain the MHW over an exceptionally shallow 74 summertime mixed layer (Amaya et al., 2020). Here, we show evidence for the role of salinity 75 anomalies in increasing upper ocean stability, and describe the propagation and persistence of the 76 2019–2020 NE Pacific MHW in the subsurface.

77

78 In this study, we examine the connections between surface MHWs and the subsurface structure 79 of temperature, salinity, and density by analyzing objectively mapped monthly Argo data in the 80 NE Pacific, comparing and contrasting the 2013–2016 and 2019–2020 MHWs. We characterize 81 the spatiotemporal evolution of anomalous subsurface conditions and their connection to mixed 82 layer properties from January 2004 through June 2020, and we quantify the change in water mass 83 properties and ocean heat content anomalies within and below the mixed layer. Understanding 84 the subsurface evolution and persistence of MHWs gives insight into the potential predictability 85 and reemergence of these events in the future, where a trend towards shallower summertime 86 MLDs is expected to increase the likelihood and intensity of MHWs in the North Pacific (D.J. 87 Amaya, personal communication, 2020). The persistence and potential reoccurrence of MHWs 88 could result in long-lasting impacts on the health of marine ecosystems, especially in the subsurface where the effects of warming on marine life (i.e., thermal stress) can persist for years 89 90 (Cavole et al., 2016).

- 91
- 92 **2 Data**

93 We analyze monthly mean SST maps from the Optimum Interpolation SST version 2 (OISSTv2)

94 dataset on a 0.25° longitude by 0.25° latitude global grid from 1982 through present (Reynolds et

95 al., 2002; 2007). These SST maps are generated from a blend of satellite (Advanced Very High

96 Resolution Radiometer only), ship, buoy (both moored and drifting), and Argo float data. The

97 satellite data are interpolated to fill gaps and are bias corrected with reference to buoys to

98 account for platform differences. We use the OISSTv2 dataset as it incorporates *in situ*

99 observations, offers complete global coverage, and spans almost 40 years.

100

We also analyze monthly mean fields from January 2004 through June 2020 from the updated 101 102 Roemmich-Gilson Argo Climatology (Roemmich and Gilson, 2009; hereafter RG09) to examine 103 the vertical structure of temperature, salinity, and density anomalies associated with MHWs. 104 Argo is a global network of autonomous profiling floats that continuously measures the 105 temperature and salinity of the upper 2,000 m of the ocean. The Argo program began in 1999 106 and now consists of over 3,800 active floats and more than 2 million hydrographic profiles 107 reported thanks to a coordinated effort from dozens of countries worldwide (Jayne et al., 2017). 108 Archived and near real-time float data are made publicly available (http://sio-109 argo.ucsd.edu/RG Climatology.html) and are incorporated into monthly maps on a 1° longitude 110 by 1° latitude grid beginning in January 2004 when the global array had at least 1,000 floats and 111 first approached sparse global coverage (RG09). These maps are made in 58 pressure layers with 112 the shallowest centered on 2.5 dbar and the deepest on 1,975 dbar, with finer resolution near the 113 surface (e.g., spaced 10 dbar apart from 10 to 170 dbar). The 2.5 dbar monthly temperature 114 anomalies in RG09 closely track the monthly OISSTv2 anomalies in the NE Pacific, capturing 115 large scale spatial and temporal variability. 116

117 In addition to the mapped temperature and salinity vs. pressure fields from RG09, we also

analyze 19,697 quality-controlled Argo profiles in the NE Pacific (35.5–51.5°N, 135.5–

119 154.5°W; box in Figure 1) to compute the MLD from January 2004 through June 2020 using the

120 density algorithm of Holte and Talley (2009). The sampling frequency from Argo in the NE

121 Pacific (35.5–51.5°N, 135.5–154.5°W) steadily increases from the early 2000s, achieving over

122 1,000 profiles per year starting in 2012 (Figure S2). These profiles were downloaded from one of

the two Argo Global Data Assembly Centers (https://nrlgodae1.nrlmry.navy.mil/argo/argo.html)
in August 2020.

125

126 3 Analysis

We define MHWs locally when SST exceeds the monthly climatological 90th percentile for at least a month using monthly data from January 2004 through June 2020. Our definition for MHWs is similar to that proposed in Hobday et al. (2016) with modifications in the length of the climatological period and in the minimum event duration. Owing to the prominence and persistence of the 2013–2016 and 2019–2020 MHWs, our definition highlights the same largescale features described in previous studies using daily data (e.g., Gentemann et al., 2017; Fewings and Brown, 2019).

134

135 Before analyzing the RG09 dataset, we fit temperature and salinity at each spatial point to the 136 mean, trend, annual, and semiannual harmonics using least squares regression from January 2004 137 through June 2020. We then remove the mean, annual, and semi-annual harmonics (but not the trend) to generate anomalies. Following MHW conventions (e.g., Hobday et al., 2016), we 138 139 choose to retain the warming trend in the analysis using a fixed climatology computed over the 140 entire record. Furthermore, the trend would not be accurately estimated over such a short period 141 and would be extremely biased by the 2013-2016 and 2019-2020 MHWs at one end of the time-142 series. Finally, detrending would effectively remove part of the strong MHW signal that we 143 observe towards the latter end of the record. We therefore retain it. Next, we smooth the 144 anomalies and the regression coefficients with a 5-month Hanning filter and then a 6° latitude x 145 6° longitude LOESS filter to reduce mesoscale signals that are retained in the RG09 maps. We 146 then reconstruct the total smoothed *in-situ* temperature and practical salinity maps using the 147 smoothed anomalies and smoothed model coefficients. We apply the thermodynamic equation of 148 seawater (Intergovernmental Oceanographic Commission et al., 2010) to compute the absolute salinity (S_A) and conservative temperature (Θ) at each space and time grid point. Using S_A and Θ , 149 150 we also compute the potential density anomaly (σ_{θ}) with reference to 0 dbar; expressed as a 151 particular potential density minus 1000 kg m⁻³. The potential density represents the density a 152 fluid parcel would acquire if it were brought adiabatically to the sea surface, thus eliminating the density dependence on pressure. We also map the RG09 fields of S_A , Θ , and pressure (P) to a 153

154 vertical density coordinate, σ_{θ} . We compute anomalies in S_A , Θ , and P in σ_{θ} coordinates, as well 155 as S_A , Θ , and σ_{θ} in P coordinates, by removing the monthly means of these quantities across the 156 entire 198-month time series at each spatial point and for each vertical coordinate system (σ_{θ} and 157 P) to get the anomalies. We describe changes in S_A , Θ , and P on an isopycnal (25.4 kg m⁻³) that 158 may outcrop during winter. When isopycnals outcrop their properties are easily modified through 159 air-sea interactions that may drive surface MHWs. Once isopycnals subduct below the mixed 160 layer, their properties are only modified through mixing, which is usually less effective than

161 direct air-sea heat and freshwater exchange.

162

163 We examine the ocean heat content anomaly (Q') within the mixed layer (10–90 dbar),

164 thermocline (100–180 dbar), and just below the thermocline (200–280 dbar). These layers of

165 equal thickness are chosen based on the vertical profiles of subsurface temperature in the NE

166 Pacific (Figure 4b). They typify the surface, pycnocline, and interior ocean in the region,

167 allowing for the distinction of the changes in Q' with depth. We define $Q' = \int \frac{1}{\sigma} \cdot c_p \cdot \Theta' dp$,

168 where $g = 9.8 \text{ ms}^{-2}$ is the acceleration due to gravity, $c_p = 3991.8680 \text{ J kg}^{-1}\text{K}^{-1}$ is the

169 standard specific heat of seawater when using Θ , Θ' is the conservative temperature anomaly,

170 and $\int dp$ is the integral over each of these three 80-dbar thick layers.

171

We apply the Holt and Talley (2009) density algorithm to 19,697 Argo float profiles in the NE
Pacific (35.5–51.5°N, 135.5–154.5°W; box in Figure 1) to estimate monthly MLDs from January
2004 through June 2020. This method searches for the depth at which the density increases by
0.03 kg m⁻³ relative to a near-surface reference level.

176

177 We quantify the bulk stratification of the upper ocean using the Brunt-Väisälä frequency squared 178 $N^2 = -\frac{g}{\rho} \frac{d\rho}{dz}$. Here, $\frac{d\rho}{dz}$ is the change in potential density with reference to 0 dbar between 2.5 and 179 200 dbar. Larger values of N² correspond to greater upper ocean stratification — a more stable 180 water column. We compute anomalies in N², again with respect to monthly long-term means, to 181 quantify the change in the stratification of the upper ocean due to MHW variations in both Θ and 182 S_A.

- 184 To further examine the relationships among Θ , S_A, and σ_{θ} , we examine ΘS_A diagrams with
- 185 contours of constant density and spice to show changes in water-mass properties between
- 186 different MHW years in the NE Pacific. ΘS_A variations along isopycnals can be quantified by
- 187 spice (Munk, 1981), where warm/salty anomalies are spicy and cool/fresh anomalies are minty.
- 188 We compute spice following McDougall and Krzysik (2015) using a potential density with
- 189 reference to 0 dbar. Isopycnal variations in spiciness can be used to describe MHW impacts on
- 190 isopycnal water-mass properties in density units.
- 191

192 **4 Results**

193 Anomalies in $\Theta - S_A$ on isopycnals can be tracked following the surface evolution of SST 194 anomalies during MHWs, and can either be warm/salty (spicy) or cool/fresh (minty), such that 195 the density of that isopycnal does not change (Movie S1). The winter-intensified 2013–2016 MHW had spicy anomalies on 25.4 kg m⁻³, which lagged the spatiotemporal evolution of SST 196 197 anomalies within the MHW (Movie S1, hatching in Figure 1). For example, surface MHW 198 conditions moved onshore by late 2014 and began to fade as early as 2015, whereas subsurface 199 spice anomalies did not reach the coast until winter 2015 and persisted into 2016 (Movie S1). By 200 comparison, summer $\Theta - S_A$ anomalies in 2019 lacked the advective nature of the 2013–2016 MHW, yet they were much more widespread. Minty anomalies on 25.4 kg m⁻³ encompassed 201 202 nearly the entire Gulf of Alaska from late summer 2018 through summer 2020, while spicy 203 anomalies lingered off the coast between Baja California and Hawai'i (Figure 1, Movie S1). 204



205

Figure 1. Spatial characteristics of NE Pacific MHWs during January 2014 (a-c) and November
 2019 (d-f); the two warmest months of SST anomalies averaged in the boxed region from 2004

208 through 2020. First column (a,d) shows SST anomalies from the OISSTv2 where diagonal

- 209 hatching indicates the locations experiencing a MHW. Hatching across columns is consistent.
- 210 The middle column (b,d) is the absolute salinity anomaly on 25.4 kg m⁻³. By definition,
- 211 conservative temperature anomalies mirror salinity anomalies on isopycnals where conditions are
- 212 either warm/salty or cool/fresh. The third column (c,f) shows the bulk upper ocean stability
- anomaly in terms of the Brunt-Väisälä frequency squared computed using the anomalous density
- difference between 2.5 and 200 dbar. All anomalies are referenced to the January 2004 through
- 215 June 2020 monthly climatology. The bounding black box represents the area defined by 35.5–
- 216 51.5°N, 135.5–154.5°W and the lime green circles in (b) and (c) mark 43.5°N, 145.5°W. Gray
- shading in panels b, c, e, and f (excluding land) shows the locations where 25.4 kg m⁻³ outcrops
- 218 in January 2014 (b,c) and November 2019 (e,f).
- 219

220 Positive stratification (N^2) anomalies occurred for both the 2013–2016 and 2019–2020 MHWs,

- however they were much greater in 2019 (Figure 1, Movie S1). Warm and fresh near-surface
- anomalies in 2019 decreased density and increased the stratification (Figure 2), whereas in 2013–

223 2016 the near-surface density reduction from a warm anomaly was partially offset by a salty

- anomaly. The increase in pressure along 25.4 kg m⁻³ beginning in 2018 reflects an increase in
- stratification even before the onset of the 2019 MHW (Figure 2). The 2019 large and positive
- stratification anomaly likely inhibited the surface MHW from penetrating as deeply as the 2013–
- 227 2016 MHW, and furthermore may have enhanced the surface build-up of heat.
- 228

229 Prior to 2013, two other noteworthy MHWs occurred in the NE Pacific from 2004–2005 and

230 2008–2009 (Figure 2). Warm subsurface Θ anomalies during these MHWs extended and

propagated to depths beyond 100 dbar and anomalies at 25.4 kg m⁻³ were spicy, similar to that of

the 2013–2016 event (Figure 2). Warm and salty anomalies reduced subsurface density and

- 233 increased the stratification of the surface layer. The 2004–2005 MHW was more stratified than
- the 2008-2009 event owing to the larger surface density anomaly (Figure 2e and Figure 5b-c).
- 235
- The simultaneous change in temperature from 0–200 dbar in 2008–2009 could have resulted
- from isopycnal heave, as indicated by the downward deflection of 26.3 kg m⁻³ (Figure 2a). Heave
- 238 can occur in response to Ekman pumping due to wind stress curl that depresses the main

- thermocline (Bindoff and McDougall, 1994), or from other dynamic features such as large-scale
- 240 Rossby waves (Xie et al., 2016) or eddies (Pegliasco et al., 2015). Positive pressure anomalies on
- 241 26 kg m⁻³ indicates a deepening of the thermocline in 2008–2009 at approximately 130 dbar
- 242 (Figure 2f). These vertical isopycnal motions are nearly adiabatic. As seen from the conservation
- of water mass properties on the isopycnal (Figure 2b,d), there is little exchange of heat or salinity
- 244 with the surrounding environment. As a result, warm and fresh anomalies in 2008–2009 occurred
- along the 150–200 isobars, however, were negligible on 26.3 kg m⁻³, which ranges from 150–200
- dbar (Figure 2).



Figure 2. Progression of monthly anomalies in (a,b) conservative temperature, (c,d) absolute salinity, (e) potential density, and (f) isopycnal pressures at 43.5°N, 145.5°W (lime green circles in Figure 1) from January 2004 through June 2020. Contours of the 25.4 kg m⁻³ (upper dashed), 25.7 kg m⁻³ (upper solid), 26 kg m⁻³ (lower dashed), and 26.3 kg m⁻³ (lower solid) isopycnal surfaces vary with pressure (a,c,e), however are constant when plotted against density (b,d,f).

- 254 Analysis of ΘS_A relationships along isopycnals provides additional insight into water-mass
- 255 property changes during MHWs. Here, spice is primarily controlled by the exchange of heat and
- 256 freshwater between the ocean and atmosphere, ocean turbulent mixing, and lateral advection.
- 257 Spicy conditions occurred each winter (December-January-February) during the 2013–2016
- MHW, most notably in waters lighter than 26.5 kg m⁻³ during the winters of 2014/15 and





Figure 3. Winter (December-January-February) (a) and summer (June-July-August) (b)
temperature-salinity relationships at 43.5°N, 145.5°W (lime green circles in Figure 1). The
average 2004–2019 DJF and 2004–2019 JJA curves are shown by the thick black lines. Contours
of constant spice (kg m⁻³) in green are perpendicular to isopycnals in gray.



- and subsurface ΘS_A anomalies increase with positive lag and density between 25.7–27 kg m⁻³.
- For example, the maximum cross-correlation on 26.3 kg m⁻³ occurs at 6 months positive lag
- 283 (Figure S3). On the other hand, subsurface anomalies (between 150–220 dbar) are most strongly
- correlated with the surface conditions for positive lags of 1–2 years, while subsurface SA
- correlations peak at 6–12 months positive lags (Figure S3 and Figure S4).

287 The downward progression of surface Θ and S_A anomalies suggest that the North Pacific Ocean 288 is capable of maintaining long-term memory of surface MHWs. One measure of memory is the 289 heat content anomaly, Q', evaluated here over equal thickness subsurface layers. The largest Q' 290 values occur within the seasonally varying mixed layer (10-90 dbar) where temperature 291 fluctuations are the strongest (Figure 4). The largest positive anomalies are present during the 292 2013–2016 MHW. After a period of strong cooling, Q' steadily increased beginning in 2018 293 through present. Prior to 2013 there were two smaller MHWs that occurred in 2004-2005 and 294 2008–2009 that also had small gains of heat content. Evaluating Q' over layers spanning the 295 pycnocline (100–180 dbar) and interior (200–280 dbar) reveals the persistence of Θ anomalies below the surface temperature variability. Once $\Theta - S_A$ anomalies get into the subsurface, their 296 297 properties are nearly conserved even after the surface cools (Figure 4).



300 Figure 4. Variations in (a) upper ocean heat content anomalies, (b) temperature anomalies and

- 301 mixed layer pressure, and (c) upper ocean stratification anomalies averaged in 35.5–51.5°N,
- 302 135.5–154.5°W (black outline in Figure 1). Ocean heat content anomalies are computed over
- three different 80-dbar pressure layers between 10–90 dbar, 100–180 dbar, and 200–280 dbar.
- 304 These intervals are shown in (b) as vertical colored lines on the right-hand side corresponding to
- 305 (a). The mixed layer pressure and 2004-2019 climatology is computed from 19,697 Argo profiles
- 306 using the Holt and Talley (2009) density algorithm. The bulk upper ocean stratification anomaly
- 307 (solid lines) in (c) is computed as N^2 between 2.5 and 200 dbar and shown with the SST
- anomaly (dashed lines). Positive values of N^2 indicate higher water column stability and greater
- 309 resistance to overturning or vertical displacement.
- 310

311 An increase in upper ocean heat content can affect the stability of the upper ocean. The depth of 312 the mixed layer also shoals, which can be seen during the winters of 2013/2014 and 2014/2015 313 (Figure 4). The increase in stratification reduces entrainment of cool water from below and can 314 exacerbate warming by reducing the thickness of the surface layer that accepts heat from the 315 atmosphere, making the surface ocean easier to warm. The upper ocean stratification anomaly 316 was noticeably higher (large N² anomaly values) in 2014–2015, with the largest values occurring 317 in 2019 (Figure 4c). The very high values in 2019–2020 arise from the anomalously fresh near-318 surface conditions during that MHW.

319

320 **5 Discussion**

321 This study examines 21st Century MHWs in the NE Pacific based on gridded SST data, and also the evolution of subsurface $\Theta - S_A$ anomalies from Argo on both isobars and isopycnals during 322 323 the 2013–2016 and 2019–2020 NE Pacific MHWs. Upper ocean salinity was anomalously fresh 324 in the Gulf of Alaska during the 2019–2020 MHW, which greatly increased the buoyancy of the 325 surface layer. Indeed, there was a net freshwater input from precipitation as can be seen in the 326 2018 precipitation anomaly in the Gulf of Alaska (Yu et al., 2019) that likely contributed to the 327 decrease in surface salinity (Reagan et al., 2019). The resulting increase in stratification during 328 2019–2020 likely contributed to the decrease in the depth (and density) to which water property 329 anomalies from this event were detrained, and in places subducted. The confinement of warm 330 anomalies to the near-surface likely enhanced the MHW's intensity.

332 There are several dynamical pathways by which surface MHW anomalies in the NE Pacific 333 could reach the subsurface; by means of detrainment, diabatic subduction (Jackson et al., 2018), 334 lateral advection (Chao et al., 2017; Zaba et al., 2020), and/or adiabatic isopycnal heave. 335 Subduction occurs in subtropical regions after temperature anomalies within the deep wintertime 336 mixed layer detrain as a result of the mixed layer retreating in late spring. During the 2014 and 337 2015 spring transition of the mixed layer depth, subsurface warming occurred along both 338 isopycnals and isobars below the mixed layer, suggesting that diabatic vertical or horizontal 339 mixing could play a role in the penetration of MHW anomalies within the seasonal pycnocline. 340 Indeed, Zaba et al. (2020) attribute positive subsurface heat content anomalies within the 341 California Undercurrent to an increase in poleward heat transport from the tropics in September 342 2015. Alternatively, subsurface warming that occurs primarily on isobars and not on isopycnals 343 was likely the result of isopycnal heave, defined as the downward deflection of a potential 344 density surface. We speculate that heave is most likely responsible for the near-simultaneous 345 appearance of anomalies below 150 dbar, for example during the 2008–2009 MHW, however the 346 exact mechanisms of heave (i.e., from Ekman pumping due to wind stress curl) are not 347 investigated here.

348

349 Once surface MHW anomalies are detrained out of the deep wintertime mixed layer, they may 350 propagate downward. The lag associated with the vertical propagation of surface anomalies 351 causes the subsurface heat content to remain anomalously high even after surface conditions 352 return to normal. This persistence of subsurface heat and the possible seasonal reemergence of 353 surface anomalies could in fact help supercharge the occurrence of multi-year events. As future 354 warming trends favor a more stratified upper ocean (Li et al., 2020), we expect that detrainment 355 out of the mixed layer may become less effective in storing MHW anomalies in the subsurface, 356 and therefore further amplify surface warming. This possibility is concerning owing to the 357 impacts that accumulated heat stress and stratification have on pelagic marine ecosystems and 358 primary production (Cavole et al., 2016; Jacox et al., 2016; Smale et al, 2019).

359

Mixed layer heat budgets are frequently used to diagnose the drivers of surface warming
 associated with MHWs; however, the influence of salinity and subsurface water mass properties

are often overlooked (Holbrook et al., 2020). Using the global Argo array data, this study motivates complementary analyses on the role of salinity and subsurface $\Theta - S_A$ anomalies to better understand the ocean's role in the persistence and evolution of long-lived events. Further investigation into the drivers of salinity anomalies and their role in the development of NE Pacific MHWs would appear to be a fruitful avenue of future research. Analysis of the full 4-D heat budget using high resolution numerical models could be undertaken to investigate the local mechanisms of subsurface warming.

369

370 Acknowledgments and Data Availability

371 HAS and LT are supported by an AI for Earth Innovation Grant sponsored by the Leonardo

372 DiCaprio Foundation and Microsoft, and wish to acknowledge cloud resources from an Azure

373 compute grant awarded through Microsoft's AI for Earth. GCJ and JML are supported by NOAA

374 Research and NOAA's Global Ocean Monitoring and Observing Program. HAS and SCR were

also partially supported by NOAA via grant NA15OAR4320063 to the University of Washington

376 through the Joint Institute for the Study of the Atmosphere and Ocean. This is PMEL

377 Contribution Number 5140. The NOAA OISSTv2 dataset was provided by the

378 NOAA/OAR/ESRL PSL, Boulder, Colorado, USA, from their Web site at <u>https://psl.noaa.gov/</u>.

379 Argo data were collected and made freely available by the International Argo Program and the

380 national programs that contribute to it (<u>http://www.argo.ucsd.edu</u> and <u>http://argo.jcommops.org</u>).

381 The Argo Program is part of the Global Ocean Observing System. Lastly, we would like to thank

382 two anonymous reviewers whose comments helped to improve this manuscript.

383

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Supporting Information for

Subsurface evolution and persistence of marine heatwaves in the Northeast Pacific

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Introduction

Additional figures and animations are provided to support the primary findings of the analysis and further visualize the spatiotemporal evolution of subsurface marine heatwave anomalies. We also include the availability of Argo mixed layer depths over time in the Northeast Pacific study domain.



Figure S1. Subsurface evolution and vertical structure of (a) conservative temperature, (b) absolute salinity, and (c) potential density anomalies in the Northeast Pacific vs time (January 2004 through June 2020), pressure (2.5 to 150 dbar) and longitude (164.5–127.5 °W) at 44.5 °N; see map inset. The objectively mapped Roemmich-Gilson Argo Climatology is used (Roemmich and Gilson, 2009). Anomalies are computed with respect to the January 2004 through June 2020 monthly means.



Figure S2. Number of Argo float profiles in the NE Pacific (35.5–51.5°N, 135.5–154.5°W; blue boxed region in map inset). Years shaded in gray are used in this analysis and overlap with the Roemmich-Gilson Argo Climatology. We use 19,697 profiles from January 2004 through June 2020. An illustration of a core Argo float is shown measuring 1.3 m in height, 20 cm wide, and approximately 40 kg in weight. These autonomous floats profile the upper 2,000 m on 10-day intervals and measure ambient seawater salinity, temperature, and pressure. The schematic of an Argo float is provided by the Argo Program (https://www.argo.ucsd.edu).



Figure S3. Lagged cross correlation between conservative temperature anomalies at (a) 2.5 dbar and (b) 25.7 kg m⁻³ with subsurface isobars (2.5–440 dbar) and isopycnals (25.7–27.0 kg m⁻³) respectively. Anomalies are averaged within $35.5-51.5^{\circ}$ N, $135.5-154.5^{\circ}$ W (boxed outline in Figure 1). Cross correlation is computed as the Pearson's r-value ranging from -1.0 to +1.0, with larger absolute values indicating higher correlation. Cross hatching indicates insignificant correlations (p-value >= 0.05) and black circles indicate the highest positive correlation for each isobar (a) and isopycnal (b).



Figure S4. Lagged cross correlation between absolute salinity anomalies at (a) 2.5 dbar and (b) 25.7 kg m⁻³ with subsurface isobars (2.5–440 dbar) and isopycnal (25.7–27.0 kg m⁻³) respectively. Anomalies are averaged within $35.5-51.5^{\circ}N$, $135.5-154.5^{\circ}W$ (boxed outline in Figure 1). Cross correlation is computed as the Pearson's r-value ranging from -1.0 to +1.0, with larger absolute values indicating higher correlation. Cross hatching indicates insignificant correlations (p-value >= 0.05) and black circles indicate the highest positive correlation for each isobar (a) and isopycnal (b).

Movie S1. Evolution of monthly (a) sea surface temperature anomalies, (b) absolute salinity on the 25.4 kg m⁻³ isopycnal, and (c) stratification anomaly between 2.5 and 200 dbars in the Northeast Pacific marine heatwave. Contours in (c) show the pressure of the 25.4 kg m⁻³ isopycnal. Sea surface temperature anomalies are from the OISSTv2 where diagonal hatching indicates the locations experiencing a marine heatwave defined when the sea surface temperature exceeds the local monthly 90th percentile averaged. Hatching over absolute salinity is consistent with (a) showing the presence of marine heatwaves in sea surface temperature. All anomalies are referenced to the January 2004 through June 2020 monthly climatology.

Movie S2. Same as in Movie S1 except on the 25.7 kg m⁻³ isopycnal.