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Key Points:
- Anomalous atmospheric forcing in the NE Pacific in winter 2013–2014
- Weak seasonal cooling due to reduced heat fluxes and anomalous advection
- SST anomalies have impacts on the ecosystem and air temperatures

Supporting Information:
- Figures S1 and S2
- Figure S1
- Figure S2

Correspondence to:
N. A. Bond,
nab3met@u.washington.edu

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Causes and impacts of the 2014 warm anomaly in the NE Pacific

Nicholas A. Bond[1], Meghan F. Cronin[2], Howard Freeland[3], and Nathan Mantua[4]

[1]Joint Institute for the Study of the Atmosphere and Ocean, University of Washington, Seattle, Washington, USA, [2]Pacific Marine Environmental Laboratory, NOAA, Seattle, Washington, USA, [3]Department of Fisheries and Oceans, Institute of Ocean Sciences, North Saanich, British Columbia, Canada, [4]Southwest Fisheries Science Center, NOAA, Santa Cruz, California, USA

Abstract Strongly positive temperature anomalies developed in the NE Pacific Ocean during the boreal winter of 2013–2014. Based on a mixed layer temperature budget, these anomalies were caused by lower than normal rates of the loss of heat from the ocean to the atmosphere and of relatively weak cold advection in the upper ocean. Both of these mechanisms can be attributed to an unusually strong and persistent weather pattern featuring much higher than normal sea level pressure over the waters of interest. This anomaly was the greatest observed in this region since at least the 1980s. The region of warm sea surface temperature anomalies subsequently expanded and reached coastal waters in spring and summer 2014. Impacts on fisheries and regional weather are discussed. It is found that sea surface temperature anomalies in this region affect air temperatures downwind in Washington state.

1. Introduction

Offshore sea surface temperatures (SSTs) in the NE Pacific were remarkably warm during the winter of 2013–2014. By February 2014, peak temperature anomalies of the near-surface (upper ~100 m) waters were greater than 2.5°C (Figures 1a–1c), while temperature anomalies were below normal in the immediate vicinity of the coast. The largest anomalies exceeded 3 standard deviations (Figure 1c and Figure S1 in the supporting information), and were the greatest observed in this region for the month of February since at least the 1980s and possibly as early as 1900. The warm anomaly in winter was most prominent in the south central part of the Gulf of Alaska but extended to the continental shelf. By May 2014 the region of anomalously warm SST extended into the coastal zone, and anomalously warm SSTs persisted throughout the NE Pacific Ocean through March 2015. In recognition of its extensive and extraordinary magnitude and its potential for impacting both the regional weather and fisheries, the lead author referred to the anomaly as "The Blob" in his 3 June 2014 newsletter for the Office of the Washington State Climatologist, and it has since taken on this moniker in the general press.

The development of extraordinarily warm SST anomalies in winter 2014 is linked to a highly anomalous weather pattern, as characterized by the distribution of anomalous sea level pressure (SLP). During the period of October 2013 through January 2014, much higher than normal SLP was present in the mean over the eastern North Pacific (Figure 2), with a peak magnitude approaching 10 hPa. For the region of 55–45°N and 150–130°W, this was a record high value for the years of 1949–2014 (about 2.6 standard deviations above normal for the period of October through January) with the next largest value being about 2.2 standardized units above normal during October 1978 to January 1979. A similar pattern of anomalous SLP occurred during January through March of 2013, accompanied by anomalous warming that lasted into the summer of 2013 (Figure 1c). Our focus here is on the winter of 2013–2014 because it was so extreme, as illustrated by the time series shown in Figure 1c.

As we will show, the unusually high SLP in the region of interest impacted the wind-forced currents and wind-generated mixing, as well as the surface heat loss due to the combination of evaporation, conduction, and net shortwave (solar) and infrared radiation. The objectives of the present paper are twofold: (1) to diagnose the mechanisms that caused the wintertime warming in the NE Pacific (NEP) and (2) to examine implications of this type of anomaly for the ecosystem in the Gulf of Alaska and for seasonal weather in the Pacific Northwest.

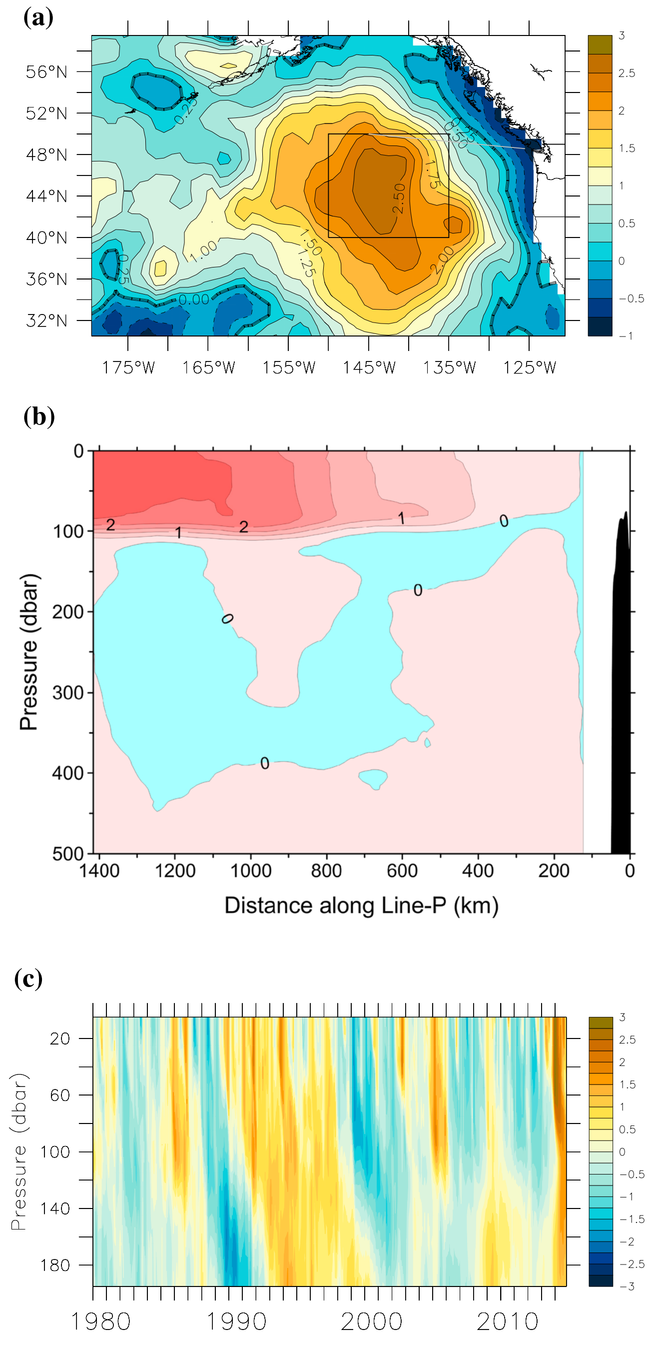

Figure 1. (a) Sea surface temperature anomalies (°C) in NE Pacific Ocean for February 2014. Anomalies are calculated relative to the mean from 1981 to 2010. (b) Upper ocean temperature anomalies (°C) along "Line P" (heavy gray line shown in part a) from 48°34.5N, 125°30.0°W to 50°145°W for February 2014. Anomalies are relative to the mean from 1956–1991. (c) Monthly temperature anomalies (normalized) from the surface to 200 m averaged over the area of 50 to 40°N, 150 to 135°W (indicated by the box shown in part a) for the period of January 1980 through November 2014.

2. Data and Methods

Our analysis of the processes responsible for the wintertime warming in the region of interest in the NE Pacific is based on data from the National Centers for Environmental Prediction (NCEP) Global Ocean Data Assimilation System (GODAS) for the period of 1980 to early 2014, as available at http://www.esrl.noaa.gov/psd/data/gridded/data.godas.html. This system is based on the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model (MOM v.3) numerical ocean model with assimilation of ocean profile information from expendable bathy thermographs, moored buoys and Argo profiling floats, and surface fluxes from the NCEP Reanalysis 2. For more information on GODAS, see *Behringer and Xue* [2004] and *Behringer* [2007].

We consider the heating of a volume bounded by 40°N and 50°N, 150°W and 135°W, and the air-sea interface to the depth where the density is 1.0 kg m^{-3} greater than at the surface for the upper and lower boundaries. The depth defined by the bottom boundary condition here is often referred to as the "mixed layer depth," above which the waters are generally mixed and similar in properties to those found at the sea surface. We use a density-based definition for the mixed layer to account for the potential effects of salinity on the stratification. The value of 1.0 kg m^{-3} is based on inspection of density profiles from GODAS for the region of interest. This value is greater than the value of 0.03 kg m^{-3} used by *de Boyer Montegut et al.* [2004] because of the substantial smoothing of the vertical gradients in density accompanying the monthly-averaged data used in our analysis.

3. Results

Here we use time series of 4 month (October–January) mean values for a variety of quantities for the region of 40–50°N, 150–135°W to put 2013–2014 in historical context. From the atmospheric forcing perspective, we

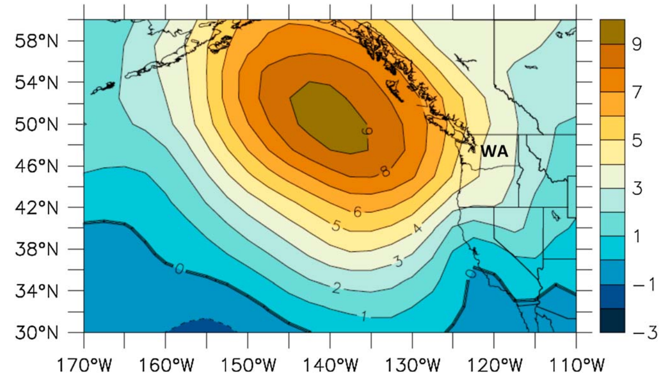

Figure 2. Mean sea level pressure anomalies (hPa) in the NE Pacific Ocean for the period of October 2013 through January 2014. Anomalies are calculated relative to the mean from 1981 to 2010.

consider the wind speed cubed, which relates to the power delivered by the atmosphere to the ocean for turbulent mixing, and the wind stress curl, which relates to the flux of vorticity to the upper ocean (Figure 3, top). The wind speed cubed was a record minimum during 2013–2014 and the wind stress curl was negative, which has precedence but is still quite unusual. From the ocean response perspective, the deepening of the mixed layer, i.e., the change in depth from September to February, was less than any previous winter during the analysis period, and the static stability at the base of the mixed layer was a record maximum (Figure 3, bottom). Based on the data sets considered here, the winter of 2013–2014 was an extreme for the region of interest.

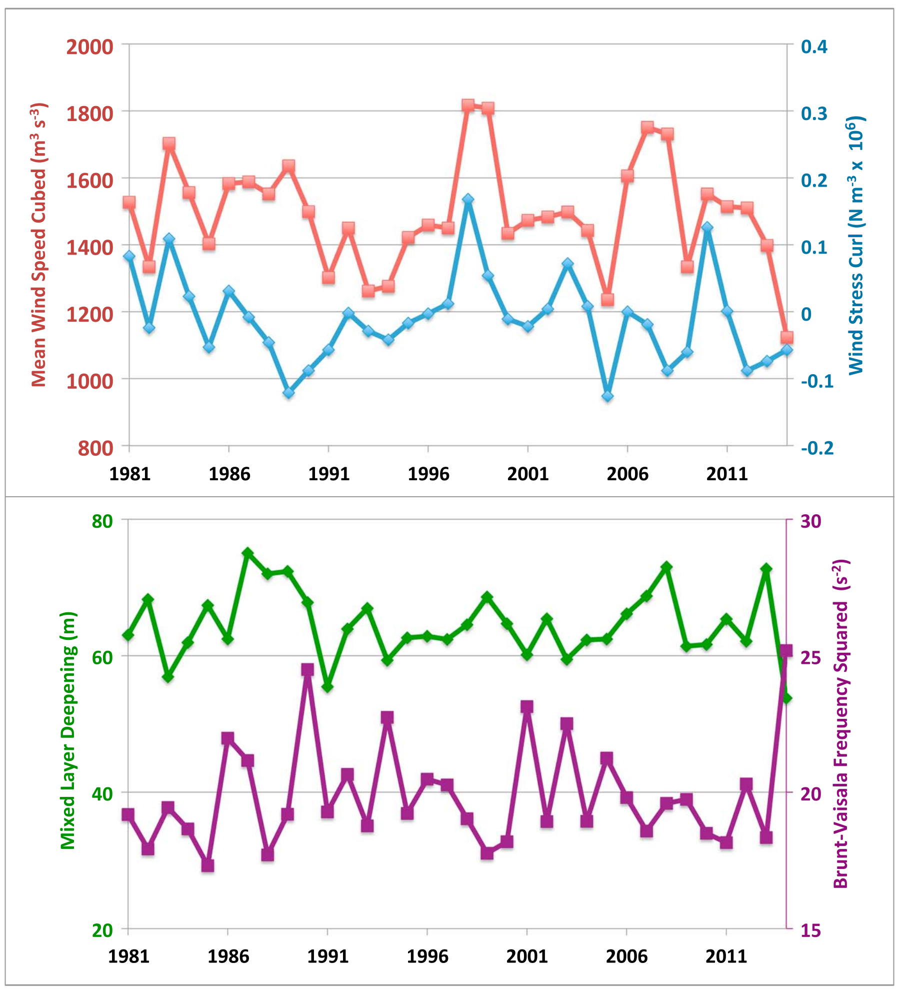

Figure 3. (top) Time series of seasonal mean (October–January) wind speed cubed (red) and wind stress curl (blue) for the area of 50–40°N, 150–135°W. (bottom) Time series of mean seasonal mixed layer deepening (September to February; green) and stratification at the base of the mixed layer (February; purple) for the area of 50–40°N, 150–135°W. The years refer to January–February values.

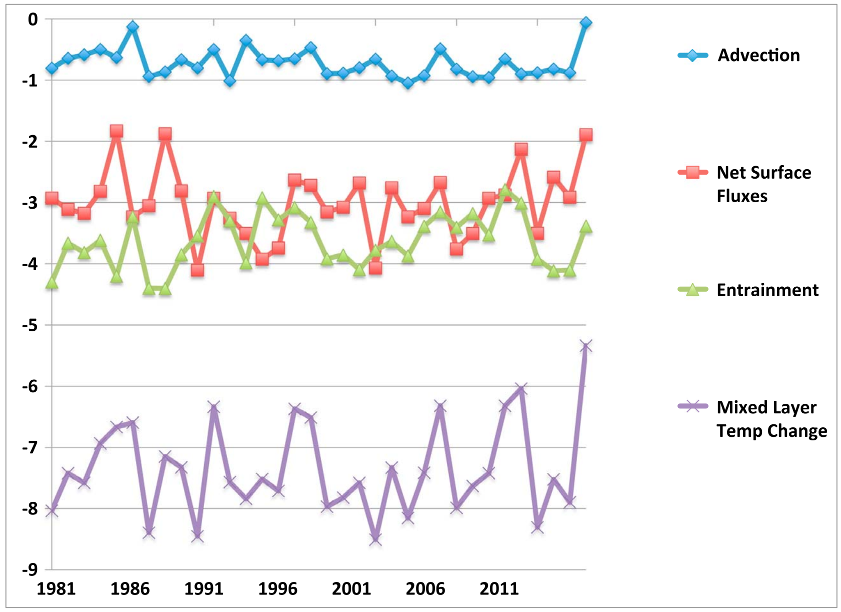

Figure 4. Seasonal values of the mixed layer temperature change from September to February for the area of 50–40°N, 150–135°W (°C; purple) and budget terms contributing to this temperature change. The black arrow points to the value for 2013–2014. Budget terms include horizontal advection (blue), net surface heat fluxes (red), and entrainment (light green). Values represent degrees (C) of temperature change associated with the individual terms.

Further insight into development of the "blob" can be gained through consideration of winter averages of the terms in a mixed layer temperature budget (Figure 4), using the framework of equation (2) in *Cronin et al*. [2013], but in an area-averaged versus point sense, with advection expressed as in *Lee et al*. [2004]. Local cooling of 5.5°C from October 2013 to February 2014 was about 30% lower than the mean, and the smallest magnitude in this record extending back to 1980. The net surface heat fluxes caused about 2°C of cooling in 2013–2014 versus a normal value of about 3°C over the 4 month period. The net effect of the heat exchange at the base of the mixed layer, often termed as entrainment and here estimated as a residual, was close to normal. It bears noting that the deduced heat fluxes due to entrainment were actually weaker than normal, but the actual cooling rate associated with the fluxes across the mixed layer was typical because these fluxes were distributed over a relatively thin mixed layer. The horizontal advection term was near zero; this term generally accounts for about 1°C cooling. The large interannual temperature anomaly thus appears to be due to a combination of anomalous advection and reduced surface heat loss.

The task now is to explain variations in the budget terms. The anomalous horizontal advection is due in part to anomalous wind-forced (Ekman) currents acting on the climatological upper ocean temperature gradient. For the southern portion of the high SLP anomaly, weaker than normal winds from the west induced anomalously weak Ekman transports of colder water from the north. An additional contribution was made by a near-normal eastward component of the current acting on a preexisting zonal gradient in the SST anomaly distribution. As shown in Figure 4, horizontal advection of heat is typically a very weak process in the NE Pacific, although it can play a role in interannual variability [*Large*, 1996]. For the 2014 event, the anomalous advection appears to be an order one process.

The net surface heat fluxes comprise the turbulent fluxes of sensible and latent heat and the radiative (solar and infrared) fluxes. During Oct 2013-March 2014, the reduced surface heat flux out of the ocean appears to be primarily associated with the turbulent flux terms. The extremely weak surface heat losses might seem somewhat surprising as one might expect that the warm SST would cause increased surface heat losses. Instead, it appears that the anomaly in the turbulent heat fluxes can be attributed partly to the wind speeds (Figure 3, top), which were the lowest in the record extending back to 1980 and the second lowest during the period of 1949–2014.

The influence of the shallower mixed layer depth during the fall to early winter of 2013–2014 may have also meant that the momentum supplied by the surface wind stress would be that much more effective toward generating mixed layer currents. This would tend to enhance the vertical shear across the base of the mixed layer, thus maintaining typical cooling rates due to entrainment despite the weaker winds. It should be noted that the GODAS surface heat flux is anomalously positive (22 W m^{-2}) relative to the NOAA Station Papa mooring observations at 50°N, 145°W [*Cronin et al*., 2012] in November 2013 and January–February 2014 (Figure S2). If the GODAS fluxes were adjusted by this bias, then the residual term involving the heat flux at the base of the mixed layer would be less negative than usual, again consistent with the reduced wind speeds. The wind stress curl and hence Ekman pumping anomalies were negative, which also is consistent with relatively weak entrainment.

In summary, the near-surface temperature anomalies that exceeded 2°C in the NE Pacific during winter 2013–2014 can be accounted for by anomalous vertical processes (air-sea heat exchanges and possibly vertical mixing across the base of the mixed layer) and oceanic horizontal advection associated with the anomalous weather pattern in the 4 month period leading up to the time of the maximum SST anomaly.

4. Biological Impacts

The region of warm SST anomalies in winter 2013–2014 spread into the coastal domain of Alaska and northern British Columbia in May 2014 and then into the nearshore waters of the U.S. Pacific Northwest in September 2014. The NE Pacific's anomalously warm water in spring, summer, and fall 2014 was coincided with a variety of unusual biological events and species sightings. From the bottom-up forcing perspective, *Whitney* [2015] documented extremely low chlorophyll levels during the late winter/spring of 2014 in the region of the warm anomalies, presumably due to suppressed nutrient transports into the mixed layer. Examples of dramatic species range shifts in summer and fall 2014 that have come to our attention include the following: (1) a skipjack tuna caught near the mouth of the Copper River in July [*Medred*, 2014]; (2) ocean sunfish and a thresher shark caught in summertime surveys off the coast of SE Alaska, where distributions of juvenile salmon and pomfret were also much different than usual (W. Fournier, personal communication, 2014); (3) a record high northern diversion rate of Fraser River sockeye salmon, i.e., the proportion of adults returning around the north versus south side of Vancouver Island [*Gallagher*, 2014]; (4) rhinoceros auklets in British Columbia preying on Pacific saury (associated with subtropical waters) rather than sand lance (associated with subarctic waters) in summer (J. Zamon, personal communication, 2014), (5) high catches of albacore tuna near the coast of WA and OR during summer and fall 2014; (6) juvenile pompano collected during surveys near the mouth of the Columbia River in summer (L. Weitkamp, personal communication, 2014); and (7) widespread strandings of Velella from British Columbia to California in July and August. There was also a massive influx of dead or starving Cassin's Auklets onto PNW beaches from October to December 2014 [*Opar*, 2015]. The list is much more illustrative than comprehensive but does suggest that the physical oceanographic conditions had substantial and widespread impacts on the ecosystem. The full ecosystem response remains to be determined, but it is liable to be profound, as occurred in the California Current during a period of weak coastal upwelling in 2005 (Warm Ocean Conditions in the California Current in Spring/Summer 2005: Causes and Consequences, *GRL* special issue, 2006).

5. Impacts on Seasonal Weather of the Pacific Northwest

The spatial extent and duration of the warm water anomalies that developed in the winter of 2013–2014 suggests the potential for a regional atmospheric response. Here we examine the strength of the relationship between the SST in the area of interest and the weather in the continental Pacific Northwest, which is downwind in the prevailing sense.

Our approach consists of a comparison between the mean SST during February in the study area with the mean surface air temperature in Washington state (indicated with "WA" in Figure 2) during the following spring months of March through May for the years of 1948–2014. A scatterplot of the relationship between these variables is shown in Figure 5; the linear correlation coefficient between them is 0.42. Similar results were found for other times of the year and for thermodynamic properties such as moist static energy in the atmos-pheric boundary layer, with slightly higher correlation coefficients for con-temporaneous comparisons.

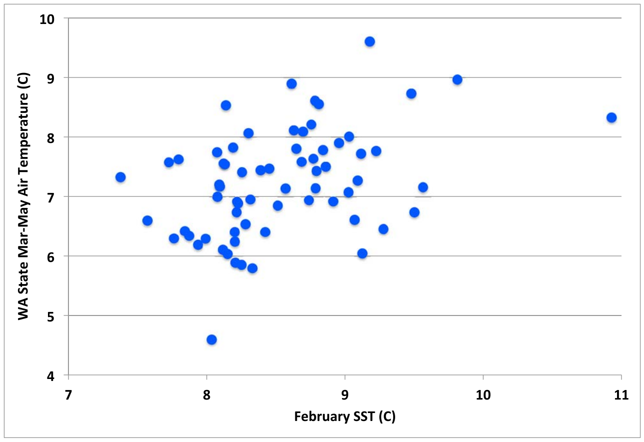

Figure 5. March–May air temperatures in Washington state (°C; *y* axis) versus February sea surface temperature (°C; *x* axis) averaged for the area of 50–40°N, 150–135°W. The year of 2014 is represented by the dot near the right-hand border of the figure.

On the other hand, the relationship between offshore SST and precipitation down-stream was negligible (not shown), presumably because of the SST's lack of influence on the regional-scale atmospheric circulation.

6. Final Remarks

A prominent mass of positive temperature anomalies developed in the NE Pacific Ocean during winter of 2013–2014. This development can be attributed to strongly positive anomalies in SLP, which served to suppress the loss of heat from the ocean to the atmosphere, and leads to a lack of the usual cold advection in the upper ocean. The extra mixed layer heat persisted through the summer of 2014 and may have represented a significant contribution to the unusually warm summer (in some locations record high temperatures) observed in the continental Pacific Northwest. The linkage between the upper ocean temperature and downstream temperatures over the coastal region of the Pacific Northwest may provide a secondary source of predictability for seasonal weather forecasts. In particular, it suggests that coupled atmosphere-ocean models such as NCEP's Coupled Forecast System model may need to properly handle the evolution of the upper ocean in the NE Pacific because of its regional influences.

The present analysis does not focus on the cause(s) of the anomalous atmospheric forcing. A broad region extending from the North Pacific across North America is known to be subject to the effects of teleconnections from the tropical Pacific in association with El Niño–Southern Oscillation (ENSO) events, i.e., the "atmospheric bridge" [e.g., *Alexander et al*., 2002; *Lau and Nath*, 1996]. But such an explanation fails to account for the winter of 2013–2014 since ENSO was in a neutral phase. On the other hand, SST anomalies in the far western tropical Pacific, and accompanying deep cumulus convection, appear to account for a significant portion of the anomalous circulation [*Seager et al*., 2014; *Hartmann*, 2015; *Lee et al*., 2015] that occurred in the winters of both 2012–2013 and 2013–2014, with intrinsic atmospheric variability probably an additional important factor.

Acknowledgments
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Erratum

In the originally published version of this paper, a definition of the mixed layer was included that was different from what was actually incorporated in the mixed layer deepening and heat budget estimates (as shown in Figs. 3 and 4). The reported value for the density difference between the upper and lower boundaries of the mixed was 0.03 kg m^{-3}, while the value that was actually used in analysis was 1.0 kg m^{-3}. The latter value was an appropriate assumption due to smoothing of vertical gradients associated with monthly-averaged data.

This error affects the second paragraph in “Section 2. Data and Methods,” which has been updated to reflect the correct density difference. This version may be considered to be the authoritative version of record.