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Formation and variation of temperature inversions in the eastern subarctic North Pacific

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[1] Hydrographic data from profiling float observations for 2001–2005 and from expendable bathythermograph observations for 1993–2005 were analyzed to study the formation and variation of temperature inversions (T-inversions) in the eastern subarctic North Pacific (SNP). The formation and variation of T-inversions differed significantly between the northern and southern regions of the eastern SNP. In the northern region, the temperature minimum (T-min) at the top of T-inversions outcropped to the sea surface and was cooled in the mixed layer nearly every winter. This process caused a seasonal cycle in the magnitude of T-inversions (ΔT), with a maximum in winter. In the southern region, the winter T-min outcropped relatively infrequently and the ΔT did not exhibit a significant maximum in winter during most years. The T-min in the southern region was likely to outcrop upstream near the date line roughly one year earlier and was then advected to the southern region. **Citation:** Ueno, H., E. Oka, T. Suga, H. Onishi, and D. Roemmich (2007), Formation and variation of temperature inversions in the eastern subarctic North Pacific, *Geophys. Res. Lett.*, *34*, L05603, doi:10.1029/2006GL028715.

1. Introduction

[2] Temperature inversions (T-inversions), lying between a subsurface temperature minimum (T-min) and a temperature maximum (T-max) underlying the minimum [e.g., *Ueno and Yasuda*, 2000, Figure 3], are widely distributed over the subarctic North Pacific (SNP) north of ca. 40°N [e.g., *Dodimead et al.*, 1963; *Uda*, 1963; *Roden*, 1964; *Favorite et al.*, 1976]. Because of the presence of a strong, permanent halocline in this region, the winter mixed layer can be colder than the underlying, more saline layer, thus forming a T-inversion. In early spring, the upper portion of the winter mixed layer begins to warm, leaving the bottom portion as a T-min. As the season progresses, the T-min is gradually eroded and weakened by further surface heating and vertical mixing.

[3] Using temperature and salinity data from 2001 to 2004 obtained using Argo profiling floats [*Argo Science Team*, 2001], *Ueno et al.* [2005] studied seasonal and interannual variability of T-inversions in the SNP, focusing on three large regions where the float distribution density was relatively high. Each year in the western SNP and Bering Sea, the winter mixed layer became colder than the T-min formed during the previous winter. That is, the T-min outcropped to the sea surface and was cooled in the mixed layer every winter, causing seasonal cycles in T-min and in the magnitude of the T-inversion (ΔT; calculated as the temperature difference between T-min and T-max). Specifically, the T-min was cold in winter and warm in fall and the ΔT was large in winter and small in fall. This seasonal cycling of ΔT occurred because the T-max temperature was relatively constant. In the eastern SNP (defined as 45°–60°N, 120°–160°W, excluding the Bering Sea), the T-min outcropped in winter 2002 and 2004 but scarcely outcropped in winter 2003, causing a monotonic decrease in ΔT from March 2002 to December 2003. These data suggest high interannual variability of T-inversions in the eastern SNP.

[4] *Ueno et al.* [2005] broadly examined T-inversion variability in the eastern SNP. However, a previous study using climatological hydrographic data [*Ueno and Yasuda*, 2000] indicated that the existence and formation mechanism of T-inversions varied with location within the eastern SNP. They found that T-inversions existed north of 52°N and south of 48°N, but did not exist between 48°N and 52°N. This was confirmed by an analysis of individual temperature profiles, which indicated that the occurrence frequency of T-inversions was high north of 52°N and between 42°N and 48°N but low between 48°N and 52°N. In addition, T-min outcropped in winter north of 52°N, but did not outcrop south of 48°N. Thus, T-inversions were formed locally in the northern region but not in the southern region [*Ueno and Yasuda*, 2000]. A numerical particle-tracking experiment by *Ueno and Yasuda* [2000] suggested that the T-inversions in the southern region were formed during the previous winter in the western area near the date line and advected to the southern region by the North Pacific Current.

[5] Despite these regional differences in the T-inversion structure, our previous study [*Ueno et al.*, 2005] did not detail the formation and variation of T-inversions in the eastern SNP. In the present study, we reexamined these aspects of T-inversions in more detail using updated Argo float data through 2005. These data include more profiles than used in our previous study, particularly for the southern region of the eastern SNP. We also analyzed temperature data from repeated expendable bathythermograph (XBT) observations between Alaska and Hawaii for 1993–2005 to characterize long-term variability of T-inversions in the eastern SNP.

2. Data and Methods

[6] We used temperature and salinity profiles recorded by Argo floats in the North Pacific north of 35°N and east of

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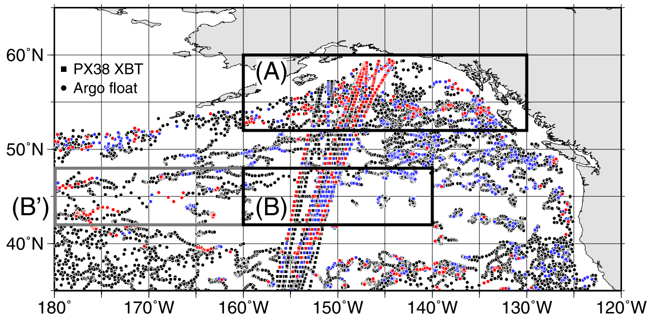

Figure 1. Distribution of XBT (squares) and Argo float (dots) observations in the eastern subarctic North Pacific (SNP). Red (blue) squares/dots represent observation points where T-min outcropped (did not outcrop) during January–March. Lines indicate Regions A, B, and B'.

180° during 2001–2005 (Figure 1), although data were extremely limited for the first half of 2001. Data were downloaded from the website of the Argo Global Data Assembly Center (http://www.argo.ucsd.edu, http://argo.jcommops.org) and quality-controlled as outlined by *Oka et al.* [2007]. We omitted profiles shallower than 500 db (500 × 10^4 Pa) and those having less than 20 vertical levels between 0 and 500 db, as outlined by *Ueno et al.* [2005]. The total number of profiles selected was 9089, among which 1641 and 585 existed in Regions A and B, respectively.

[7] We also used temperature profiles along line PX38 between Alaska and Hawaii for 1993–2005 (Figure 1) obtained from the high resolution XBT program of the Scripps Institution of Oceanography [e.g., *Douglass et al.*, 2006]. The along-track resolution off and near the coasts was 30–50 km and 10 km, respectively. We used profiles averaged vertically over 10-m intervals, except for values at 0–10 m depth. Line PX38 was observed twice annually in 1993, 1994, 2004, and 2005, and 3–4 times a year from 1995 to 2003. There was a winter (January–March) observation every year with the exception of 1993.

[8] For each profile, we determined the temperature minimum (T-min) and maximum (T-max) at the top and bottom of the T-inversion, as well as the temperature difference between T-min and T-max (ΔT), following *Ueno and Yasuda* [2005]. T-inversions with ΔT smaller than 0.01°C were omitted. A T-min in an Argo profile was considered to outcrop when the difference between the T-min density and the sea surface (10 m depth) density was smaller than 0.03 kg m^{-3}, as per *Ueno et al.* [2005]. A T-min obtained from XBT data was considered to outcrop when the difference between the T-min temperature and the sea surface (average 10–20 m depth) temperature was smaller than 0.1°C. This value (0.1°C) is the median temperature difference between the sea surface and the mixed layer bottom obtained from the Argo data for the regions between 42°N and 60°N and 130°W and 160°W using the density criterion of 0.03 kg m^{-3}. We also used NOAA optimum interpolation monthly sea surface temperature anomaly (SSTA: deviation from the monthly climatology) data [*Reynolds et al.*, 2002], and NCEP/NCAR reanalysis surface heat flux data [*Kistler et al.*, 2001].

3. Results

[9] We examined T-inversions in the eastern SNP, focusing on two regions, Region A (52°–60°N, 130°–160°W, excluding the Bering Sea; Figure 1) and Region B (42°–48°N, 140°–160°W). These regions were characterized by high occurrence frequencies of T-inversions, compared to the area between 48° and 52°N and the area east of Region B, which was demonstrated by climatological data [*Ueno and Yasuda*, 2005] and Argo and PX38 XBT data in our study. The infrequent T-inversions between 48° and 52°N were considered to be because (1) winter surface cooling in the area was weak, (2) the T-max was relatively cold, and (3) advection of the T-min layer water from the west was weak [*Ueno and Yasuda*, 2005].

[10] We focused on variation in ΔT rather than T-min/T-max temperature variations, because ΔT was less affected by eddies and areal sampling bias, and likely gave a more robust measure of the regional impact of wintertime surface cooling in the eastern SNP [*Ueno et al.*, 2005]. For example, both T-min and T-max in Region B, where relatively small number of Argo profiles likely leads to areal sampling bias, changed abruptly in April 2003 and August 2004 (Figure 2b), because two floats were deployed in April 2003 and three in August 2004 in the southern area of Region B where T-min/T-max temperatures were relatively high [*Ueno and Yasuda*, 2005]. However, on those occasions, ΔT did not change abruptly.

[11] In Region A, T-min outcropped at considerable rates (>40%) in winter and ΔT reached a maximum in late winter

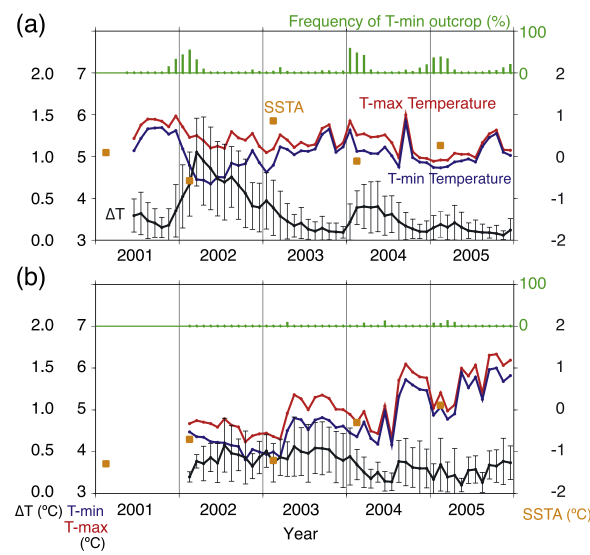

Figure 2. Time series of ΔT (black line) and temperatures at T-min (blue line) and T-max (red line) from Argo float observations, averaged monthly in (a) Region A and (b) Region B. Vertical bars for ΔT represent ±1 standard deviation. The green bar charts indicate monthly frequency of T-min outcrops. Months with fewer than three observations are not included. Orange squares indicate SSTA averaged from January to March in Region A (Figure 2a) and Region B' (Figure 2b).

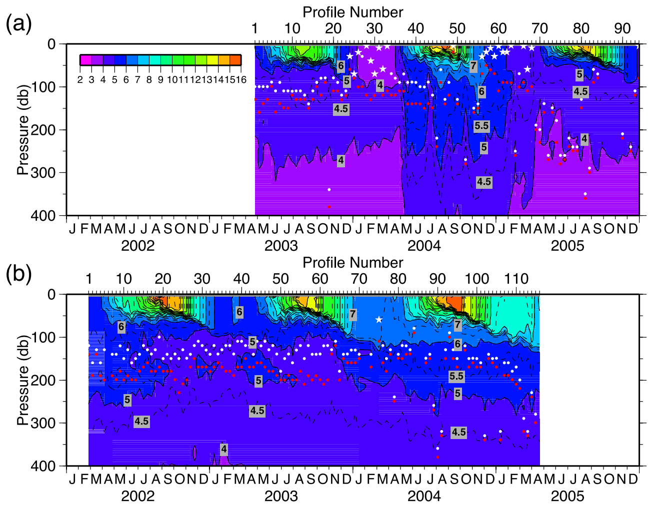

Figure 3. Exemplary time-pressure sections of potential temperature (°C) in (a) Region A and (b) Region B, obtained from an Argo profiling float with WMO ID 4900344 and 4900119, respectively (WMO ID is a World Meteorological Organization identifier). The float 4900344 (4900119) drifted in the area of 53°–58°N, 148°–156°W (46°–47°N, 147°–152°W). White stars (dots) represent outcropping (non-outcropping) T-min, while red dots denote T-max.

in 2002, 2004, and 2005 (Figures 2a and 3a). In these years, ΔT changed seasonally, decreasing from late winter to the next fall. The maximum ΔT in winter varied annually: 1.1°, 0.4°, and 0.2°C in 2002, 2004, and 2005, respectively. The maximum ΔT was negatively correlated with winter SSTA in this region, which was −0.6°, −0.1°, and 0.3°C in the respective years. That is, when the winter mixed layer was cold, the formation of a low T-min resulted in a large ΔT. The T-min scarcely outcropped in winter 2003, when the winter mixed layer was significantly warmer (SSTA = 0.9°C) and shallower [*Freeland and Cummins*, 2005] than in the previous year. Consequently, ΔT did not exhibit a significant maximum in late winter 2003 and decreased nearly monotonically from March 2002 to December 2003. The ΔT variation in Region A was similar to that in the eastern SNP (45°–60°N, 120°–160°W, except the Bering Sea) presented by *Ueno et al.* [2005], because of the relatively high float distribution density and large ΔT variability in Region A.

[12] In Region B, T-min scarcely outcropped throughout 2002–2005, and ΔT did not exhibit a significant maximum in late winter (Figures 2b and 3b). T-inversions in this region were probably formed by subsurface advection of the T-min water that outcropped previously in the western, upstream region, as suggested by *Ueno and Yasuda* [2000]. The potential density at T-min in Region B was 26.0–26.3 kg m^{-3}. This density range outcropped in winter west of Region B (160°W–180°) [*Suga et al.*, 2004, Figure 3c]. ΔT in Region B decreased in mid-2004, likely in association with an increase in winter SSTA from 2003 to 2004 averaged over 42°–48°N and 160°W–180° (named Region B') with some time lag (Figure 2b). This relationship is further discussed below using the long-term XBT data. The Argo observations also demonstrated that the T-min outcropped at a high rate in Region B', much more frequently than in Region B (Figure 1), supporting the suggestion of *Ueno and Yasuda* [2000]. However, the Argo data in Region B' were temporally limited. Therefore, we compared the ΔT in Region B with winter SSTA in Region B' here.

[13] We also examined the long-term variability of T-inversions in the eastern SNP using line PX38 XBT data for 1993–2005. In Region A, T-min outcropped at considerable rates (30–90%) and ΔT exhibited a seasonal cycle with a maximum in winter, except in 2003 (Figure 4a). Winter ΔT was negatively correlated with winter SSTA near the XBT line (correlation coefficient = −0.74). These data indicate that the seasonal variability of T-inversions and its relationship with SSTA in this region (as revealed by the Argo data; Figure 2a) were maintained in the long term, with only one exception (2003).

[14] In Region B, the frequency of winter T-min outcropping was relatively low (0–50%) and ΔT did not exhibit a significant maximum in winter, except in 1998 and 1999, indicating that T-inversions in this region were mainly formed by horizontal advection (Figure 4b). However, during the 1998 and 1999 winters, T-min outcropped at high rates (>90%) and was relatively colder, increasing ΔT significantly. Net downward surface heat flux averaged within Region B between the previous October and March was −66 Wm^{-2} in 1998 and −70 Wm^{-2} in 1999, which were much higher than the average for 1993–2005 (−51 Wm^{-2}). This cooling likely decreased the winter SSTA in Region B from 0.5°C in 1997 to −0.9°C in 1999. In 1994, 1995, and 2003, T-min partially outcropped, but ΔT did not increase in winter, possibly because winter cooling was not as strong. The ΔT during the years with infrequent outcropping was small from 1994 to 1997 and

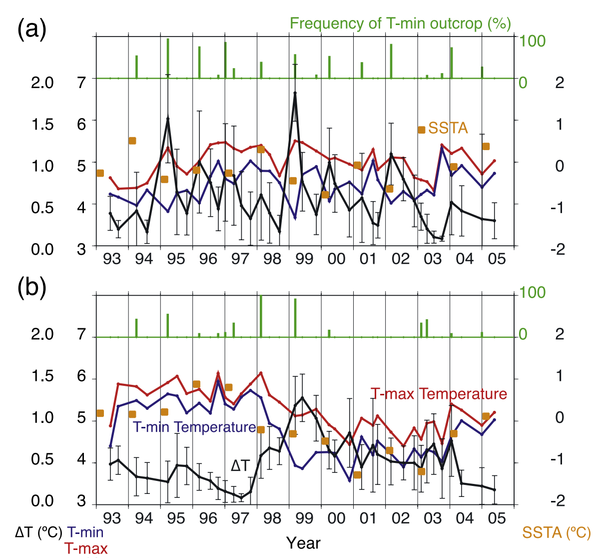

Figure 4. As in Figure 2, but based on the PX38 XBT line observations. Before averaging, some observations were omitted so that the along-track resolution was nearly uniform. Sea surface temperature anomalies (SSTA) were averaged in the areas of (a) 52°–60°N, 144°–153°W and (b) Region B'.

2004 to 2005 and relatively large from 2000 to 2003. This ΔT variation corresponded to the winter SSTA variation in the upstream (Region B'), as suggested by the Argo data analysis. Lag correlation coefficients between winter SSTA in Region B' and winter ΔT in Region B for the infrequent-outcropping years (1994–1997, 2000–2005) were −0.54, −0.76, and −0.25 with time lags of 0, 1, and 2 years, respectively. The highest correlation with a 1-year lag, which was significant at the 95% confidence level, suggests that the advection time of the T-min water from Region B' to line PX38 by the North Pacific Current was roughly 1 year. This is consistent with the result of the numerical particle-tracking experiment performed by *Ueno and Yasuda* [2000].

[15] Differences in winter SSTA in Region B' and ΔT in Region B between 1994 and 1997 and 2000 and 2003 may be associated with the 1998–1999 climate regime shift over the North Pacific [e.g., *Minobe*, 2002]. The ΔT difference may also have been affected by the intensification of the eastward North Pacific Current during 1996 and 1997, as determined by analysis of PX38 XBT data and output of an ECCO model [*Douglass et al.*, 2006]. The intensified North Pacific Current may have transported the T-min water with less vertical diffusion from Region B' to Region B, thus increasing ΔT in Region B.

4. Conclusions

[16] We studied the formation and variation of T-inversions in the eastern SNP through analyses of Argo profiling float data for 2001–2005 and PX38 XBT data for 1993–2005. Both analyses indicated that formation and variation differed between the northern and southern regions of the eastern SNP (Regions A and B, respectively). In Region A, T-min outcropped and was cooled nearly every winter. As a result, ΔT had a significant maximum in winter, and the winter ΔT tended to be large when winter SSTA in the region was low. In Region B, the winter T-min outcropped relatively infrequently, and ΔT did not have a significant maximum in winter, except in 1998 and 1999. We suggest that during 1994–1997 and 2000–2005, T-min in Region B was formed in the upstream region near the date line and then advected to Region B in roughly 1 year. During 1998 and 1999, T-min outcropped and was cooled in winter because of exceptionally strong surface cooling, resulting in a significant increase in ΔT.

[17] **Acknowledgments.** The Argo float data used in this study were collected and made freely available by the International Argo Project and the national programs that contribute to it (http://www.argo.ucsd.edu; http://argo.jcommops.org). Argo is a pilot program of the Global Ocean Observing System. The authors thank S. Masuda for helpful comments and fruitful discussions, and also thank two anonymous reviewers for helpful and constructive comments.

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