Seasonal and interannual variability of temperature inversions in the subarctic North Pacific

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[1] Hydrographic data from profiling floats obtained during 2001–2004 were analyzed to study seasonal and interannual variability of temperature inversions (T-invs) in the subarctic North Pacific (SNP). In the western SNP and Bering Sea, the temperature minimum at the top of T-invs outcropped and was renewed every winter, causing a seasonal cycle in the magnitude of T-invs, with the maximum at the end of winter. In the Gulf of Alaska in the eastern SNP, the temperature minimum outcropped in winters 2002 and 2004, but scarcely outcropped in winter 2003. Consequently, the magnitude of the T-invs showed remarkable interannual variation; its monotonic decrease through winter 2003 overwhelmed the seasonal cycle. The year-to-year variation of the magnitude of the T-invs in each region of the SNP was consistent with and thereby attributable to that of the winter sea surface temperature anomaly there. **Citation:** Ueno, H., E. Oka, T. Suga, and H. Onishi (2005), Seasonal and interannual variability of temperature inversions in the subarctic North Pacific, *Geophys. Res. Lett.*, *32*, L20603, doi:10.1029/2005GL023948.

1. Introduction

[2] Temperature inversions (T-invs) are intrinsic features of the subarctic North Pacific (SNP) north of *ca*. 40°N, associated with the strong permanent halocline [*Dodimead et al.*, 1963; *Uda*, 1963; *Roden*, 1964; *Favorite et al.*, 1976; *Ueno and Yasuda*, 2000, 2005; *Miura et al.*, 2002]. They are thought to be formed mainly by wintertime surface cooling, preserving the memory of wintertime atmospheric conditions. After their formation, T-invs gradually weaken as the season progresses, due to surface heating and vertical mixing. They often vanish during fall in the eastern SNP, while they generally survive throughout the year in the western SNP [*Ueno and Yasuda*, 2000]. To better understand air–sea interactions in the SNP, it is essential to clarify the seasonal cycle and year-to-year variation of T-invs.

[3] T-invs in the SNP have been examined mostly using historical hydrographic data, which are quite limited in winter. Therefore, the formation and seasonal evolution of T-invs are not fully understood, and their interannual variation remains unclear. The Argo Project [*Argo Science Team*, 2001], which began in 2000 and involved the deployment of 3,000 profiling floats to monitor the temperature and salinity of the world's oceans in 10-day cycles, has been rapidly easing these limitations. Using Argo float data, *Wirts and Johnson* [2005] investigated seasonal and interannual upper ocean variability in the southeastern Bering Sea, and *Freeland and Cummins* [2005] documented the variation in the ocean circulation of the eastern SNP. In this paper, we discuss the formation and seasonal/interannual variation of T-invs in the entire SNP, using the float data from 2001–2004.

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2. Data and Method

[4] We used temperature and salinity profiles recorded by Argo floats (http://www.argo.net/) in the North Pacific north of 30°N during 2001–2004. These profiles typically had a maximum depth of 2000 db (2000 × 10^4Pa) and a vertical resolution of 5–25 db at depths shallower than 1000 db and 50–100 db at deeper than 1000 db. We used only those profiles reaching deeper than 500 db and having more than 20 vertical levels between 0 and 500 db, since most T-invs in the SNP occur above 500 db [*Kobayashi*, 2004]. We used 15,211 profiles, although the data were limited in the first half of 2001.

[5] For each profile, the difference (ΔT) between the temperature maximum (T-max) at the bottom of the T-inv and the minimum (T-min) at the top of the T-inv was determined following *Ueno and Yasuda* [2005]. T-min was considered to outcrop when the difference between the T-min density and sea surface density was smaller than 0.03 kg m^{-3}. This density criterion, when used for individual profiles, detected the mixed layer bottom accurately, compared to the previously used larger values, such as 0.125 kg m^{-3} [*de Boyer Montégut et al.*, 2004]. Note that an 0.03 kg m^{-3} density difference criterion will allow profiles with as much as an 0.3°C temperature difference between surface temperature and the T-min to be classified as ventilated in these regions. The density at the sampling depth nearest 10 db was regarded as the sea surface density because the floats cannot conduct measurements at depths shallower than several decibars. We also used climatological hydrographic data from the World Ocean Atlas 2001 (WOA) [*Boyer et al.*, 2002; *Stephens et al.*, 2002]. For the sea surface temperature anomaly (SSTA: deviation from the monthly climatology), we used NOAA optimum interpolation SSTA data [*Reynolds et al.*, 2002].

3. Results

[6] The Argo data detected T-invs with ΔT larger than 0.1°C existing ubiquitously in the SNP (Figure 1). ΔT

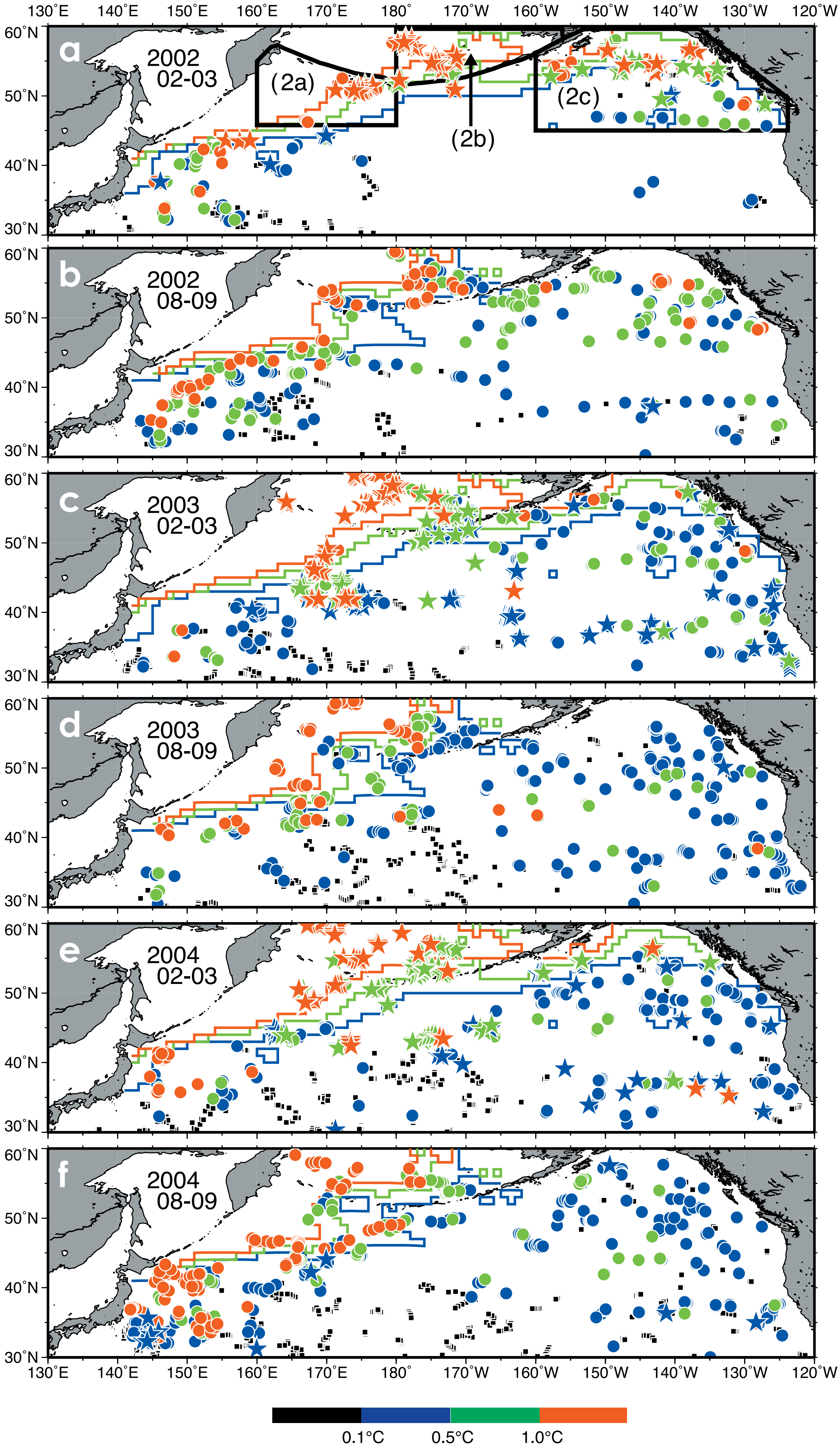
a
2002
02-03
(2a)
(2b)
(2c)
b
2002
08-09
c
2003
02-03
d
2003
08-09
e
2004
02-03
f
2004
08-09
130°E 140°E 150°E 160°E 170°E 180° 170°W 160°W 150°W 140°W 130°W 120°W
60°N 50°N 40°N 30°N
0.1°C 0.5°C 1.0°C

Figure 1

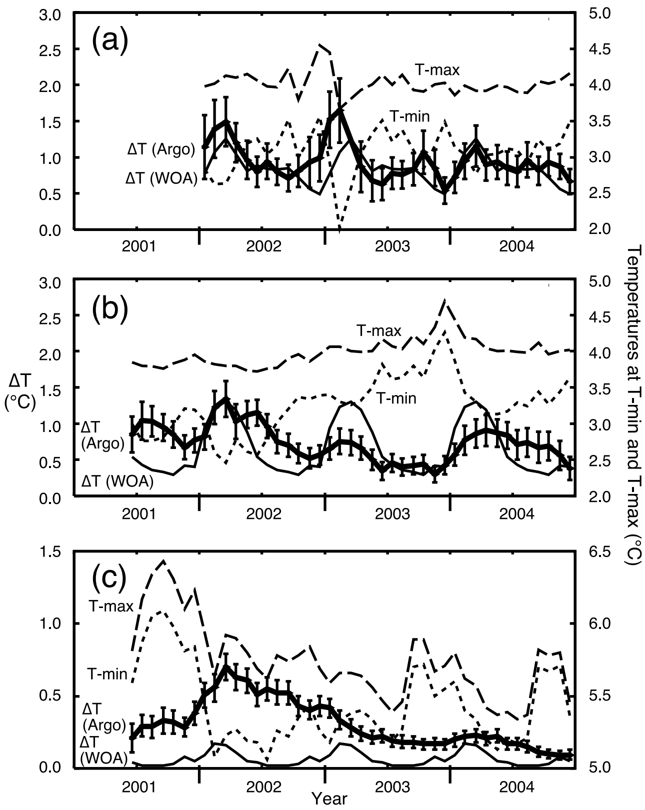

Figure 2. Time series of ΔT (thick solid line) and temperatures at T-min (dotted line) and T-max (dashed line) averaged in the area (a) 160–180°E, 45–60°N except the Bering Sea, (b) east of 180° in the Bering Sea, and (c) 120–160°W, 45–60°N except the Bering Sea (see Figure 1a for locations), calculated from Argo float data. Vertical bars for ΔT represent the standard error. The profiles without a T-inv were excluded from the calculations. The thin solid line shows the time series of ΔT, calculated from the WOA for the area deeper than 500 db.

increased to the west and north, and was especially large in the western SNP and Bering Sea. The T-invs in the Argo data extended much more widely than that in the WOA. For example, in the Argo data, ΔT larger than 0.1°C was observed in the eastern SNP east of 160°W year-round, where T-invs seldom occurred during summer in the WOA. In the Mixed Water Region east of Japan (*ca*. 140–160°E and 33–45°N) between the Oyashio Front and Kuroshio Extension Front [*Kawai*, 1972], ΔT larger than 1.0°C was often recorded in the Argo data, but T-invs did not occur in the WOA. These differences probably resulted from the strong spatial and temporal smoothing used in the WOA.

[7] In the western and central SNP and in the Bering Sea, T-min generally outcropped in late winter (Figures 1a, 1c, and 1e). In these areas, T-min is thought to be formed locally in the winter mixed layer. In contrast, T-min almost did not outcrop in the Mixed Water Region, where T-min was formed not in the local winter mixed layer, but in the subsurface layer, probably due to lateral intrusion of cold freshwater originating from the Oyashio region [e.g., *Nagata*, 1979]. In the Gulf of Alaska (east of 160°W and north of 52°N) in the northeastern SNP, T-min outcropped in winter 2002 and partially outcropped in winter 2004, but scarcely outcropped except in the coastal area during winter 2003. In the southeastern SNP (east of 160°W and 45–48°N), it outcropped only in limited areas in winter 2004, and never in winters 2002 and 2003, although ΔT larger than 0.5°C was observed constantly. This supports *Ueno and Yasuda*'s [2000] hypothesis that T-invs in this area are maintained by subsurface advection of the T-min water from the western and central SNP.

[8] To examine the quantitative seasonal and interannual variation of ΔT and its relation to those of the T-min outcrop and SSTA, ΔT and the temperatures at T-min and T-max were averaged for three regions, the western SNP, eastern Bering Sea, and eastern SNP (Figure 2), where the float density was relatively large during the analysis period (Figure 1). In the western SNP where T-min outcropped every winter, ΔT had a significant maximum every late winter (Figure 2a). In this area, the variation of the T-max temperature was small except around the end of 2002, and the fluctuation in ΔT was determined primarily by that of the T-min temperature, which decreased every winter due to the T-min outcrop. The winter ΔT (T-min temperature) was relatively large (cold) in 2002 and 2003 and small (warm) in 2004. This is consistent with the interannual variation in the winter SSTA for the area, which was −0.8 to 0.2°C in 2002, −0.5 to 0.0°C in 2003, and −0.2 to 0.0°C in 2004.

[9] In the eastern Bering Sea, where T-min also outcropped every winter, ΔT showed seasonality similar to that in the western SNP (Figure 2b). In this area, the T-max temperature fluctuation was also small, except around the end of 2003, and the ΔT fluctuation was mostly determined by the T-min temperature variation. The winter ΔT was large in 2002, small in 2003, and intermediate in 2004, which corresponded to the year-to-year variation in the winter SSTA: −1.0 to 0.0°C in 2002, 0.2 to 1.5° in 2003, and 0.0 to 1.0°C in 2004. This relation between the T-min temperature and SSTA in the eastern Bering Sea was also reported by *Wirts and Johnson* [2005].

[10] ΔT in the eastern SNP was much larger than that from the WOA, and represented remarkable interannual variation, in contrast to the western SNP and eastern Bering Sea (Figure 2c). It increased from November 2001 to March 2002, decreased from March 2002 to December 2003, and increased again in winter 2004. The monotonic decrease in ΔT through winter 2003 corresponds to the fact that T-min

Figure 1. Maps of the magnitude of the T-invs during February–March and August–September 2002–2004, constructed from Argo float data. The symbol color denotes the magnitude of the T-invs: red, ΔT > 1.0°C; green, 0.5°C < ΔT < 1.0°C; and blue, 0.1°C < ΔT < 0.5°C. Stars (circles) represent T-invs whose T-min outcrops (does not outcrop). Black dots represent profiles with ΔT < 0.1°C, including those without a T-inv. Red, green, and blue contours represent isolines of ΔT = 1.0°, 0.5°, and 0.1°C, respectively, calculated from WOA. Black lines in the top panel indicate the areas analyzed in Figures 2a, 2b, and 2c.

there scarcely outcropped during that period (Figure 1c). The interannual variation of ΔT was consistent with that of the winter SSTA in the region, which was -1.0 to $-0.2°C$ in 2002 and 0.0 to 1.5°C in 2003. In contrast to the western SNP and eastern Bering Sea, the ΔT variation did not simply correspond to the T-min temperature variation. This will be discussed in the next section.

4. Discussion

[11] The temperatures at T-min and T-max in the eastern SNP showed a conspicuous short-term (less than one year) fluctuation, in contrast to a relatively modest variation in ΔT (Figure 2c). This short-term fluctuation probably arose because each of the temperatures at T-min and T-max showed strong spatial variation in the area, ranging between 4 and more than 10°C (not shown), associated with predominant fronts and eddies there [e.g., *Tabata*, 1982]. The profiling float density was not sufficiently high to smooth out this large spatial variation when the T-min and T-max temperatures were averaged in the area. Particularly, the float distribution was strongly biased to the east in 2001, causing extremely warm T-min and T-max temperatures during that period. Nevertheless, since a high (low) T-min temperature tended to be associated with a high (low) T-max temperature for each profile (not shown), ΔT varied spatially much less than each of the T-min and T-max temperatures, resulting in the modest temporal variation in the area-averaged ΔT. In this context, ΔT likely gives a more robust measure of the regional impact of wintertime surface cooling when it is examined or monitored using the Argo float array, which is intended for large-scale monitoring and does not resolve mesoscale variability itself.

[12] It has been proposed that the SST in the northeast Pacific is related to El Niño/La Niña events, and is high during El Niño events and low during La Niña episodes [e.g., *Schwing et al.*, 2002]. Therefore, the warm SST and small ΔT in the northeastern SNP in winter 2003 were likely caused, at least in part, by the 2002/2003 El Niño event. The results of our study will facilitate further research on the impact of climate variation on the upper layer structure in the SNP.

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