GEOPHYSICAL RESEARCH LETTERS, VOL. 29, NO. 0, 10.1029/2002GL015021, 2002

Temporal changes in dissolved oxygen of the intermediate water in the subarctic North Pacific

Andrey Andreev and Shuichi Watanabe

Japan Marine Science and Technology Center, Yokosuka, Japan

Received 28 February 2002; accepted 12 June 2002; published XX Month 2002.

[1] Using an approximately 50-year data set, the changes in dissolved oxygen (DO) on isopycnals in the intermediate layer of the subarctic North Pacific were analyzed. The temporal variations in DO on a decadal scale in the western subarctic Pacific display a negative correlation with those in the eastern subarctic Pacific. From 1950 to 2000 there is an average increase in the Apparent Oxygen Utilization (AOU) with a rate of 0.3 ± 0.2 (95% confidence interval) μmol kg^{-1} y^{-1} in the Western Subarctic Gyre (WSG) and Alaska Gyre (AG). The increase in AOU coincides with an increased temperature in the intermediate layer- (0.31 ± 0.28°C century^{-1} in the WSG and 0.54 ± 0.32°C century^{-1} in the AG) and decrease in surface-water salinity in the Bering Sea (-0.32 ± 0.22 century^{-1}). It is hypothesized that the changes are correlated with the North Pacific Index (NPI), which fosters meridional transport of salt to the Bering Sea when it is high. The gradual decrease in NPI thus has caused a freshening and a subsequent decrease in the ventilation resulting in an AOU increase in the intermediate waters of the subarctic North Pacific. *INDEX TERMS:* 4215 Oceanography: General: Climate and interannual variability (3309); 4820 Oceanography: Biological and Chemical: Gases; 9355 Information Related to Geographic Region: Pacific Ocean

1. Introduction

[2] As predicted by model simulations [*Manabe and Stouffer*, 1993; *Sarmiento et al.*, 1998; *Matear and Hirst*, 1999], anthropogenic climate change should lead to increased stratification in the surface layer of polar regions (as a result of increased precipitation in high latitude oceans and decreased meridional salt transport) and thus to decreased deep-water overturning. Increased stratification should cause accumulation of dissolved inorganic carbon and nutrients, and DO reduction in the deep-water layer. DO can be considered as a good indicator of these changes [*Sarmiento et al.*, 1998] due to the existence of an approximately 50-year, relatively high accuracy (error < 1–2%) data set (NOAA Oceanographic Data Center, Japan Ocean Data Center).

[3] We show that DO variations in the intermediate layer of the subarctic North Pacific during the last 50 years are consistent with coupled ocean/atmosphere model simulations of an anthropogenic climate-warming scenario: the existence of high-amplitude decadal variations with a tendency to decreases in DO. The oscillations and trends in DO in the intermediate layer of the subarctic North Pacific were mainly due to variations in saline water supply to the Bering Sea and, thereby changes in the overturning of intermediate water. There is a strong relationship between these changes, and the changes in the atmospheric circulation pattern over the North Pacific.

2. DO in the Intermediate Layer of the Subarctic North Pacific

[4] The North Pacific Subarctic Gyre (NPSG) consists of the Western Subarctic Gyre (WSG) and the Alaska Gyre (AG) (Figure 1). The western boundary of the NPSG is formed by the East Kamchatka Current (EKC), originating in the western part of the Bering Sea, and the Oyashio Current, which is a mixture of the EKC and the Okhotsk Sea waters [*Favorite et al.*, 1976]. The Subarctic Current, Alaskan Stream Current and Alaska Current form the southern, northern and eastern boundaries of the NPSG, respectively (Figure 1).

[5] The distributions of the salinity and AOU (the difference between the equilibrium and measured concentrations of DO) at σ_θ = 26.8 (50–900 m) (Figure 2) manifest the general features of the intermediate-water formation and transformation in the northern North Pacific (NPIW) [*Reid*, 1965; 1997]. Low salinity and high oxygen (low AOU) tongues are observed in the Bering Sea, Okhotsk Sea and the Kuroshio - Oyashio mixed zone, and are stretched northeastward by the Subarctic current. In *Reid*'s [1997] composite map of the DO distribution at σ_θ = 26.8 for the North Pacific, the 1966 data were considered "more reasonable" than the earlier data [*Reid*, 1965] with higher DO off the Kamchatka Peninsula and northern Japan. There was a difference between the distributions of each of salinity, AOU and the depth of 26.8σ_θ in the subarctic North Pacific in 1948–1956 and 1958–1964 (Figure 2). In 1948–1956, the WSG was meridionally stretched along the Kamchatka Peninsula. Enhanced meridional water transport was observed in the central — northern North Pacific (Figures 2a and 2c). The intermediate waters of the EKC were characterized by high DO and low salinity (Figure 2). In 1958–1964, zonal water transport prevailed in the subarctic North Pacific (Figures 2b and 2d), and the intermediate waters of EKC were characterized by lower DO (higher AOU) than in 1948–1956. However, in the eastern subarctic North Pacific, relatively high oxygen and low salinity signals were observed.

[6] Between 1950 and 2000 the DO distribution on isopycnals in the intermediate layer of the WSG and the Okhotsk Sea underwent interdecadal oscillations and trends [*Andreev and Kusakabe*, 2001]. Interdecadal varia-

0094-8276/02/2002GL015021$05.00

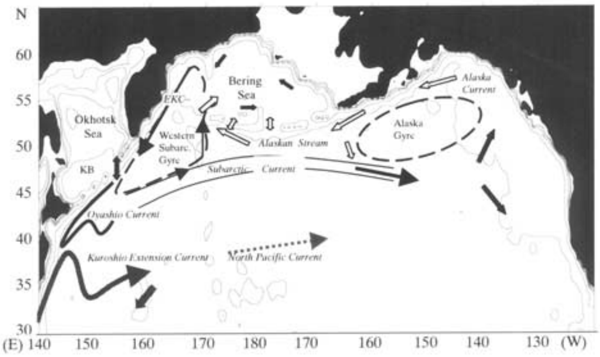

Figure 1. Schematic representation of the circulation in the northern North Pacific (after *Favorite et al.* [1976] and *Ohtani* [1970]). EKC and KB are East Kamchatka Current and Kuril Basin, respectively.

tions in AOU and temperature (salinity) on isopycnals in the intermediate layer can also be seen in the eastern subarctic North Pacific (Figure 3). The temporal variations in AOU and temperature in the WSG display a negative correlation with those in the AG. The interdecadal variation in AOU shows a good correlation with the intensity of the Aleutian Low pressure cell, represented by the North Pacific Index (NPI) (an averaged sea-level atmospheric pressure in the northern North Pacific (30–60N) in winter [*Trenberth and Hurrel*, 1994]) (Figure 3). The cross-correlation coefficient between the NPI, smoothed with a 5-year running mean, and the 1-year lagged AOU at σ_θ = 27.0 in the WSG was −0.70 (n = 31, F statistic is significant at the 0.1% level). The cross-correlation coefficient between the AOU at σ_θ = 27.0 in the AG and the 1–2-year lagged NPI, smoothed with a 5-year running mean, was 0.40 (n = 40, F statistic is significant at the 1% level). From 1950 to 2000 in the intermediate layer of the subarctic Pacific there is an average increase in the AOU (0.3 ± 0.2 (95% confidence interval) μmol kg^{-1} y^{-1} in the WSG and AG) and temperature (0.31 ± 0.28°C century^{-1} in the WSG and 0.54 ± 0.32°C century^{-1} in the AG).

[7] *Andreev and Kusakabe* [2001] showed that the phase and amplitude of the decadal variations in DO in the WSG were close to those in the Kuril Basin of the Okhotsk Sea. The DO concentration in the Subarctic Current waters is determined by the DO concentration in the EKC and the Okhotsk Sea waters. Variations in the formation rate of the intermediate water in the Okhotsk Sea [*Talley and Nagata*, 1995], probably could not generate the strong interdecadal DO signal observed in the subarctic North Pacific. The integral transport of the Okhotsk Sea water to the subarctic North Pacific (3–5 Sv) is several times smaller than the transport rate of the EKC (15–25 Sv) [*Talley and Nagata*, 1995]. Between 1949 and 2000, the changes in DO in the Subarctic Current waters were mainly related to the changes in DO in the EKC water. When the DO in the EKC water was high (1949–1954) there was also relatively high DO in the Subarctic Current water and vise versa (1959–1966 and 1997–2000). A high oxygen and low temperature signal (advected by the Subarctic Current) appeared in the eastern subarctic with a ~10-year delay, compared with the western subarctic (Figure 3).

[8] In 1981 and 1984, anomalous high DO (low AOU) and low temperature waters were observed in the intermediate layer of the Alaska Gyre (Figure 3). During the mid 1980s relatively high tritium concentrations on the 26.8σ_θ and 27.0σ_θ surfaces were found in the Alaska Gyre [*Van Scoy et al.*, 1991a]. The observed high concentrations of tritium were related to enhanced cross-isopycnal mixing [*Van Scoy et al.*, 1991a] or direct winter ventilation of the intermediate layer [*Van Scoy et al.*, 1991b] in the Alaska Gyre. Direct ventilation of the intermediate layer of the Alaska Gyre may occur when the Aleutian Low is strong and many severe winter cyclones pass through the Gulf of

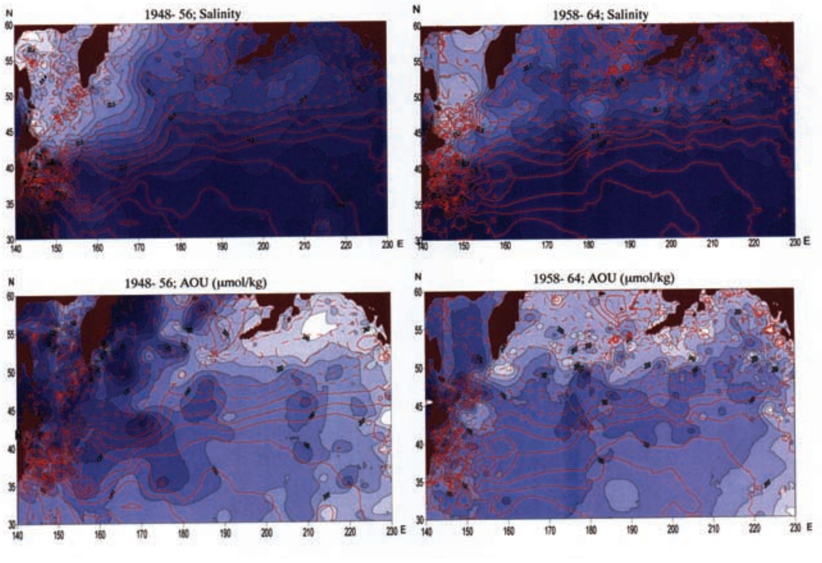

Figure 2. Composite maps of salinity and AOU (DOequil. - DO) (μmol kg^{-1}) distribution at σ_θ = 26.8 (50–900 m) in the North Pacific in 1948-56 and 1958-64. The depth of σ_θ = 26.8 is shown by red dotted (50–200 m) and solid (250–900 m) lines.

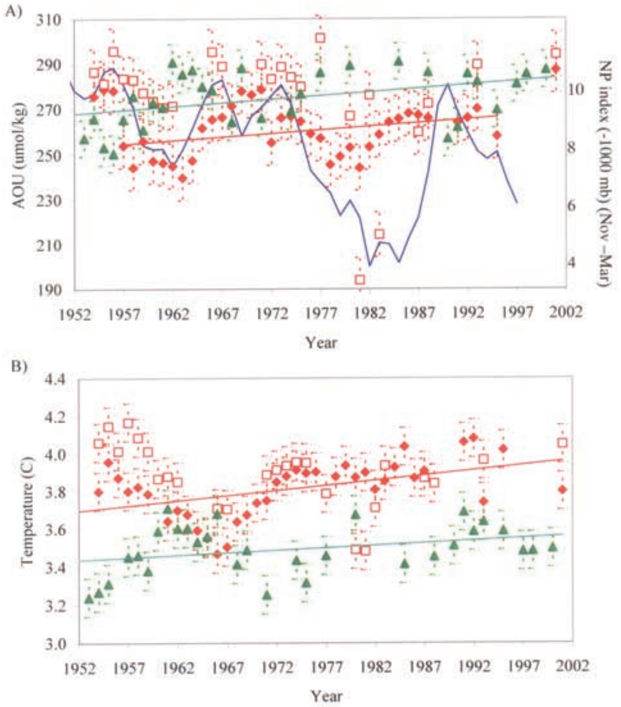

Figure 3. Temporal variations in (A) AOU (μmol/kg) and (B) temperature in the western (~48–60°N, 160–170°E) (green triangles) and eastern (solid red diamonds - 49–52°N, 142–147°W; open red squares - 55–59°N, 141–150°W) subarctic Pacific at σ_θ = 27.0. AOU and temperature data were grouped by year and then for each group an average and its 95% confidence intervals (error bars) were computed. Red and green solid lines are the computed trends in (A) AOU (0.3 ± 0.2 μmol kg^{-1} y^{-1} in the WSG and AG), and (B) temperature (0.31 ± 0.28°C century^{-1} in the WSG and 0.54 ± 0.32°C century$_{-1}$ in the AG). The blue line (A) shows the temporal variation in the North Pacific index, smoothed with a 5-year running mean.

Alaska (such as between 1980 and 1990) [*Van Scoy et al.*, 1991b]. Another possibility is that NPIW was initially ventilated in the northwestern North Pacific during the 1960s and then the high oxygen (and tritium) water was advected to the Alaska Gyre. However, this possibility was rejected by *Van Scoy et al.* [1991b], because in 1987 the concentration of tritium in the EKC was lower than that in the Alaskan Gyre (taking into account the loss of tritium due to mixing and decay during transport by the Subarctic Current). In the 1980s, the significant deep-water formation did not take place in the Bering Sea, and the EKC was characterized by low DO. However, in the late 1960s and early 1970s, there were higher DO concentrations in the EKC and Subarctic Current. NPIW ventilated in the northwestern North Pacific during the 1960s would have received larger amounts of tritium than water that is currently being ventilated, because maximum surface-tritium values were observed in the high northern latitudes during the mid 1960s [*Van Scoy et al.*, 1991b]. Therefore, the observed high oxygen and tritium waters in the Alaska Gyre in the 1980s may have originated in the western subarctic North Pacific in late 1960s-early 1970s and then advected to Alaska Gyre.

3. Discussion

[9] The observed changes in the EKC can be related to variations in the formation of dense water in winter, and thus the changes in the ventilation of the intermediate layer in the Bering Sea. The stratification of the subarctic North Pacific is determined by a strong halocline located at the base of the surface-water layer (~100 m depth). The halocline prevents the deepening of the upper water layer due to winter cooling because the surface water is too fresh [*Warren*, 1983]. The necessary component for deep ventilation is the salt supply. It can be added to seawater as brine during the formation of ice in the shelf areas of the Bering Sea [*Schumacher et al.*, 1983]. Another source of salt for the surface layer of the Bering Sea is the advection of the more saline water from low latitude areas through the Aleutian Islands straits. Figure 4 shows the temporal variations in salinity at the lower boundary of the surface layer (90–100 m) in the southern Bering Sea. Variation in the transport of high-salinity water to the Bering Sea should be related to the variation in the atmospheric forcing. Figure 4 indicates that there is a good correlation (r = 0.42, n = 38, F statistic is significant at the 1% level) between the surface salinity in the southern part of the Bering Sea and the NPI. Data of the NOAA-CIRES Climate Diagnostics Center shows that there is a strong correlation between the NP index and the surface meridional wind in the central subarctic Pacific. The cross - correlation coefficient between the NPI and the surface meridional wind (October to March: 1958 to 2000) is ≥0.9 (courtesy of the NOAA-CIRES Climate Diagnostics Center). A low NPI corresponds to a strong Aleutian Low over the NPSG, with an enhanced zonal wind component in winter. A high NPI reflects the prevailing meteorological situation in winter, with a high-pressure ridge over the central Pacific from the subtropics to the subarctic, and low pressure over the eastern and western

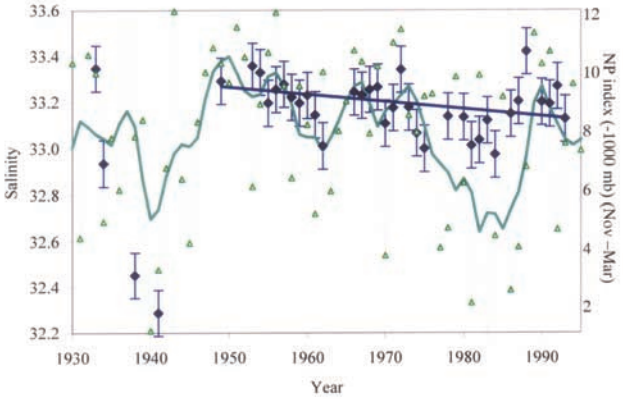

Figure 4. Temporal variations of surface-water (90–100 m) salinity in the Bering Sea (~50°–60°N, 180°–170°W) (blue diamonds), and the North Pacific Index (green triangles). The blue solid line is the computed trend in salinity (−0.31 ± 0.22 century^{-1}). The green thick solid line is the NP index over time, smoothed with a 5-year running mean.

North Pacific [*Ponomarev et al.*, 1999], and thus an increased meridional wind component. Such meteorological conditions lead to increased meridional transport of saline water from low to high latitudes in the central North Pacific, and thereby trigger the formation of dense water (and intermediate layer ventilation) in the Bering Sea (1950–1955, 1970–1973 and 1990–1992).

[10] A decrease in the surface water salinity, and thus an increase in the stratification in the eastern subarctic Pacific over the last 60 years, was shown by *Freeland et al.* [1997]. Such changes can be related to increases in precipitation over the northeastern North Pacific in the absence of any processes such as advection [*Freeland et al.*, 1997]. The decrease in surface salinity in the Bering Sea between 1960 and 2000 (-0.31 ± 0.22 century^{-1}) (Figure 4) (and thus increase in stratification) can be attributed to the decrease in the meridional salt transport, and thereby reduction in the overturning of intermediate layer. This should result in increased AOU, and increased temperature (increased salinity) on isopycnals in the intermediate layer of the subarctic North Pacific. The increase in AOU in the intermediate layer coinsides with a decrease in the NP index with a rate of 0.06 ± 0.04 (95% confidence interval) mb y^{-1} [*Andreev and Kusakabe*, 2001].

[11] The observed trends in salinity of the surface water of the Bering Sea, and DO in the intermediate layer of the subarctic North Pacific are in good agreement with the prediction of coupled ocean/atmospheric models using a changing climate scenario [*Manabe and Stouffer*, 1993; *Sarmiento et al.*, 1998; *Matear and Hirst*, 1999]. But also, the observed trends in the DO and salinity may be a natural event that probably took place previously in the North Pacific around 1750 and 1905 [*Biondi et al.*, 2001].

4. Conclusion

[12] By using DO data we have shown that the variations in the intermediate layer of the subarctic North Pacific during last 50 years are consistent with the simulations of coupled ocean/atmosphere models using an anthropogenic climate-warming scenario: the existence of high amplitude decadal variations with a tendency to decreases in DO. The oscillations and trends in the DO of the intermediate waters of the North Pacific subarctic were mainly due to variations in saline water supply to the Bering Sea and, thereby changes in the ventilation of intermediate layer. There is a good correlation between these changes and the changes in the atmospheric circulation pattern over the North Pacific, demonstrated by the North Pacific Index.

[13] **Acknowledgments.** We thank an anonymous referees for valuable comments which helped to improve the paper.

References

Andreev, A. G., and M. Kusakabe, Interdecadal variability in dissolved oxygen in the intermediate water layer of the Western Subarctic Gyre and Kuril Basin (Okhotsk Sea), *Geophys. Res. Let.*, *28*, 2453–2456, 2001.

Biondi, F., A. Gershunov, and D. R. Cayan, North Pacific Decadal Climate Variability since 1961, *J. Of Climate*, *14*, 5–10, 2001.

Freeland, H., K. Denman, C. S. Wong, F. Whitney, and R. Jacques, Evidence of change in the winter mixed layer in the Northeast Pacific Ocean, *Deep -Sea Res.*, *44*, 2117–2129, 1997.

Favorite, F. A., A. J. Dodemead, and K. Nasu, Oceanography of the Subarctic Pacific Region, 1960-71, *Bulletin of the International North Pacific Fishery Commission*, *33*, 1–187, 1976.

Manabe, S., and R. J. Stouffer, Century- scale effects of increased atmospheric CO2 on the ocean — atmospheric system, *Nature*, *364*, 215–218, 1993.

Matear, R. J., and A. C. Hirst, Climate change feedback on the future oceanic CO2 uptake, *Tellus*, *51B*, 722–733, 1999.

Ohtani, K., Relative transport in the Alaska Stream in winter, *J. Ocean. Soc. Japan*, *26*, 271–282, 1970.

Ponomarev, V. I., O. O. Trusenkova, D. D. Kaplunenko, E. I. Ustinova, and A. M. Polyakova, The ENSO Signal in the Northwestern Pacific, Impacts of the 1997/98 El Nino Event on the North Pacific Ocean and its Marginal Seas, *PICES Sci. Rep.*, *10*, 9–32, 1999.

Reid, J. L., Intermediate waters of the Pacific Ocean, *The Johns Hopkins Oceanographic Studies*, *2*, pp. 1–85, 1965.

Reid, J. L., On the total geostrophic circulation of the pacific ocean: flow patterns, tracers, and transports, *Prog. Oceanog.*, *39*, 263–352, 1997.

Sarmiento, J. L., T. M. C. Hughes, R. J. Stouffer, and S. Manabe, Simulated response of the ocean carbon cycle to the anthropogenic climate warming, *Nature*, *393*, 245–248, 1998.

Schumacher, J. D., K. Aagaard, K. C. H. Pease, and R. B. Tripp, Effects of shelf polynya on flow and water properties in the northern Bering Sea, *J. Of Geophys. Res.*, *88*, 2723–2732, 1983.

Talley, L. D. , and Y. Nagata (Eds.), The Okhotsk Sea and Oyashio region, *PICES Sci. Rep.*, *2*, pp. 1–227, 1995.

Trenberth, K., and J. W. Hurrel, Decadal atmosphere – ocean variations in the Pacific, *Climate Dyn.*, *9*, 303–319, 1994.

Van Scoy, K. A., R. A. Fine, and H. G. Ostlund, Two decades of mixing tritium into the North Pacific Ocean, *Deep Sea Res.*, *38*, 5191–5219, 1991a.

Van Scoy, K. A., D. B. Olson, and R. A. Fine, Ventilation of North Pacific Intermediate Waters: The Role of the Alaskan Gyre, *J. Of Geophys. Res.*, *96*, 16,801–16,810, 1991b.

Warren, B. A., Why is no deep water formed in the North Pacific?, *J. Mar. Res.*, *41*, 327–347, 1983.

A. Andreev and S. Watanabe, Japan Marine Science and Technology Center, 2- 15 Natsushima- cho, Yokosuka, 237–0061, Japan. (andreev@jamstec.go.jp)