# Deep convection and brine rejection in the Japan Sea

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[1] Direct water mass renewal through convection deeper than 1000 m and the independent process of dense water production through brine rejection during sea ice formation occur at only a limited number of sites globally. Our late winter observations in 2000 and 2001 show that the Japan (East) Sea is a part of both exclusive groups. Japan Sea deep convection apparently occurs every winter, but massive renewal of bottom waters through brine rejection had not occurred for many decades prior to the extremely cold winter of 2001. The sites for both renewal mechanisms are south of Vladivostok, in the path of cold continental air outbreaks. *INDEX TERMS:* 4283 Oceanography: General: Water masses; 4243 Marginal and semienclosed seas; 4223; 4215 Climate and interannual variability (3309). **Citation:** Talley, L. D., V. Lobanov, V. Ponomarev, A. Salyuk, P. Tishchenko, I. Zhabin, and S. Riser, Deep convection and brine rejection in the Japan Sea, *Geophys. Res. Lett.*, *30*(4), 1159, doi:10.1029/2002GL016451, 2003.

## 1. Introduction

[2] Overturn in the ocean that reaches to greater than 1000 m depth is often referred to as "deep convection". Such deep ventilation occurs in only a very few regions, generally in confined patches associated with local cyclonic circulation (reviewed in *Marshall and Schott* [1999]). Deep convection occurs in the Greenland Sea [*Rudels*, 1990], Labrador Sea [*Clarke and Gascard*, 1983], Mediterranean Sea [*Schott and Leaman*, 1991], and Weddell Sea [*Gordon*, 1982].

[3] The second process that creates the ocean's densest waters is the rejection of salty brine during sea ice formation. When brine rejection occurs in relatively shallow water the density increase can be significant. Brine rejection into shelf waters along the Antarctic continental margin [e.g. *Rintoul*, 1998; *Gordon*, 1998] and the Arctic margins [*Aagaard et al.*, 1981] produces dense waters that sink to the abyssal ocean. Brine rejection in the deep Greenland Sea assists the density increase that results in deep convection [*Rudels*, 1990]. Brine rejection in the Okhotsk Sea is the densest source of water in the North Pacific [*Talley*, 1991].

[4] Our winter observations add the Japan Sea (Figure 1) to these small groups of deep convection sites and regions with deep "ventilation" through brine rejection. The observed deep structures were complex superpositions of relatively unstratified layers, like those identified in other deep convection regions. While it had been suggested that the densest Japan Sea water formation is located south of Vladivostok [*Kawamura and Wu*, 1998; *Senjyu and Sudo*, 1993] and that brine rejection in Peter the Great Bay (PGB) creates dense water [*Ponomarev et al.*, 1991], ours were the first direct observations. The summer 1999 survey covered the Japan Sea, with the high salinity accuracy necessitated by the small variations below 500 m, and with full sampling for oxygen, nutrients and carbon, all having larger deep variations than salinity. The winter (February–March) 2000 survey (hereafter "W2000") concentrated on the Japan Sea north of the subpolar front (40° to 40°30′N). The winter (February–March) 2001 survey (hereafter "W2001") revisited, in a much colder winter [*Kim et al.*, 2002; *Senjyu et al.*, 2002], the deep convection and brine rejection locations observed in W2000.

## 2. Japan Sea Properties and Forcing

[5] The Japan Sea (Figure 1) is a nearly completely enclosed marginal sea, with a typical depth of 3000 to 3650 m in the Japan Basin. Warm, saline, low density waters enter from the south through the shallow (130 m deep) Tsushima Strait. Cooled, freshened and somewhat denser Japan Sea waters exit to the Pacific and Okhotsk Seas through Tsugaru, Soya and Tatar Straits. All waters between potential density $\sigma_\theta = 26.0$ (Tsushima Strait inflow density) and the bottom density of $\sigma_\theta = 27.352$ (central Japan Basin, from our summer 1999 survey) are produced within the Japan Sea.

[6] The Japan Sea's dense water is produced in the cold, fresh north, which has a subpolar cyclonic circulation separated from the subtropics by the east-west subpolar front, apparent in sea surface temperature, with many mesoscale features (Figure 1b). Surface water is carried to PGB and the deep convection region south of there by the subpolar western boundary current, the Primorye Current. In winter the Primorye Current separates and flows offshore (southward-extending cold tongue at about 130°30′E in Figure 1b), as traced by subsurface autonomous floats that profiled from the surface to 800 m every 10 days (track in Figure 1a). This separation is likely due to the Siberian northwesterly jet that blows onto the Japan Sea at PGB [*Kawamura and Wu*, 1998. Large, warm anticyclonic eddies that reach to the ocean bottom are commonly found just west of the cold tongue (41°N, 131°E), under anticyclonic


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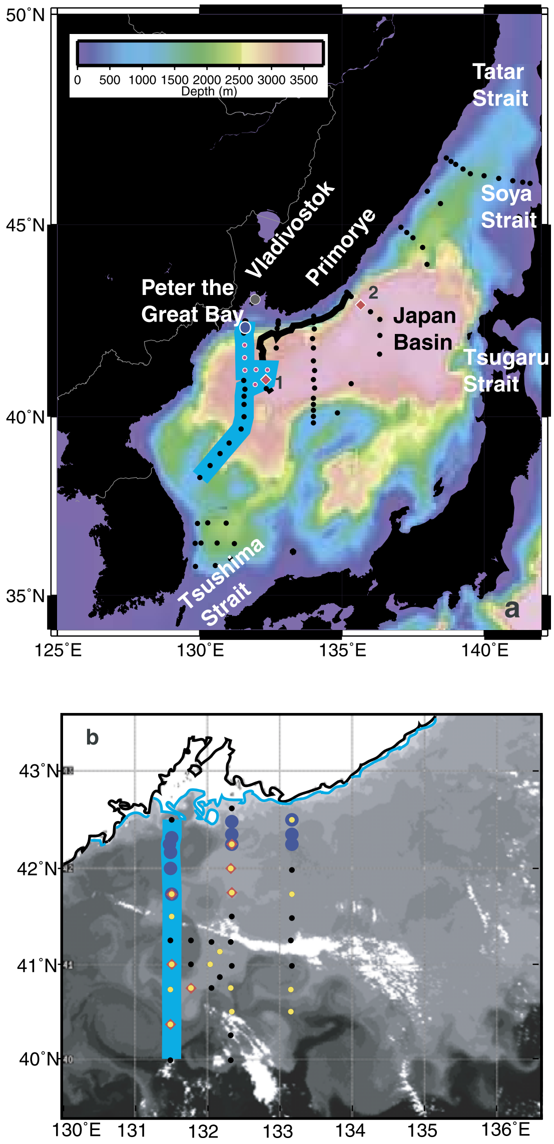


**Figure 1.** (a) Feb. 28–Mar. 15, 2000, stations with bathymetry (m). (b) Feb. 24–Mar. 3, 2001 with NOAA AVHRR sea surface temperature from 25 Feb. 2001 (from S. Ladychenko). Light is cold. Clouds, ice, land: white. Ice edge: light blue curve. Sections in Figure 4: thick blue. Black track: subsurface float Aug. 2, 1999–Feb. 27, 2000. Red diamonds - deep open ocean mixing (900–1500 m); magenta dots - high oxygen on isotherms at 500–1000 m depth; blue dots - brine rejection; yellow dots - surface oxygen saturation <94%.

wind stress curl. Surface salinity is higher (34.10) in this cold tongue than along the coast, and although slightly warmer (0.6 to 1.6°C), creates the densest surface water outside the ice-covered area ($\sigma_\theta > 27.31$ in W2000).

[7] The winter surface heat loss associated with the northwesterlies is large (400–750 Watts $m^{-2}$) just south of PGB [*Kawamura and Wu*, 1998; Clive Dorman, personal communication, 2003]. Ice begins forming in December. The northwesterlies at PGB maintain coastal polynyas with continuous ice formation and brine rejection.

[8] W2000 was slightly colder than average, as seen in air temperature at Vladivostok (Figure 2). W2001 was extremely cold [*Kim et al.*, 2002; *Senjyu et al.*, 2002], with air temperature 3–5°C below normal, resulting from an anomalously strong Siberian high and deep Aleutian Low. Sea surface temperature in W2001 in the northern Japan Sea was more than 2°C below the 30-year average (Japan Meteorological Association and National Oceanic and Atmospheric Administration websites). The last similarly cold winter was in 1976–1977. Sea ice formed in winter 2001 along the southern Sakhalin and Hokkaido coasts, which is unusual. Ice cover in PGB was slightly more extensive than in W2000.

## 3. Observations of Deep Mixing

[9] The W2000 cruise took place the week after and the W2001 at the end of the coldest winter conditions. Deep convection signatures are: thick well-mixed layers, undersaturated surface oxygen, and enhanced oxygen on isotherms between 500 and 1500 m. "Deep" is relative to the pycnocline depth of several hundred meters. The oxygen signal reflects recent vertical mixing of surface layers with more oxygen-depleted waters from below, with insufficient time for resaturation at the surface.

[10] Thick, well-mixed layers were found at 2 stations in W2000 and at 7 stations in the more spatially-limited, colder W2001 (Figures 1 and 3). In W2000, the two stations were: "1" in the cold tongue south of PGB, with thick layers to deeper than 1200 m, enhanced oxygen at 500–1000 m, and low surface oxygen saturation at many adjacent stations; and "2" in the northeastern Japan Basin with a well-mixed layer to about 400 m. Region "2" was probably an encounter with mixing typical of the whole subpolar gyre axis, based on the depth of high oxygen saturation throughout, and is not especially "deep". The numerous stations in W2001 with deep mixing were located mostly near "1", with a few subsurface thick layers swept into the warm anticyclonic eddy to the west.

[11] The W2000 station "1" was actually a double mixed layer, with a 500 m layer overlying a second layer extending to about 1100 m (Figure 3). In W2001, the thick well–mixed layers were equally complex. The best–mixed layers (to 800–1000 m) in W2001 occurred at three stations over the topographic spur (Mt. Siberia) at 132°20′E. All had low surface oxygen saturation (<82% for two and 92% for one).

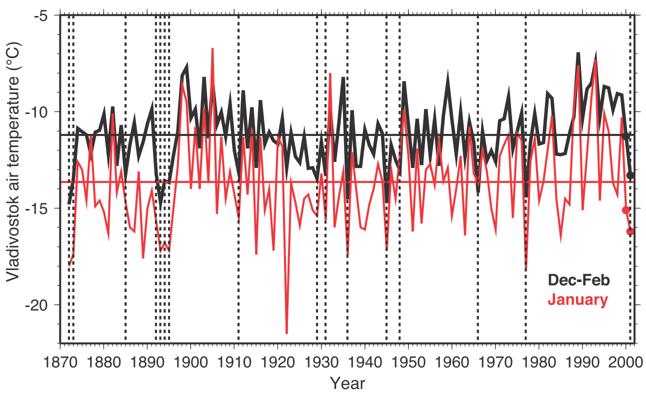


**Figure 2.** Air temperature at the Vladivostok WMO station. Red: Jan. monthly averages and mean (line). Black: Dec/Jan/Feb averages and mean. Heavy dots: W2000 and W2001. Vertical lines: DJF average temperature <–13°C.

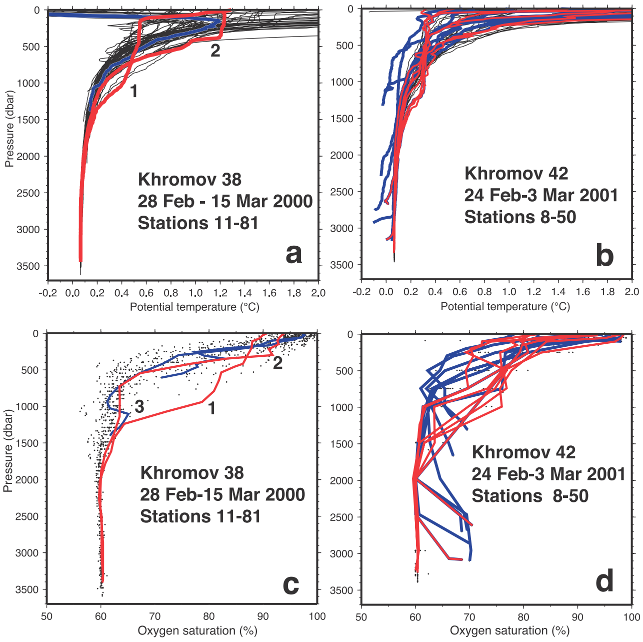


**Figure 3.** Deep convection and brine rejection profiles. Potential temperature (°C) for (a) all W2000 and (b) all W2001 stations. (c) and (d) oxygen saturation (%) profiles for the same. Red: profiles with deep ventilation (>900 m); blue: with brine rejection. CTD temperatures and discrete oxygen samples (24/station in W2000 and 12 in W2001).

Four stations had well-mixed layers of 800–900 m thickness separated from the sea surface by a well stratified layer of 300–400 m thickness and high oxygen saturation. Three of these stations were within 10 km of the front separating the cold tongue and warmer waters (Figure 1b), suggesting that the mixed layers were pulled downward beneath the surface waters of the anticyclonic eddy. The salinities of the thick, well-mixed layers were higher than the ambient waters, indicating a northeastern source.

[12] Winter surface densities were high where surface oxygen was undersaturated. These were most extreme at the deep mixing stations. Surface oxygen saturation was much lower overall in W2001 than in W2000. Dynamic height at the surface relative to deeper levels was low along the subpolar gyre axis, and was lowest at the W2001 stations with deep mixed layers along 132°20′E, suggesting enhanced cyclonic flow. This region of low surface oxygen and low dynamic height could be considered a convection "patch" [*Marshall and Schott*, 1999], within which individual mixing events of small horizontal extent occurred at different times. Despite the record cold and widespread mixing in W2001, there was no evidence of convection to the bottom.

[13] The source of water for the cold tongue and convection "patch" was the Primorye Current, based on satellite surface temperature and on subsurface float tracks. Two profiling floats that took this path in W2000 showed relatively well-mixed waters starting in mid-January and resembled the W2000 shipboard profiles overall, but not the more completely mixed layers found at "1".

[14] The heat loss required to produce the March 2000 deep mixing profile from summer waters in the Primorye Current was about 500 W/m$^2$ if lost over three months, consistent with *Kawamura and Wu* [1998] and Dorman (personal communication, 2003). Apparent heat loss in W2001, calculated the same way, was 1.5 to 2 times greater than in W2000, with integrated heat losses of up to 1000 W/m$^2$ if computed over 3 months.

## 4. Observations of Brine Rejection

[15] Every winter, brine rejection creates very high salinity waters in the shallow parts of PGB, with dense, salinity-enriched waters found out to the continental shelf edge. However, the amount of brine-rejected water that influences the open Japan Sea, after spilling down the slope and mixing with ambient water, varies dramatically. Our W2000 observations are probably typical of most years, with enriched oxygen at mid-depth (1200 dbar and 27.325$\sigma_\theta$) on the continental slope. A similar feature was apparent even in the summer 1999 survey.

[16] The surprise and bonus of the cold W2001 cruise was the large, widespread volume of brine-rejected water, observed in PGB, down the continental slope and at great depth along the base of the continental slope (stations in Figure 1b, deep oxygen penetration in Figures 3 and 4). The properties (temperature, salinity and oxygen content) of the brine-rejected waters diverged widely from station to station, suggesting separate plumes of the original dense shelf water as it plunged down the slope. The potential temperature of the new bottom water was −0.12° to 0.05°C, much colder than the climatological, widespread abyssal potential temperature of 0.06° to 0.07°C (Figure 3).

[17] Following the February 2001 cruise, several additional short cruises documented the development and mixing of these newly-ventilated waters [*Lobanov et al.*, 2002]. Similar-strength renewal did not occur in 2001–2002, but the newly-ventilated bottom waters from W2001 were still apparent in the central Japan Basin in April 2002, with smaller temperature and salinity anomalies.

## 5. Discussion

[18] Japan Sea winter subpolar mixed layers of 300–400 m depth are similar to the North Atlantic's Subpolar Mode Water [*Senjyu and Sudo*, 1993; *McCartney and*

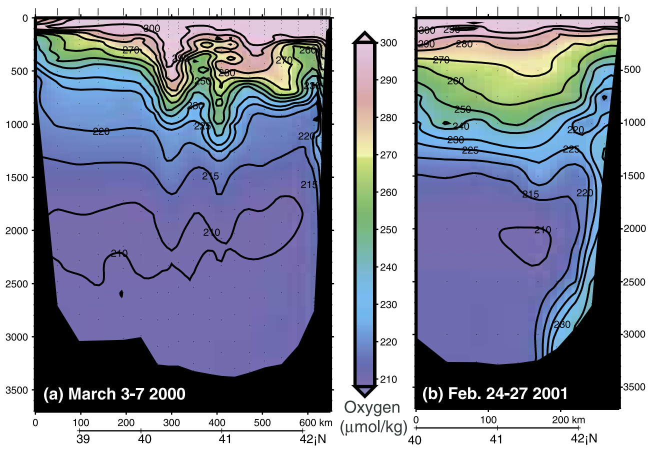


**Figure 4.** Oxygen (µmol/kg) along 131°30′E: (a) March 3–7, 2000 and (b) Feb. 24–27, 2001. Sections in Figure 1.

*Talley*, 1982], culminating in convection to greater than 900 m in the northwest, resembling Labrador Sea Water formation. Japan Sea convection is also similar to convection in the Gulf of Lions [*Schott and Leaman*, 1991]. Both have strong northwesterlies creating large air-sea fluxes, a boundary current that turns southward, localized cyclonic doming, and connection to the open ocean through shallow straits, resulting in less stratified deep waters than in the open ocean. The two regions are characterized by cyclonic wind stress curl [*Kawamura and Wu*, 1998; *Heburn*, 1987], which may precondition through reduced stratification.

[19] Our observations suggest that brine rejection is the main ventilation mechanism, at least in recent decades, for the bottommost waters of the Japan Sea because: there was a small signal of brine rejection even in the previous, normal winter; deep convection in even the very cold winter did not reach past mid-depths; and winters as cold as 2000–2001 occur every twenty to thirty years (Figure 2). (A prolonged period of different, colder conditions might however allow deep convection to renew bottom waters.)

[20] Japan Sea properties are not in steady state. New bottom waters escape only through upwelling and downward diffusion of properties, within the decadally-changing stratification [*Kim and Kim*, 1996]. A deep warming and oxygen decrease since the 1930s [*Minami et al.*, 1998; *Ponomarev et al.*, 1996; *Gamo et al.*, 1986; *Kim et al.*, 1998] continued into our surveys. The very cold W2001 produced much denser shelf water ($\sigma_\theta$ = 27.49 to 27.7) than the average bottom water (nearly uniform and around $\sigma_\theta$ = 27.35). The new bottom waters in W2001 were colder than on all but 2 (in 1933) of the World Data Center hydrographic stations from the 1920s to the present. Bottom water oxygen also became inhomogeneous, up to 240 μmol/kg on some stations but at the 1999–2000 value of 215 μmol/kg at others (Figure 4). Continuing Japan Basin surveys will show whether the W2001 renewal reversed deep oxygen and temperature trends.

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