# Oyashio west path culmination as the consequece of a rapid thermohaline transition in the Pacific Subarctic

**Konstantin ROGACHEV**

Pacific Oceanological Institute, Vladivostok, Russia

**Abstract**

Oyashio and Kamchatka Currents are western boundary currents of the Pacific subarctic gyre. The Kamchatka Current transports fresh water in the surface layer to the Sea of Okhotsk. Large Oyashio eddies propogate against the current and bring warm subtropical water in their cores up to the Strait of Boussole. Here, I present the evidence of the recent rapid change of stratification in the Oyashio and Sea of Okhotsk during the last decade. There were significant changes in the thermohaline structure in the Western Subarctic during the period from 1990 to 1997. The transition began during the reinforcement of the Coastal Oyashio. The main consequences of this thermohaline transition from one ocean state to another are changes of the Oyashio path and restratification of its water. It indicates that the ocean climate in the Western Subarctic depends strongly on the Oyashio path.

## Introduction

The waters of the Kamchatka Current, having warm water at depth of 200–300 m, enters the Sea of Okhotsk through the deep Kuril Straits (Fig. 1). This current brings cold and fresh water in the surface layer (0–100 m). Kamchatka Current water, penetrating through these Straits, forms a cyclonic circulation inside the Sea and mixes with Soya Current water (SC in Fig. 1) in the Kuril Basin (Alfultis and Martin, 1987). There is significant cooling of the Kamchatka Current water in the Sea of Okhotsk. While the Alaska Current brings warm water to the Western Subarctic, most of the water is of the Western Subarctic formed by the lateral mixing of the Kamchatka Current water and cold water of Okhotsk Sea origin (Ohtani, 1970). Therefore, the exchange between the Sea of Okhotsk and North Pacific is essential for cooling, freshening and change of stratification at intermediate depths (100–800 m). The Soya Current flows along the Hokkaido coast and brings the warm Japan Sea water into the sea (Takizawa, 1982). This current is known to be driven by a large difference in sea level between the Japan and Okhotsk Seas (Takizawa, 1982; Ohshima, 1994). The seasonal cycle of this current is clear, and Soya inflow is not observed from December to March, due to either higher Okhotsk Sea levels or the low difference of the sea level across the Strait.

A principal feature of the Pacific Subarctic is its high stratification. Wintertime convection there seems to be limited to the upper 150 m (Reid, 1973). This is quite different compared with the northern North Atlantic. The reason for no deep convection in the northern North Pacific is that the surface water is too fresh. According to Warren (1983), the low surface salinity is due partly to a low evaporation rate, which in turn, is due to a relatively low surface temperature.

Recently, the Sea of Okhotsk interannual cycle was studied by Yang and Honjo (1996). They found its hydrographic structure is sensitive to interbasin exchanges between the Japan and Okhotsk Seas. The doubling of the Soya Current transport (SC on Fig. 2) results in higher salinity in the surface and deepens vertical mixing. Reducing the Soya Current leads to more freshening of the mixed layer, restricting deep vertical mixing.

Here, I consider a case of the rapid thermohaline transition from low stratified periods with different thermohaline structure in the western Subarctic. The first one was observed 7–8 years ago prior to the thermohaline transition in the North Pacific which occurred in 1990–1997. I described this case using the INPOC (International North Pacific Ocean Climate Study; see Rogachev et al. (1996a,b, 1997)) array of CTD stations in the Oyashio. One of the basic findings of this project was the discovery of the thermohaline transition in the subarctic Pacific. This means there are rapid and significant changes in the water column properties to a depth of 1000 m in western subarctic boundary currents. A main consequence of this transi-

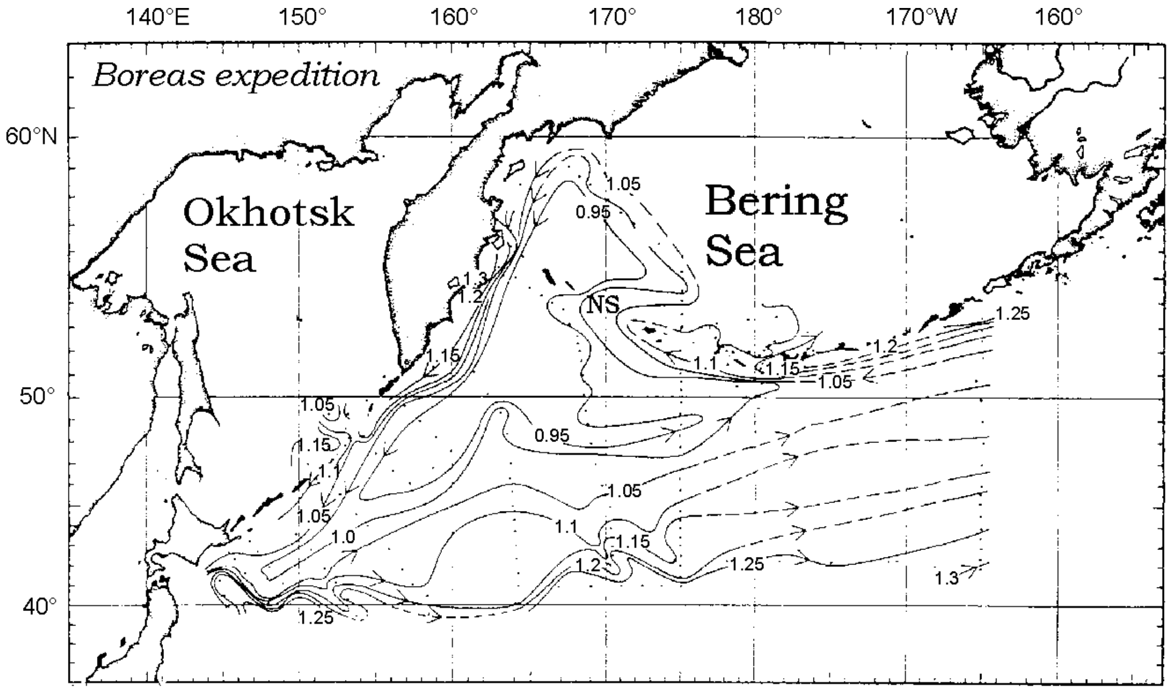


**Fig. 1** Geopotential anomaly at the sea surface relative to 1000 dbar (10 J/kg) (after Reid (1973)). NS is Near Strait.

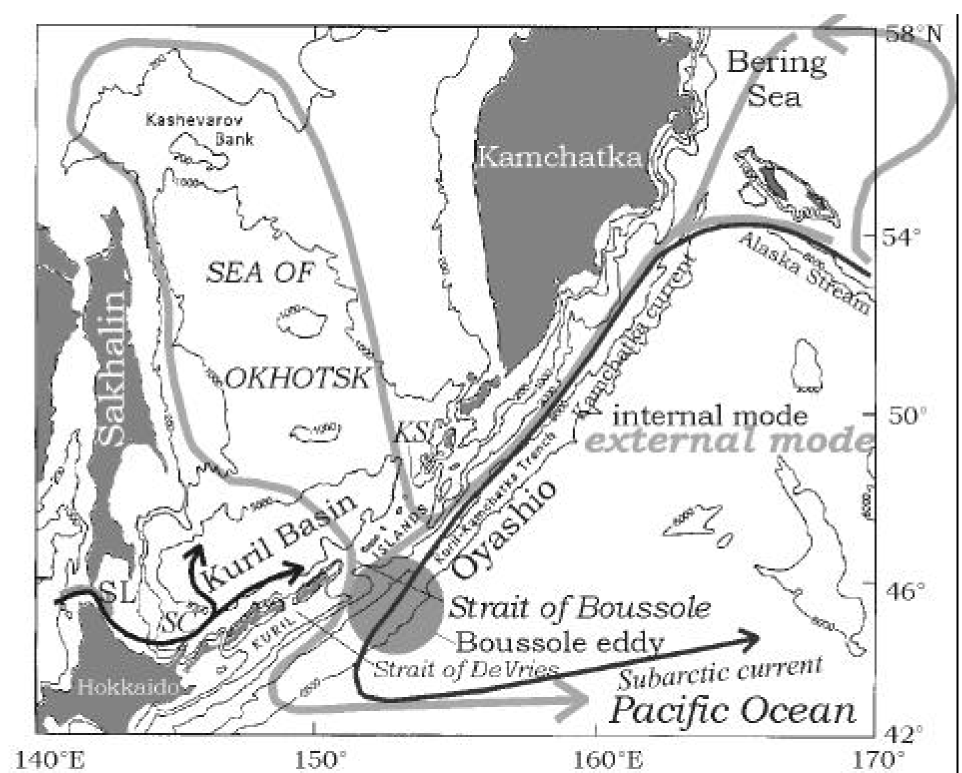


**Fig. 2** Scheme of the two circulation modes based on the recent thermohaline transition in the western subarctic. Black and grey lines represent internal and external modes, or different circulation regimes. KS is Krusenshtern Strait, SL is Strait of Laperouse, SC is Soya Current.

tion is the change of the Oyashio path and restratification of its water. The stratification was destroyed before the transition due to a high inflow of saline subtropical waters to the Sea of Okhotsk and Oyashio in 1990 and a weak transport of the subarctic water by the coastal Oyashio (Rogachev, 1997). However, during the transition there was a significant change of water mass thermohaline structure and a change of the main Oyashio path (Fig. 3). It appears that notable changes have occurred also within large areas of the Arctic Ocean and subarctic Pacific during the past decade (Latif and Barnett, 1996; Qüadfasel et al., 1991)

## Data and method

The initial data were collected while carrying out the INPOC project (Rogachev et al., 1996a,b, 1997). The program involved four cruises in the Oyashio from 1990–1992 and was continued by the Pacific Oceanological Institute (POI) in 1993, 1994 and 1996. Most of those cruises covered the area with a high resolution station grid (the distance between stations was 18–20 km). From the analysis of these data it is possible to determine the horizontal structure of the Oyashio fresh-core eddies, which are the major features of the region (Rogachev and Goryachev, 1991; Rogachev et al., 1996a,b). The

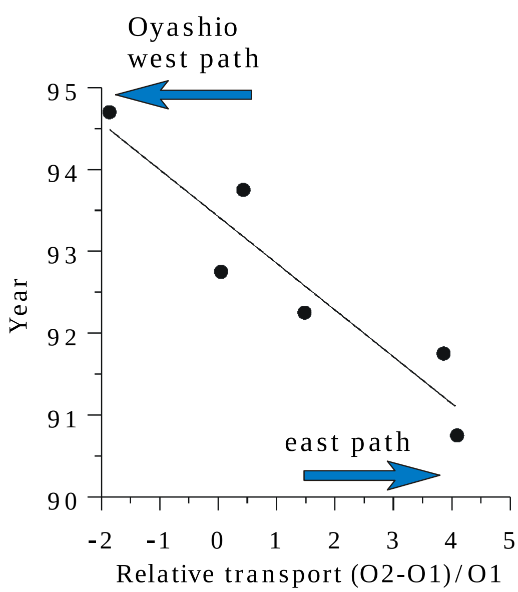


**Fig. 3** Transport difference between offshore (O2) and coastal Oyashio (O1) relative to the coastal Oyashio in 1990. Note a shift to the Oyashio west path.

added data I used is the study conducted on board the R/V *Hokko Maru* under the joint project of the Hokkaido National Fisheries Research Institute (HNFRI) and the Pacific Research Institute of Fisheries and Oceanography (TINRO) (Kono and Kawasaki, 1997). I used potential vorticity as the property of the stratification, which is determined as $Q = f/r(\partial s_q/\partial z)$, where $f$ is the Coriolis parameter, $r$ the density, $z$ is the vertical coordinate, and $s_q$ is sigma theta. To estimate $Q$, the density was calculated at standard depths.

## Results

### *Rapid changes in the western subarctic*

For the past 7 years, evidence of the thermohaline transition event has appeared within the core of the Pacific and Soya waters entering the Sea of Okhotsk. In 1997 the Pacific water almost completely displaced warm and salty Japan Sea water, whereas the opposite situation was observed in 1990. For instance, high salinity water flowed out to the Pacific Ocean through the Strait of Boussole in 1990. However, the high salinity area was limited by a narrow zone in 1996 and 1997. While Soya warm water inflow was weak, the low salinity subarctic water area enlarged. More dramatic events occurred at the ocean side of the Kuril Islands. For instance, Figure 4 shows rapid penetration of the cold upper layer at sigma-$T$ = 26.3 from Kamchatka to Hokkaido during the 7-yr period. A major consequence of this transition are changes in the stratification and the main Oyashio path from offshore to coastal (Rogachev, 1996b, 1997). I call it Oyashio west path culmination (Fig. 3). Potential vorticity time series show a six-fold increase at 500 db (Fig. 5). In particular, there was a minimum of potential vorticity at 400–500 db in 1990 which, seven years later, became a maximum of the potential vorticity in 1996. This change of potential vorticity vertical distribution reflects variations of the stratification in the Oyashio and its fresh-core eddies.

## Discussion

The present data show that there was a thermohaline transition in the western subarctic during 1990–1997, which is evident in the change of the Oyashio path and its thermohaline structure. There was a prominent penetration of salty Soya Current water to the Sea of Okhotsk in 1990. This process changed stratification and surface salinity.

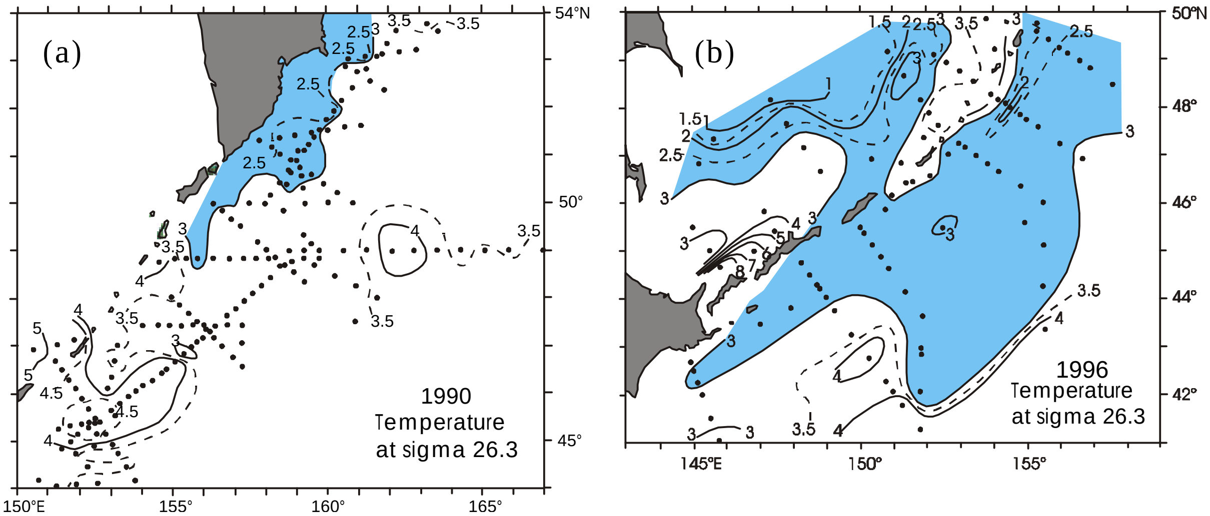


**Fig. 4** Cooling at the surface layer during a thermohaline transition. Temperature at sigma-*T* = 26.3 in (a) August 1990 and (b) August–September 1996. Low-temperature area is shaded.

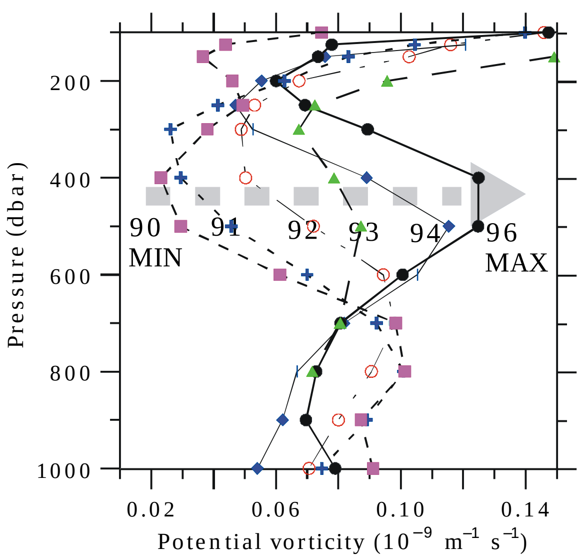


**Fig. 5** Potential vorticity profiles for the central stations in Boussole eddies during the thermohaline transition. Arrow shows increase of stratification from 1990 to 1996.

Stratification was initially destroyed in 1990 by the increased influx of salty water and low southward transport by the Western Subarctic boundary currents (Rogachev, 1997). The vertical profiles of the salinity in the Kamchatka Current have a very sharp halocline at 100–200 m depth (Nagata and Ohtani, 1989). A distinct mesothermal layer (warm subarctic intermediate layer) is associated with this halocline. The halocline off the southern Kuril Islands is almost erased, and salinity decreases much more gradually. The mesothermal layer becomes unclear and its depth is increased in comparison with the Kamchatka Current region. Therefore, the fresh water budget of the Okhotsk Sea should affect the interbasin water exchange between Japan and Okhotsk seas.

The recent Oyashio west path culmination is associated with the cooling of the surface layer (Fig. 4). This cooling of the surface layer provides a feedback for the decrease of evaporation which may sustain the salinity anomalies.


## Acknowledgments

This work was partially supported by the Russian Fund for Basic Research. E. Carmack, B. Lake and J. Love from the Institute of Ocean Sciences, Canada, made significant contributions to the INPOC study. M. Kashiwai and Y. Kawasaki from the Hokkaido National Fisheries Reasearch Institute, Japan, kindly permitted us to use the R/V *Hokko Maru* data for this research.


## References


Alfultis, M.A. and Martin, S. 1987. Satellite passive microwave studies of the Sea of Okhotsk ice cover and its relation to oceanic processes, 1978–82. *J. Geophys. Res., 92,* 13,013–13,028.

Kono, T. and Kawasaki,Y. 1997. Modification of the western subarctic water by the exchange with the Okhotsk Sea. *Deep-Sea Res., 44,* 689–712.

Latif, M. and Barnett, T.P. 1996. Decadal climate variability over the North Pacific and North America : Dynamics and predictability. *J. Climate, 9*, 2407–2423.

Nagata, Y. and Ohtani, K. 1989. The gap in research plans for the subpolar region in the north Pacific. pp. 57–112. In *The Third Japan–US WOCE Workshop*, Kyoto, Japan.

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

Oshima, K.I. 1994. The flow system in the Japan Sea caused by a sea level difference through shallow straits. *J. Geophys. Res., 99*, 9925–9940.

Qüadfasel, D. Sy, A. Wells, D. and Tunik, A. 1991. Warming in the Arctic. *Nature, 350*, 385.

Reed, R.K. and Stabeno, P.J. 1993. The recent return of the Alaskan Stream to Near Strait. *J. Mar. Res., 51*, 515–527.

Reid, J.L. 1973. *Northwest Pacific Ocean Waters in Winter*. The John Hopkins University Press, Baltimore, 96 pp.

Rogachev, K.A. 1997. Recent speeding up of the Pacific subarctic circulation. *International WOCE Newsletter, 26*, 40–42.

Rogachev, K.A. and Goryachev, V.A. 1991. Mixing in warm-core rings of the Kuroshio. *J. Geophys. Res., 96*, 8773–8777.

Rogachev, K.A., Tishchenko, P.Ya., Pavlova, G.Yu., Bychkov, A.S., Carmack, E.C. Wong, C.S. and Yurasov, G.I. 1996a. The influence of fresh-core rings on chemical concentrations ($CO_2$, $PO_4$, $O_2$, alkalinity, and pH) in the western subarctic Pacific Ocean. *J. Geophys. Res., 101*, 999–1010.

Rogachev, K.A., Salomatin, A.S. and Carmack E.C. 1996b. Concentration of pelagic organisms at mesoscale fronts in the western subarctic Pacific: Small fish on long waves. *Fish. Oceanogr., 5*(3/4), 153–162.

Takizawa, T. 1982. Characteristics of the Soya Warm Current in the Okhotsk Sea. *J. Oceanogr. Soc. Japan, 38*, 281–292.

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

Yang, J. and Honjo, S. 1996. Modelling the near-freezing dichothermal layer in the Sea of Okhotsk and its interannual variations. *J. Geophys. Res., 101*, 16,421–16,433.