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Meridional mixing of water masses in the Kuroshio Extension: Origins of North Pacific Intermediate Water anomalies

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NONTECHNICAL SUMMARY

Freshwater layers were discovered at intermediate depths north of the Kuroshio Extension front in February 2013. The anomalous layers of freshwater were determined to have originated in the Sea of Okhotsk, where sea ice and vertical tidal mixing create Okhotsk Sea Mode Water (OSMW). OSMW is the coldest and freshest source of North Pacific Intermediate Water (NPIW) and therefore has a unique temperature, salinity and potential density signature. Of the four stations that had freshwater anomalies, three showed structure in their salinity-depth profiles indicating the presence of some OSMW. However, one station along the Kuroshio Extension exhibited a freshwater layer that appears to be nearly unmixed OSMW at 751m. The percentage of pure OSMW present along the cruise transect was determined using intermediate water from the Western Subarctic Gyre (WSAG), and surface water from the Western Subtropical Gyre (WSTG). Intermediate WSAG and surface WSTG water were the salty, cold and warm maximums, respectively, used in the three-source method of determining water content.

The other, less distinct, freshwater anomalies have traces of OSMW but are not yet well mixed with their surrounding environment. Large eddies could have encapsulated the freshwater parcels and carried them south from the WSAG. Argo floats were able to verify that by observing similar variations in salinity profiles while deployed across the northwestern Pacific. The floats that observed the largest variations in salinity were tracked by GPS in a circular trajectory, which is indicative that they were moving within an eddy, and compared to satellite altimetry of the region.

ABSTRACT

In February 2013, several freshwater anomalies of North Pacific Intermediate Water (NPIW) were observed at six conductivity-temperature-depth (CTD) stations north of 33°30'N. The anomalous layers of freshwater were 100 – 150m thick and ranged in depth from 200 – 900m. The freshest of the anomalies exhibited properties of 33.5 psu and 26.7 σ_θ, which is coincidental with Okhotsk Sea Mode Water (OSMW). Additional anomalies observed north of the concentration of OSMW were less distinct. The variation in salinity was only 0.3 psu and occurred at shallower depths. These additional anomalies were partially mixed parcels containing 67% - 83% OSMW.

Argo floats deployed to the same region recorded similar OSMW signatures. Based on the circular trajectories of Argo float GPS fixes and the variable salinity profiles recorded, it is likely that anomalous freshwater layers are being encapsulated and moved within mesoscale eddies southward – perpendicular to the Kuroshio Extension.

High biological productivity and a significant ocean-atmosphere flux of CO_2 make the Kuroshio a commercially and economically important area of research. The immense level of primary productivity in this region feeds large fisheries of sardines and anchovies (Yasuda et al., 2003; Kaneko et al., 2012), upon which Japan has based a heavy portion of their fishing industry. Physical deviations in sea surface temperature (SST) off the eastern coast of Japan may be caused by mesoscale meanders of the Kuroshio due to eddy/mean flow interaction (Waseda et al., 2003). Such deviations of SST can severely impact coastal spawning grounds of the sardine fisheries (Noto et al., 1999).

The coldest water in the North Pacific comes from the Sea of Okhotsk (Talley, 1997;Yasuda, 1997) before moving south as a component of the Oyashio (Talley, 1997). Water parcels being exported through the Bussol' Straight, the largest straight in the Kuril Basin of the Okhotsk Sea, are called Okhotsk Sea Mode Water (OSMW), which is characterized by low salinity, temperature, and 26.6-27.0 σ_θ (Talley, 1991; Yasuda, 1997; Gladyshev et al., 2003). Annual production of OSMW depends on tidal mixing and the sea ice formation along the continental shelf in the northwestern polynya of the Okhotsk Sea (Gladyshev et al., 2003). As the salinity and temperature minimum in the North Pacific, variance in the OSMW export to the Oyashio has the potential to impact physical characteristics of downstream regions (i.e. the Kuroshio Extension).

The Kuroshio Extension is a region of strong flows that requires increased observations of its physical properties in order to understand its importance. The main component of the North Pacific Intermediate Water (NPIW) originates in the Sea of Okhotsk (Talley et al., 1995) as OSMW, which mixes with Western Subarctic Gyre (WSAG) surface water to become more saline as it travels south as the Oyashio. The composite OSMW/WSAG encounters the warmer, more saline waters from the Western Subtropical Gyre (WSTG) in the Mixed Water Region (MWR) immediately east of the Japanese coast. The Oyashio surface water is overrun by the 'old' subtropical NPIW and sinks to intermediate depths of 600 – 800m (Talley et al., 1995, 1997). This 'new' NPIW is broadly defined as being the salinity minimum for the entire water column along the Kuroshio Extension.

Freshwater anomalies were detected at intermediate depths by conductivity-temperature-depth (CTD) measurements at six stations north of 33°30'N. The least saline anomalous parcel showed salinity intrusions characteristic of OSMW along a density gradient of 26.72 σ_θ. Talley (1991) discovered a similarly distinct anomaly at 43°5'N, 153°20'E that he concluded could only have originated in the Kuril Basin of the Okhotsk Sea. Talley was only able to determine the anomaly's origin, thickness (100m), and maximum width (150km). Without knowing the shape or volume of the anomaly, he could not conjecture on the possible similarity to compact lenses of Mediterranean water that appear in the Atlantic Ocean. The anomaly viewed by Talley additionally exhibited anti-symmetric ADCP profiles for the adjacent stations, indicating that the lens of Okhotsk water was encapsulated within an eddy (Talley, 1991). It is the intent of this study to calculate the percentage of OSMW in the anomalous freshwater parcels discovered in February 2013.

METHODS

In February 2013, 23 CTD stations were collected to a depth of 2000m from Yokohama, Japan to 40°32'N, 149°49'E (fig. 1). The CTD used was a Seabird 911*plus* attached to a rosette of 24 10-liter Niskin bottles. Argo floats were deployed at stations 3 – 13. Shipboard CTD casts taken within 1km of each Argo float as they resurfaced along the return cruise path. The Argo floats were programmed to transmit their data every 5 days.

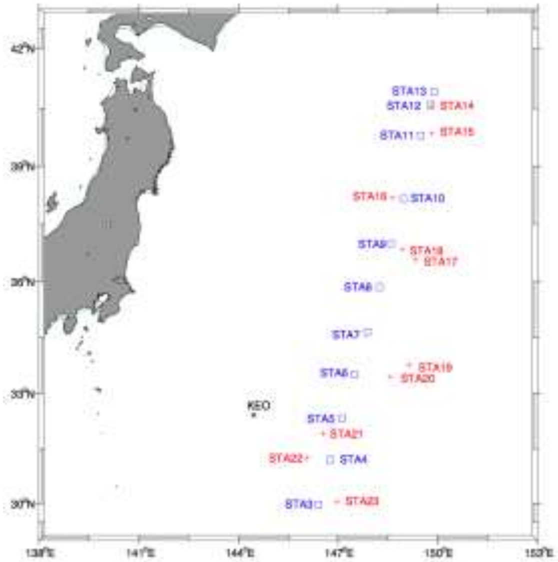

Figure 1. Stations occupied by the R/V *Melville* in February and March 2013. A black * and blue squares indicate stations along the outbound cruise track. Red +'s indicate stations along the return path.

In order to compare Argo float GPS positions to mesoscale eddies, gridded near-real time (NRT) satellite altimetry datasets were accessed from Archiving, Validation and Interpretation of Satellite Oceanographic (AVISO). The altimetry data is from January 2013 to April 2013; or 1 month preceding the cruise until 1 month following the cruise. The gridded NRT altimetry products have a ¼° x ¼° resolution. AVISO data was analyzed in MatLab in order to identify mesoscale eddies and current fronts from sea surface height (SSH) in the same region as that of the cruise track (29°N, 138°E - 43°N, 153°E).

As heat and salinity are conservative below the ocean's surface (Talley et al., 2011), it is possible to use three boundary conditions to determine the percentage of each water source that a parcel contains. A water parcel's observed temperature, T_4, must be some mixture of T_1, T_2 and T_3; Where T_1, T_2, and T_3 are the temperatures of the three water sources or boundary conditions. The same holds true for salinity as represented by S_1, S_2, S_3, and S_4. The percentage of each water source, denoted by *a*, *b*, and c, must add up to 1. The following equation solves for *a*, *b*, and *c*:

$$\begin{bmatrix} a \\ b \\ c \end{bmatrix} = \begin{bmatrix} T_1 & T_2 & T_3 \\ S_1 & S_2 & S_3 \\ 1 & 1 & 1 \end{bmatrix}^{-1} \begin{bmatrix} T_4 \\ S_4 \\ 1 \end{bmatrix}$$

OSMW is characterized by boundary conditions T_1 and S_1, whose properties are taken from empirical data (Talley et al., 1995; Yasuda, 1997; Gladyshev et al., 2003), when a=1, b=0, and c=0. The other two boundary conditions were chosen as the most saline cold and warm water observed in CTD data. The most saline cold water, WSAG intermediate water, is characterized by the values T_2 and S_2, which were taken from the northern-most station at 1000m. The most saline warm water, WSTG surface water, is characterized by the values T_3 and S_3, which were taken from the southern-most station at the surface. MatLab analysis was utilized to estimate the percentage of OSMW from the variables listed in table 1.

Boundary condition		Temperature		Salinity (psu)	
OSMW (a=1,b=0,c=0)	26.6 – 27.0 σ_θ	T_1	1-2°C	S_1	33.5
WSAG I.W. (a=0,b=1,c=0)	27.5 σ_θ	T_2	2°C	S_2	34.5
WSTG S.W. (a=0,b=0,c=1)	25.1 σ_θ	T_3	18°C	S_3	34.8

Table 1. Variables of the matrix equation associated with their respective source water's physical properties. σ_θ is provided as a reference only.

RESULTS

Strong halocline structure was present in shipboard CTD casts at stations 6 – 11 at depths ranging from 200m-900m (fig. 2). The salinity variability seen north of 33°30'N was not present to the south of the Kuroshio Extension. The most prominent freshwater intrusion occurred in station 6, centered at 751m. Station 7 had 3 prominent freshwater layers at progressively increasing depths. Station 8 exhibited a 0.3 psu deviation at 350m, but the shape of the profile did not reveal any trend due to the amount of variation in the entire water column. Station 9 had a single notable anomalous feature at 250m. The 250m freshwater layer at station 9 exhibited a 0.4 psu variation. A small salinity deviation appeared in station 10 at 270m but was only 10m thick. Station 11 exhibited a fresh layer of water (33.6 psu) just below it's mixed layer at 200m. The freshwater intrusion at station 11 was 150m thick.

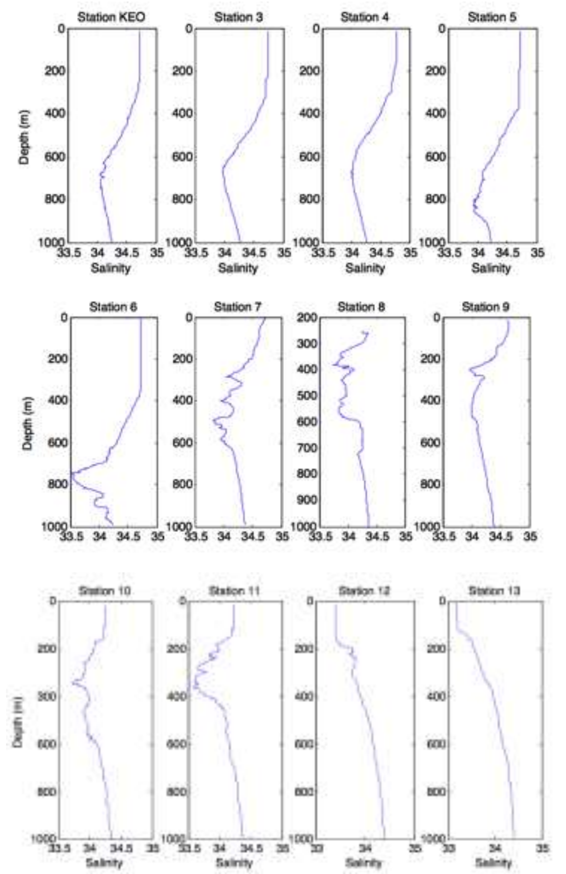

Figure 2. Salinity-depth profiles of stations 3 – 13 and KEO. Station 6 and 7 occupy the same region as the Kuroshio Extension.

OSMW is concentrated at the surface in the north and diffuses southward as it sinks to intermediate depths (fig. 3). The percentage of OSMW exceeded 50% in several 100-150m thick layers at stations 6 – 13. Notable freshwater layers exhibited in figure 2 share station number and depth with significant OSMW percentages.

Argo float profiles showed similar features north of 33°30’N, where temperature-salinity plots along a density gradient (TS plots) are provided in Figure 4a. Float 8387 observed salinities as low as 33.50 psu proximal to station 6. Figure 4b illustrates a less variable region of the northwest Pacific Ocean to the south of 33°30’N for comparison. Trajectory maps of Argo floats in figure 4a and 4b illustrate constant changes in velocity vectors.

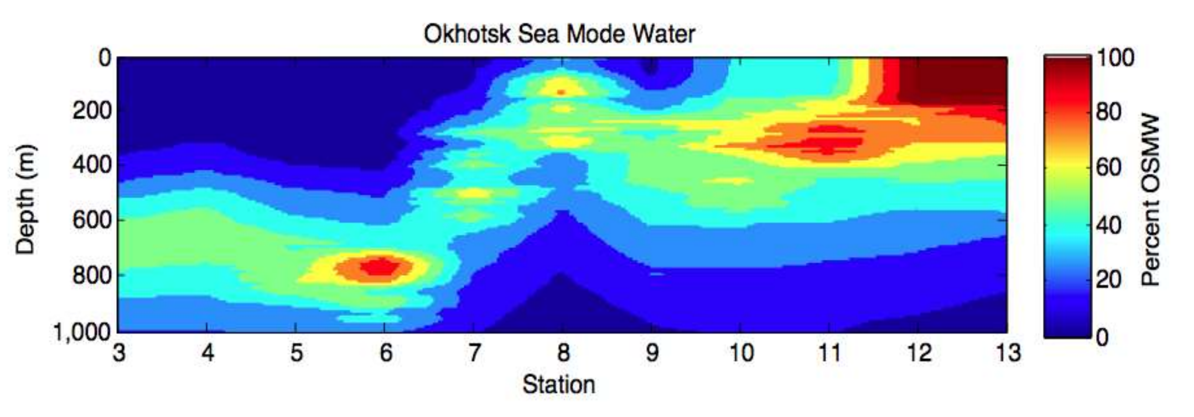

Figure 3. Cross section of northbound cruise transect to 1000m. Concentrations of OSMW are shown in red.

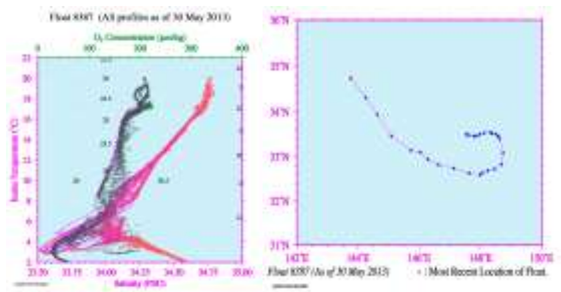

Figure 4. a) TS plot and trajectory of Argo float 8387. The magenta line in the TS plot indicates salinity. Background lines indicate the density gradient of the water being sampled. The red star indicates the most recent location of float 8387.

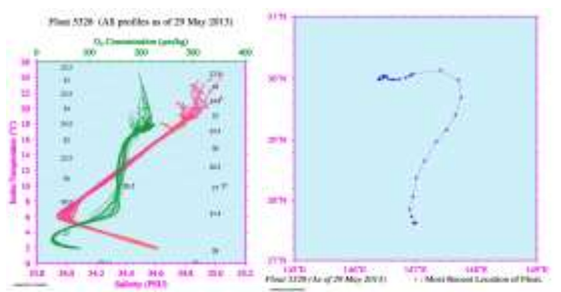

Figure 4. b) TS plot and trajectory of Argo float 5328. The magenta line in the TS plot indicates salinity. Background lines indicate the density gradient of the water being sampled. The red star at 27.62°N, 146.97°E indicates the most recent location of float 5328.

DISCUSSION

The fresh water parcels seen between 200-900m would appear to create an unstable water column, if not for their cold temperature. At station 6, a potential density of 26.7 kg m^{-3} correlates to the salinity minima 33.5 psu at 751m (fig. 5) is synonymous with OSMW from the Sea of Okhotsk (Gladyshev et al., 2003). The anomaly at station 6 was calculated to be 99% similar to OSMW. Therefore, this anomaly is either OSMW that has traveled from the Kuril Straights without any dilution or is a well-mixed composite of several water sources that happens to have achieved the same water properties as OSMW. If the anomaly were a composite parcel owing its characteristics to several sources, then the mixing that had occurred along the way would not likely have left it so distinctly similar to OSMW. It is more probable that the anomaly witnessed at station 6 is a pure lens of OSMW, similar to an anomaly studied by Talley (1991). Like Talley's observed freshwater anomaly in 1991, the pure OSMW signature does not appear in CTD stations to the north or south at depths greater than 600m. This supports an earlier conclusion that such lenses are small in nature being only 150m thick and no more than 260 km wide (Talley, 1991). The extent of the anomaly perpendicular to the direction of the cruise path is unknown so no volume estimates can be attempted.

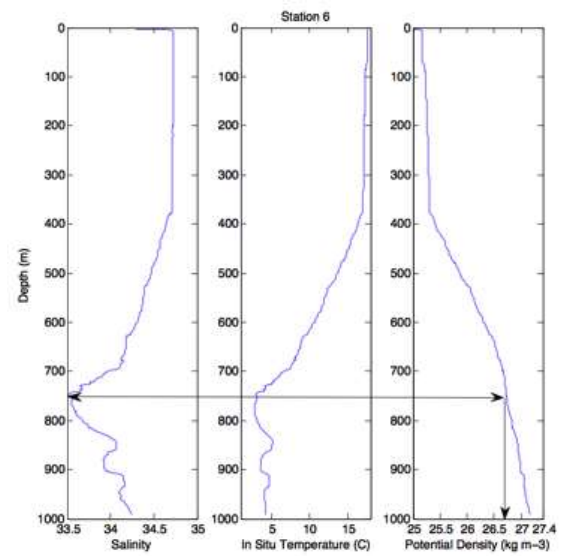

Figure 5. Depth profiles of station 6; Salinity, temperature and potential density are arrayed for comparison. Center of the anomalous freshwater layer is shown with a black double-headed arrow. A single-headed arrow points to the anomaly's potential density.

Stations 12 and 13 were calculated to have 99% OSMW in their mixed layer. However, this unlikely to occur anywhere but the Kuril Basin, where OSMW is created. Applying the same three boundary conditions to CTD data from all 11 stations may have skewed results in individual stations. It is also probable that there are more than three sources of water that any one parcel is comprised of. Therefore, the fresh water at the surface in stations 12 and 13 that was calculated to be 99% OSMW is most likely a product of WSAG surface water, whose physical properties are similar to OSMW. That may also apply to the intermediate depth anomalies but is less likely because small, concentrated lenses of water like that observed at station 6 are formed from passing through a narrow geographical formation like the Bussol' Straight (Talley, 1991).

A general trend of deepening salinity minima towards the south can be observed in figure 2. The cold, fresh WSAG surface water is overrun by warm, salty water from the south (Talley et al., 1995). A possible explanation for the multiple freshwater layers in station 7, 8 and 11 could be mixing from the WSAG directly to the Kuroshio Extension, despite that the direction of mixing would have to be perpendicular to the direction of current flow. The entire NW Pacific region is saturated with mesoscale eddies (Mitsudera et al., 2001; Kaneko et al., 2012), that could encapsulate WSAG water and enable it to penetrate south without being heavily mixed in doing so (K. M. Nolan unpubl.). This is supported by the circular trajectories of Argo float 8387 (fig. 6), which has also observed a significant variation in salinity values. Floats 8387 and 5328 both travel in circular patterns that correspond with gradients of SSH (fig. 6), which indicates that they are both deployed in eddy currents. It is unclear why float 5328 doesn't record salinity variation similar to float 8387 as they are both deployed south of the Kuroshio Extension. Further research is required to understand the extent and vehicle of concentrated OSMW penetration into the NPIW.

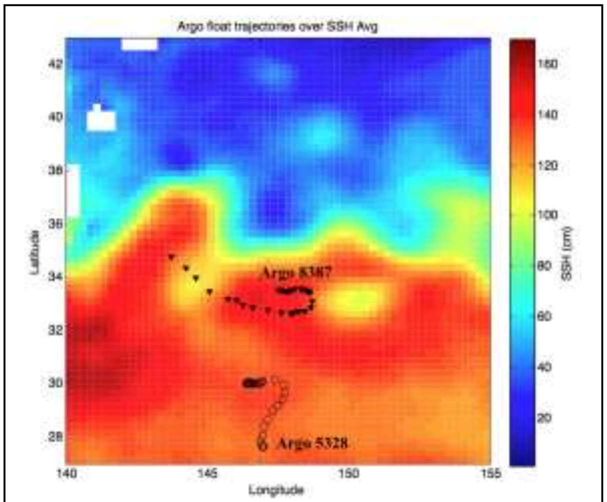

Figure 6. Contour map of SSH. Argo float 8387 positions are shown as filled V's and float 5328 positions are shown as empty O's.

CONCLUSION

Freshwater anomalies appear in the NW Pacific amidst and north of the Kuroshio Extension front. 100-150m thick layers of water significantly fresher than the surrounding water column is characteristic of the anomalies that were observed in February 2013. The temperature and potential density of each layer gives it a distinct signature that can be used to calculate the percentage of OSMW that contributed to the anomalous water properties. Only one anomaly (located at 33°30'N) appeared to contain 99% OSMW; All other anomalies were a mixture of OSMW and other sources.

The anomalies were likely encapsulated within wandering mesoscale eddies that traveled south from the Kuril Basin. Argo floats support this hypothesis by 1) tracking their position via GPS within mesoscale eddies and 2) recording salinity profile deviations similar to those observed at stations 6 – 11. Argo floats south of the Kuroshio extension also moved in circular patterns but didn't record variations in salinity.

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