High Salinity Waters Found off the Kii Peninsula

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Water having salinity higher than 35.00 is rarely found in the vicinity of Japan, but Takeuchi (1985) found such abnormally high salinity water to the south of the Kii Peninsula on August 2, 1984. By using the data compiled by JODC for the period from 1975 to 1996, we analyzed the occurrence frequency and structure of such high salinity water in the region south of the Kii Peninsula. The occurrence frequency distribution of the salinity values indicates that saline water higher than 34.95 is very unusual in this area. However, the occurrence frequency of saline water higher than 34.95 is about 2.5%, and that higher than 35.00 is about 0.6%. These values appear to be significant enough statistically. It should be noted that the R/V Soyo-maru observed saline water higher than 35.00 on almost the same day as the R/V Wakayama in August 1984. The oceanic structures when the high salinity water found are analyzed.

1. Introduction
The water salinity of the North Pacific Ocean is much lower than that of the Atlantic Ocean, and saline water higher than 35.00 is rarely observed in the vicinity of Japan. However, Takeuchi (1985) reported that the R/V Wakayama of the Wakayama Prefectural Fisheries Experimental Station found such abnormally saline water to the south of the Kii Peninsula on August 2, 1984, though such saline water had never been found during routine observations of surveyed transects by the R/V Wakayama, at least since 1984 when the Neil-Brown CTD system was installed.

In order to examine the occurrence frequency and the structure of such abnormally saline water in the area south of the Kii Peninsula, we analyzed historical data compiled by the Japan Oceanographic Data Center (JODC) for the period from 1975 to 1996.

2. Data Used
JODC supplied the compiled historical data in the form of a CD-ROM. We analyzed the data in the area from 28°N to the Japanese coast and between 134°E and 138°E (Fig. 1) and for the period from 1975 to 1996. The total number of the observation points is 2,167. In the preliminary stage of analysis, we surveyed the data also in the Japan Sea, and found about 13 observation points where saline water higher than 35.00 are reported. It is unbelievable that such saline waters are found in the Japan Sea where the salinity values are usually considerably lower than those in the Western North Pacific. We found that these observation points were taken by vessels belonging to one non-research organization. By way of precaution, we excluded the data observed by this organization from our analysis.

In the data compiled by JODC, temperature and salinity values are given both for the observed depths and the standard depths (interpolated values) in the case of serial observations, and only at the standard depths in the case of CTD observations (the same data are duplicated also for the observed depths column). We used basically the values for the observed depths column.

Much of the data observed by Japanese local agencies have not been compiled in the JODC data set, and no data taken by the Wakayama Prefectural Fisheries Experimental Station is included at least since 1975.

We found 12 observation points where saline water higher than 35.00 was found in vertical sections. The names of agencies, research vessels, dates of observations and number of observation points are shown in Table 1. The case observed by the R/V Wakayama is also shown in Table 1. The occurrence frequency of saline water higher than 35.00 is quite small, so we shall call such high salinity water as “abnormally saline water”. However, 13 such observation points are significant enough for us to suggest that such abnormally saline water intrudes sporadically into the region under consideration.
3. Occurrence Frequency of High Salinity Waters

We divided the area under consideration into 26 sub-domains, A through to Z, as shown in Fig. 1, by longitudinal and meridional lines of 1 degree intervals. The number of observation points in our analyzed period is given in the middle row of each sub-domain by numerals. Numbers of observations where saline water higher than 34.95 and 35.00 were observed are shown in the bottom row without and with parentheses, respectively.

We selected salinity values from 34.70 through to 35.00 at intervals of 0.05. The occurrence frequency of observations where salinities higher than each of these selected values was computed. The frequencies in % are shown in Fig. 2 for each sub-domain. The frequency decreases with increasing of salinity value, but the manner of decrease is different between sub-domains. By using this decreasing manner, we classified the sub-domains into three groups:

1. The frequency of waters with 34.70 or higher salinity is relatively high (say, >80%). The rate of decrease is small for salinity values lower than 34.80, but decreases rapidly between 34.80 and 34.90 (full lines in Fig. 2).

2. The frequency at 34.70 has moderate values between 80 and 60%. The frequency decreases almost linearly from 34.70 to 34.90 (dotted lines in Fig. 2).

3. The frequency at 34.70 is lower (<60%). The rate of decrease is rapid for lower salinities, but slow for higher salinities (dashed lines in Fig. 2).

In Fig. 1, the sub-domain belonging to group (1) are shown by a hatched area, those to group (2) by a dotted area, and those to group (3) by a white area, respectively. Group (3) is located near coast where the fresh water supply from land would be significant. The area of group (1) appears in the domain of the subtropical water, which is usually located to the south of the Kuroshio axis. The area of group (2) is located between those of (1) and (3).

The curves in Fig. 2 belonging to groups (2) and (3) decrease towards nearly zero by 34.90. Though the occurrence frequency of 34.90 water is considerably low, the decreasing manner of these curves suggests that the salinity value of 34.90 is not unusual and may result from usual salinity fluctuations in the region under consideration. However, the occurrence of saline waters having salinity higher than 34.95 appears to be somewhat abnormal. Such abnormal high salinity waters may occur in region accompanying sporadic event-like phenomena.

4. Case Studies When the Abnormally Saline Water Higher than 35.00 was Found

4.1 R/V Wakayama and Soyo-maru in August 1984

The R/V Soyo-maru observed abnormally saline water higher than 35.00 on the same day as the R/V Wakayama (Table 1). Sites of these observations are shown in Fig. 3. Among five observation lines running in a north-south direction, the westernmost line just off Cape Shionomisaki was surveyed by the R/V Wakayama on August 2, and the two middle and two eastern lines by the R/V Soyo-maru on July 23–27 and on August 1–2, respectively. The bold portions of the observation lines indicate that the abnormally saline water higher than 35.00 was found in the vertical section.

It should be noted that the abnormally saline water was found along the observation lines occupied on August 1–2, but not found along the lines occupied about one week before. Cross-marks (×) attached on the observation lines indicate the place where the highest salinity value was found and/or where the stratum of abnormally saline water was found at its thickest in each north-south cross-section. The
The temperature field at the 200 m level is also shown in Fig. 3. The cross-marks (areas of the highest salinity) are located at the temperature maxima in the north-south section at the 200 m level, namely, just south of the strong current zone of the Kuroshio. Judging from the density structure below 200 m depth, the flow would be directed eastward though its magnitude was considerably smaller. The high salinity water might be elongated in the east-west direction by this eastward current.

The salinity and density (sigma-t) cross-sections are shown in Fig. 4 along the line which is produced by connecting the cross-marks in Fig. 3. One additional datum at 32°40′

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**Table 1. List of the observation points where saline water higher than 35.00 was found in vertical sections in the region south of the Kii Peninsula in the period from 1975 to 1996. Twelve points were found in the data set compiled by JODC, and one was taken by the R/V Wakayama of the Wakayama Prefectural Fisheries Experimental Station.**

<table>
<thead>
<tr>
<th>Res. vessel</th>
<th>Organization</th>
<th>Date</th>
<th>Number of obs.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Takuyo</td>
<td>Hydrographic Department, MSA</td>
<td>May 10, 1981</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td></td>
<td>May 18, 1981</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>May 19, 1981</td>
<td>1</td>
</tr>
<tr>
<td>Shumpu-maru</td>
<td>Kobe Marine Observatory, JMA</td>
<td>May 4, 1981</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Oct. 13, 1981</td>
<td>1</td>
</tr>
<tr>
<td>Soyo-maru</td>
<td>Tokai Reg. Fisheries Research Lab., JFA</td>
<td>Aug. 1, 1984</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Aug. 2, 1984</td>
<td>3</td>
</tr>
<tr>
<td>Ryofu-maru</td>
<td>Japan Meteorological Agency</td>
<td>July 21, 1991</td>
<td>1</td>
</tr>
<tr>
<td>Wakayama</td>
<td>Wakayama Pref. Fisheries Experimental Station</td>
<td>Aug. 2, 1984</td>
<td>1</td>
</tr>
</tbody>
</table>

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**Fig. 2. Salinity values from 34.70 through to 35.00 at intervals of 0.05 were selected as reference salinity values. The occurrence frequency of observations where salinities higher than each of these selected values was computed for each sub-domain. The frequencies in % are plotted against the selected salinity values. Identification of each sub-domain is shown in the right-top portion of the figure. Sub-domains are classified into three groups according to the decreasing manner of the frequency curve. See text for further details.**

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High Salinity Waters  635
Fig. 3. Site of the observations conducted by the R/V Soyo-maru of the Japan Fisheries Agency, and the R/V Wakayama of the Wakayama Prefectural Fisheries Experimental Station in 1984: the westernmost north-south line off Cape Shionomisaki was surveyed by the R/V Wakayama on August 2, and the two-middle and two eastern lines by the R/V Soyo-maru on July 23–27 and August 1–2, respectively. The bold portions of the observation lines indicate that the abnormal saline water higher than 35.00 was found in the vertical section. Cross-marks indicate the place where the highest salinity value was found and/or where the stratum of abnormally saline water was found at its thickest in each north-south section. Temperature field at 200 m depth is also shown.
High Salinity Waters 637

N and 136°18′ E was also used as this point is located in the maximum temperature zone at the 200 m level (see Fig. 3). The abnormally saline water exists in mid-depths: from 50 m to 110 m in Soyo-maru lines and from 25 m to 65 m in Wakayama line. Though the depth ranges are different to each other, both abnormally saline waters are located in the similar density surfaces. This may suggest that both waters originate from the same source water. The fact that the abnormally saline water is separated by relatively less saline water, which was observed one week before, would suggest the temporal or spatial scale of the abnormally saline water is considerably small, and this would be related to its very low occurrence frequency discussed in the previous section.

Another difference in oceanic structures between August 1–2 and July 23–27 is that a sharp seasonal thermocline exists in July, but it is significantly weakened in August. Takeuchi (1985) reported that a severe storm affected this area just before the observation time of the R/V Wakayama. The surface layer might have been mixed up and homogenized by storm. As discussed later, some of the abnormally saline waters extend up to the surface. It is highly possible that the abnormally saline water in the surface layer had disappeared due to the heavy precipitation and strong wind force.

Fig. 4. Salinity (full lines) and density (sigma-t: dotted lines) cross-sections along the line which is produced by connecting the cross-marks in Fig. 3. The portion where the salinity is higher than 35.00 is shown by a shaded area. The observation points are shown by dots. The dates of the observations are shown in the upper column.

Fig. 5. Site of the observations conducted by the R/V Takuyo of the Hydrographic Department, Japan Maritime Safety Agency in May, 1981. The bold portions of the observation lines indicate that the abnormal saline water higher than 35.00 was found in the vertical section. Cross-marks indicate the place where the highest salinity value was found and/or where the stratum of abnormally saline water was found at its thickest in each north-south section.
Fig. 6. Current field and path of Kuroshio (upper figure) and the temperature field at 200 m depth (in °C; lower figure) cited from the Prompt Report of Oceanic State, No. 11, 1981, which is based on data taken in the period from May 13 to 31, 1981.
4.2 R/V Takuyo in May, 1981

The R/V Takuyo of the Hydrographic Department, Japan Maritime Safety Agency found the abnormally saline water at 5 stations in the region under consideration in May, 1981 (Table 1). The observation area of the R/V Takuyo extends further toward east, and the abnormally saline water was also found on the observation line along 138°E. Here we shall analyze the whole data taken by the R/V Takuyo in May 1981.

The observation lines are shown in Fig. 5. The observations consist of two legs: off from Suruga Bay to Enshunada on May 8–12, and off the Kii Peninsula and Shikoku on May 18–22. The portions where the abnormally saline water was found are shown by bold lines, and the cross-marks indicate the places where the highest salinity value was found and/or the thickest stratum of abnormally saline water was found in each north-south section. The current field and path of the Kuroshio (upper figure of Fig. 6) and temperature field at 200 m level (lower figure of Fig. 6) are cited from the Prompt Report of Oceanic State (13–31 May, 1981) issued by the Hydrographic Department, MSA. The observed abnormally saline water is located near the southern boundary of the observation area, and north-south extent might be greater than seen in Fig. 5.

The salinity and density (sigma-t) cross-sections are shown in Fig. 7 along the line which is produced by connecting the cross-marks in Fig. 5. The abnormally saline water was found far to the south of the Kuroshio in this case, and might be in the weak current zone of the Kuroshio Counter Current flowing southwestward (see the upper figure of Fig. 6). As the abnormally saline water was observed in both of two legs of the voyage by the R/V Takuyo, the time scale of the water mass might be longer than observed in August, 1984. Another different characteristic of this saline water is that its domain extends to the surface.

4.3 Observations along the 137°E meridian

The other abnormally saline water were observed along the 137°E meridian: by the R/V Shumpu-maru of the Kobe Marine Observatory, JMA on May 4, 1981 (a) and on October 13, 1981 (b), and the R/V Ryofu-maru of the Japan Meteorological Agency on July 21, 1991 (c). The north-south cross-sections of the salinity and the density (sigma-t) of these observations are shown in Figs. 8a through 8c, respectively. The abnormally saline water extends to the surface in cases (a) and (c), and is found in the mid-layer in case (b). The sub-surface saline water higher than 34.90 in Fig. 8a (also Fig. 5) suggests that the abnormally saline
Fig. 8. Abnormally saline waters observed along 137°E: by the R/V Shumpu-maru of the Kobe Marine Observatory, JMA, on May 4, 1981 (a) and on October 13, 1981 (b), and by the R/V Ryofu-maru of the Japan Meteorological Agency on July 21, 1991 (c). Salinity fields and density fields (sigma-t) are shown by full lines and dotted lines, respectively. The abnormally saline water higher than 35.00 is shown by a shaded area.
water occasionally extends further in the sub-surface layers. The abnormally saline water in case (c) was found near 28°N. The Japan Meteorological Agency maintains a long observation line along 137°E and surveys it twice a year from 1967. Saline water higher than 35.00 is usually found in the region between 10°N and 20°N and that to the south of 5°N (Andow, 1987). Saline water higher than 35.00 appears to be very common to the south of 20°N. The variations of area of the saline water higher than 35.00 are shown in Fig. 9 from the winter cruises in the period from 1967 to 1982 (Saeki, personal communication). The area of the high salinity domain between 10°N and 20°N are very changeable year by year, and sometimes its northern edge exceeds 25°N. The abnormally saline water seen near 28°N in Fig. 8c may be considered to originate from this saline water, though it is isolated in cross-section.

5. Possible Source of the Abnormally Saline Water

High salinity water would be produced at the surface by excess evaporation. Levitus *et al.* (1994a) produced an annual mean salinity atlas for the world ocean at various depths. The salinity distributions in the North Pacific Ocean are cited and are shown in Fig. 10 for the surface, and the 30 m, 50 m, 100 m, 150 m and 250 m depths. Saline water higher than 36.25 is found in the sub-tropical central South Pacific (around 120°W, 15°S), but no such saline water is found in the North Pacific. The salinity of the most saline water in the North Pacific is less than 35.50. Saline water higher than 35.00 can be found in the domain roughly between 150°E and 130°W, and between 20°N and 30°N. The maximum value does not appear at the surface, but at 30 m depth. In the corresponding temperature atlas (Levitus *et al.*, 1994b), no significant temperature difference is found between the surface and 30 m depth. Presumably, the high salinity waters generated sporadically at the surface have sunken due to their relatively high density. The area of the saline water domain is also at a maximum at the 30 or 50 m depths. No such saline water is found below 250 m depth.

The abnormally saline water found in August, 1984 suggests that the water might have been carried into region by the current of the outer edge of Kuroshio. However, the salinity in the Kuroshio area near the Philippines is considerably low (Fig. 10). The temporal variation of the highest salinity value found in the section crossing the Kuroshio northwest of Okinawa (PN line) is shown in Fig. 11 (Saeki, personal communication) for the period from 1955 to 1982. The maximum salinity value does not exceed 35.00 during this period. The surface Kuroshio water is usually affected by the coastal water from the East China Sea and diluted somewhat before it flows out again into the North Pacific. So, it is hard to assume that the abnormally saline water carried directly by the current of the Kuroshio.

The abnormally saline water found in May, 1981 appears to be influenced by the current of the Kuroshio Counter Current, however, as the water in the Counter Current would have been influenced by the less saline Oyashio water, it is hard to consider that the Counter Current brings this abnormally saline water directly, too.

Presumably, eddy activities or other sporadic events would play an important role in the process which brings the abnormally saline water into the region under consideration, and this results in the very low occurrence frequency of the abnormally saline water.

6. Concluding Remarks

It is shown that the frequency of the saline water higher than 34.95 is considerably lower than salinities of lower than 34.90 in the region to the south of the Kii Peninsula: the
Fig. 10. Annual mean salinity distributions in the North Pacific Ocean at the surface, and at 30 m, 50 m, 100 m, 150 m and 250 m depths (after Levitus et al., 1994).
occurrence frequency of the saline water higher than 34.95 is about 2.5%, and that higher than 35.00 about 0.6%. However, these frequency is statistically significant enough to conclude that the abnormally saline water higher than 35.00 is brought into the region sporadically.

The source region of the abnormally saline water and the route along which the water have been brought into the area has not been clarified. In order to find these, we are trying to expand the area of analysis to the whole western North Pacific. However, the analysis of extreme values such as the abnormally saline water discussed here is severely influenced by the quality of the data. Careful evaluation of the data quality is needed in the further investigations.

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References