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Characteristics of the Basin Water in Funka Bay

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Abstract

Characteristics of the basin water in Funka Bay were investigated by making use of the oceanographic data in 1974.

It is considered that lots of particulate organic matter is accumulated in the basin water. Because of the decomposition of this accumulated POM, the basin water maintains nutrients of high concentrations from spring through autumn, although the basin water is intermittently renewed by advection and lateral mixing. In winter, the nutrients released from the POM constitute the nutrients of the Winter Funka Bay Water. This water is formed in the bay and is the origin of the basin water. Also, the accumulated POM is thought to be important as a food for the benthos in the bay.

Introduction

Funka Bay lying in the south of Hokkaido Island is a caldera-like bay with the radious of about 26 km and a maximum depth of 107 m. It joins with the Pacific Ocean through a sill of the maximum depth of about 85 m at its east side. Fig. 1 shows the location of the bay, its bottom topography and the current systems around the islands of Japan.

According to Ohtani1) and Ohtani et al.2),3),4), two major water masses occupy the bay periodically through a year. One is the cold and less saline Oyashio Water (O&Oi), and the other is the warm and salty Tsugaru Warm Water (Tw) originating from the Kuroshio. O&Oi occupies the bay from spring through summer, and Tw occupies from autumn through winter. Tw in the bay is transformed through winter into the Winter Funka Bay Water (Fw) which becomes moderate in concentrations of nutrients and homogeneous in temperature and salinity. Because the density of Fw at the end of winter is larger than those of O&Oi and Tw, Fw remains in the basin being affected by the overlying waters from spring through autumn. In this paper, this water is defined as the basin water.

Ohtani1) suggested that nutrients of high concentrations in the basin water originated from some organic sources produced in the bay. Furthermore, Yanada et al.5) reported that much of nutrients were released from the organic matter sedimented on the bottom and then calculated the material budgets of the bay for a year6). He concluded that 52% of the nitrogen and 80% of the phosphorus of particulate organic matter sunk to the layer deeper than 50 m. These suggest the importance of the basin water in material budgets of the bay.

In this paper, the characteristics of the basin water and its change are discussed, based on monthly observations.

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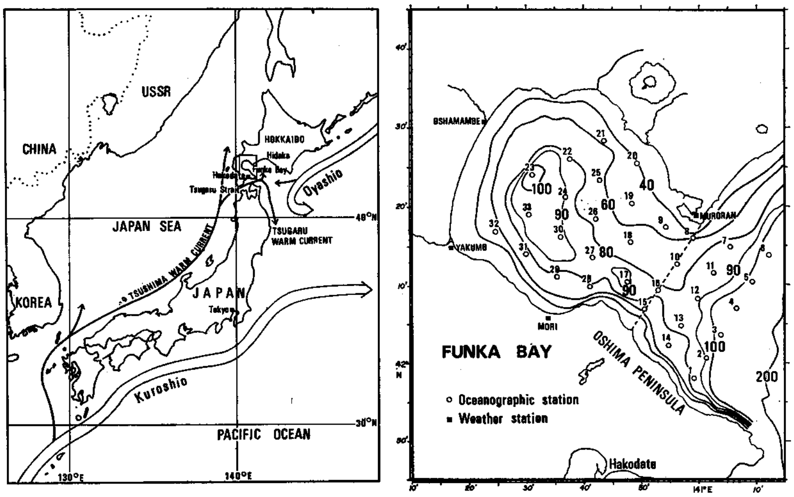

Fig. 1. (left) Position of Funka Bay and schematic representation of the current systems around Japan concerning Funka Bay. (right) Location of the Oceanographic and meteorological stations, and the bottom topography in meters. The dashed line is the boundary between the inside and outside of the bay defined in this paper.

Observations and Data Source

The monthly oceanographic observations were conducted by the R/V Ushio-Maru of the Faculty of Fisheries, Hokkaido University from February 1974 to January 1975, at 33 stations as shown in Fig. 1. Water samples for determination of salinity, dissolved oxygen and nutrients were collected by Nansen water samplers with reversing thermometers. Temperatures and salinities were processed by the authors and others. D.O. and nutrients were analyzed by Dr. Y. Maita, Dr. M. Yanada and the students of the Laboratory of Marine Chemistry, Faculty of Fisheries, Hokkaido University. The preliminary data reports were published in 1974[7] and 1975[8]. In this paper, data on temperature, salinity, D.O. saturation ratio and phosphate phosphorus as a representative of the nutrients were quoted.

The meteorological data cited here were observed at four agricultural weather stations around the bay[9]. Their positions are also shown in Fig. 1.

Results and Discussions

1. *Hydrographic conditions in the basin*

The distributions of temperature, salinity, PO_4-P concentration and saturation ratio of dissolved oxygen at the depth about 2 m above the bottom are shown in Figs. 2–6.

In February, Fw is occluded in the basin, as shown by the isohaline of 33.7‰ and isotherm of 5°C. PO_4-P concentration in Fw is at a level of 1.0μg–at/l and D. O. saturation ratio is around 90%. In the vertical section shown by Ohtani and

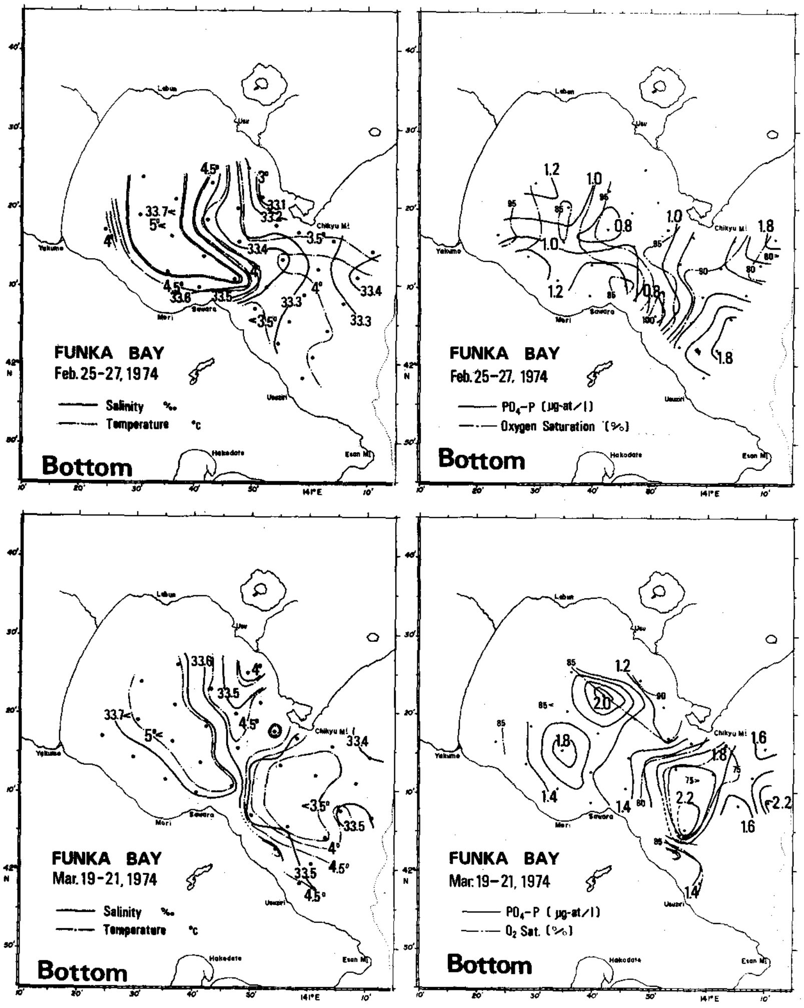

Fig. 2. Distributions of temperature, salinity, PO$_4$-P concentration and D.O. saturation ratio above the bottom in February (upper) and in March (lower).

Kido[10]), the upper water is less saline than 33‰ and colder than 3.0°C, which indicates that O&Oi has entered the bay and occupies the upper layer of the bay. The temperature and salinity of O&Oi are lower than those of Fw in the basin, and so clear thermocline and halocline are formed between Fw and overlying O&Oi, in contrast with the small differences in the PO$_4$-P concentration and D.O. saturation ratio between them.

In March, Fw is still occluded in the basin as shown by the isotherm of 5°C and isohaline of 33.7‰, and it keeps the same temperature and salinity as in February. PO$_4$-P concentration of Fw, however, increases to about 1.6 μg-at/l and D.O. saturation ratio conversely decreases to about 80%, which indicates decom-

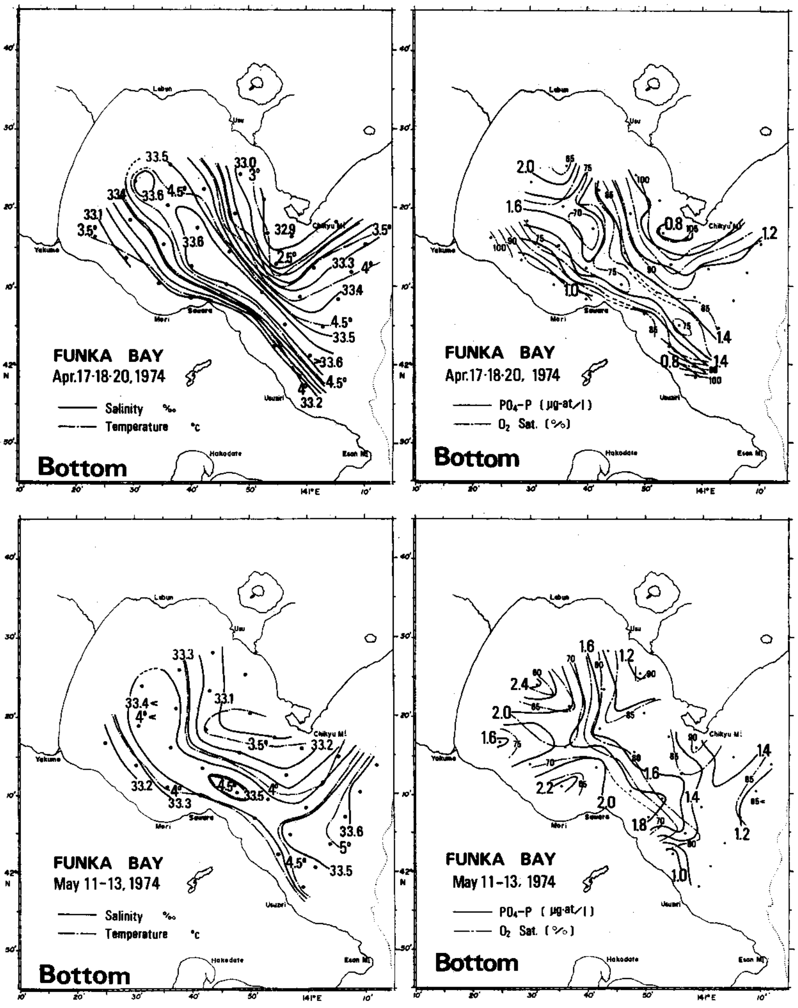

Fig. 3. As in Fig. 2 except in April (upper) and in May (lower).

position of organic matter accumulated on the bottom in the basin. Clear boundaries in the vertical sections of temperature and salinity are also found above the basin water.$^{10)}$ PO_4-P concentration in the upper layer of the overlying O&Oi decreases to about 0.6 μg-at/l and D.O. saturation ratio increases to higher than 105% because of phytoplankton activity$^{10)}$. So the vertical differences in PO_4-P and D.O. are increased, in comparison with those in February.

In April, the temperature and salinity of the basin water decreases to about 4.5°C and 33.6‰ respectively, which indicates the increase of the overlying O&Oi. PO_4-P concentration of the basin water which is the transformed Fw in the basin increases to more than 1.6 μg-at/l and D.O. saturation ratio decreases to lower than 75%. The outflow of the basin water from the bay over the sill is shown

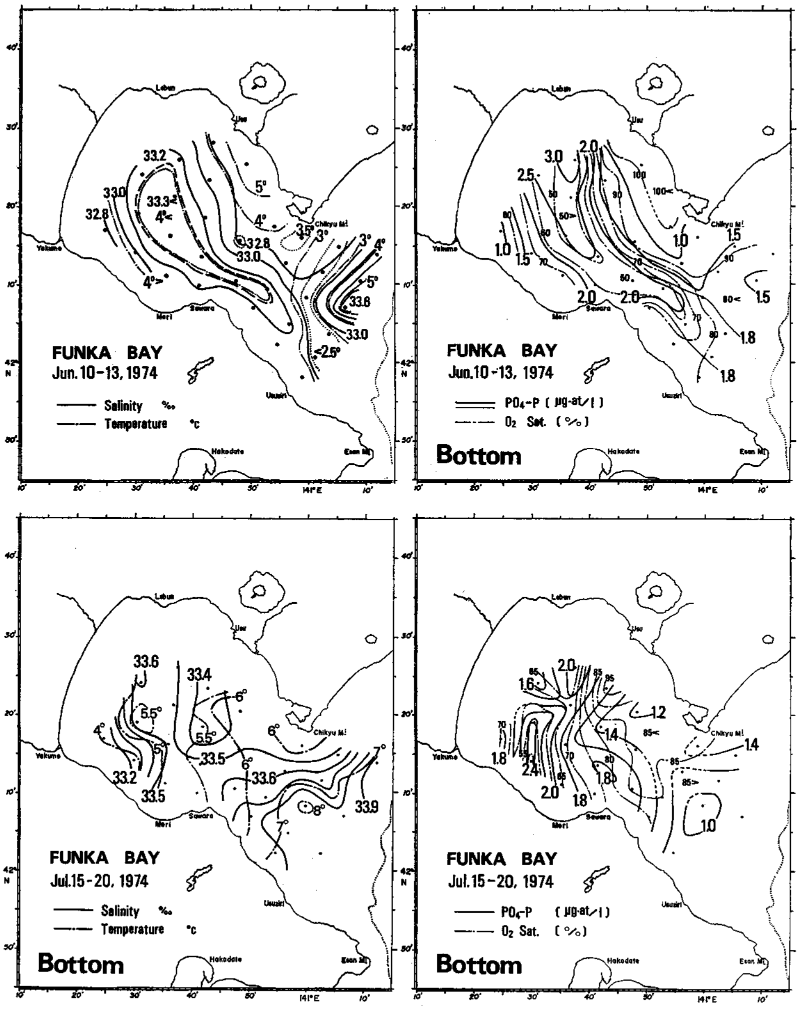

Fig. 4. As in Fig. 2 except in June (upper) and in July (lower).

by the isotherm of 4.5°C, isohaline of 33.5‰, isolines of PO_4-P of 1.4 μg-at/l and D.O. saturation ratio of 80% which stretch from the inside to outside of the bay along the sea valley. In the vertical sections[10], the thermocline and halocline reach the bottom, which indicates that the area of O&Oi increases downward. Since the temperature of the surface water rises from increasing insolation and air temperature, a dichothermal structure with cold O&Oi at mid-depth are formed in the bay.[10] PO_4-P in O&Oi is still less than 0.6 μg-at/l by biological consumption and D.O. saturation ratio is still more than 100%, and the vertical differences in PO_4-P and D.O. between the basin water and the overlying O&Oi increase.[10] Therefore large gradients are formed between the basin water and the overlying waters in the PO_4-P concentration and D.O. saturation ratio as well as in tempera-

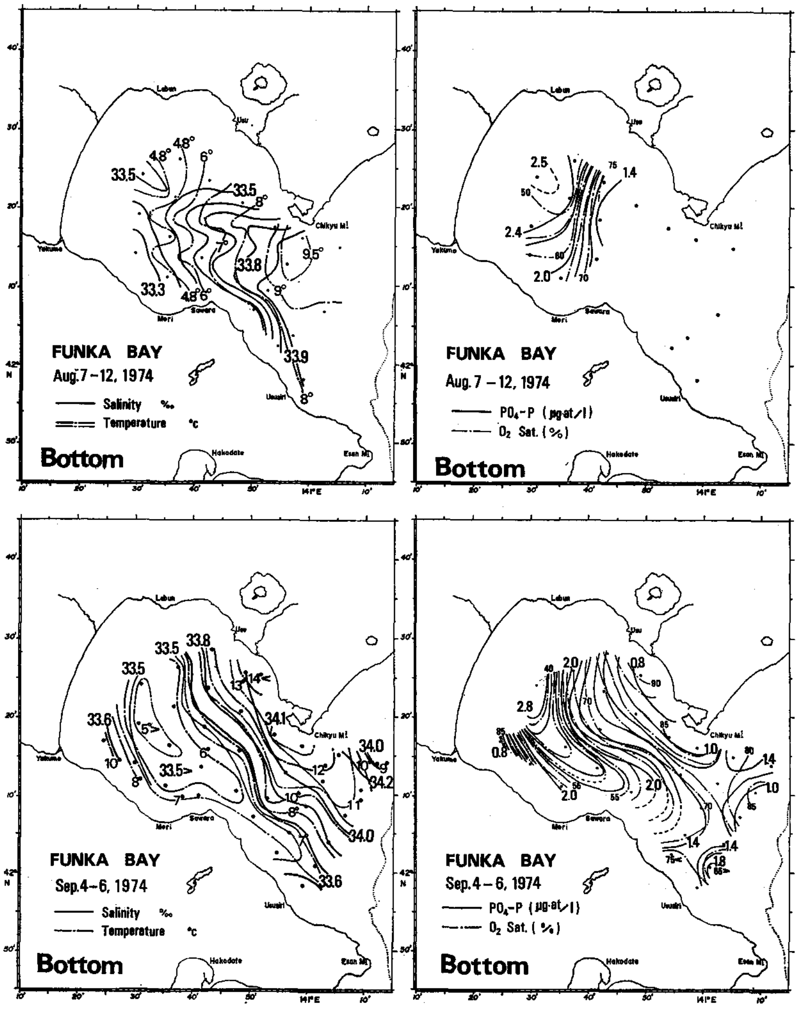

Fig. 5. As in Fig. 2 except in August (upper) and in September (lower).

ture and salinity.

In May the temperature and salinity in the basin water further decrease to the levels of 4°C and 33.4‰ respectively. PO_4-P concentration in the basin water increases to more than 1.8 μg-at/l and D.O. saturation ratio decreases to less than 70%.

The isotherm of 4°C and isohaline of 33.4‰ stretch to the outside of the bay, and give an impression that the basin water flows out of the bay. But the patterns such as temperature and salinity are not found in the distributions of PO_4-P and D.O. Thus the patterns of temperature and salinity are considered to indicate a trace of the outflow of the basin water prior to the observation in this month.

In June, the salinity of the basin water decreases about 0.1‰ from that in May and is at a level of 33.3‰, but the temperature scarcely changes from May.

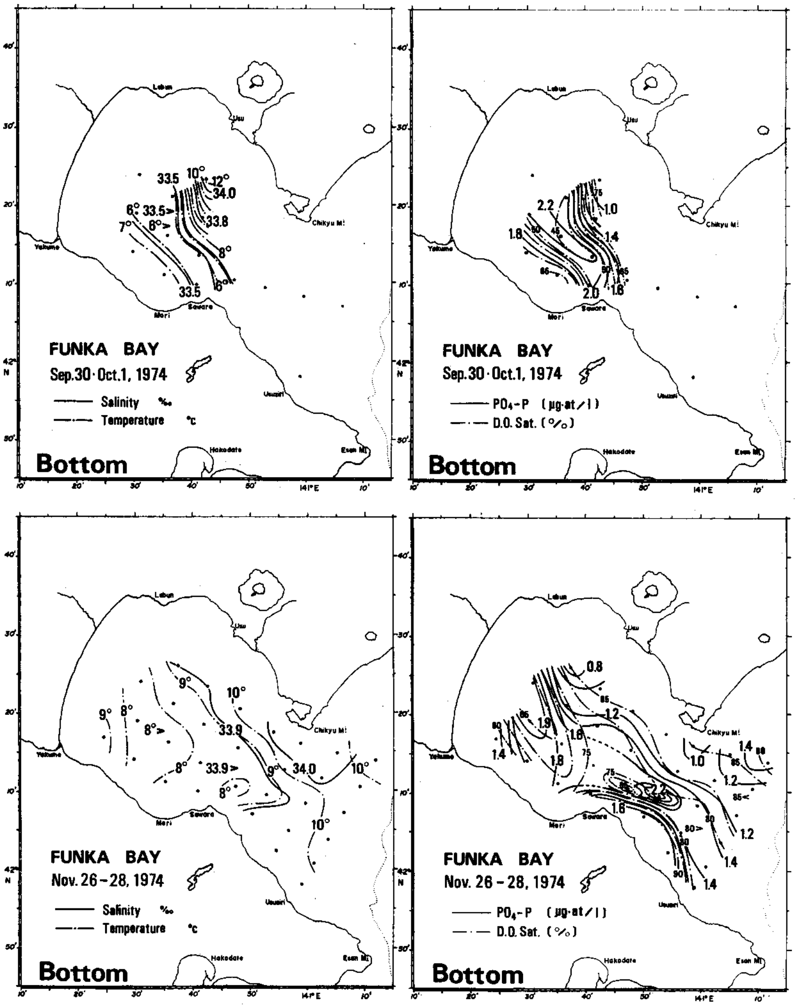

Fig. 6. As in Fig. 2 except on September 30 and October 1 (upper), and in November (lower).

PO_4-P concentration of the basin water becomes more than 2.5 μg-at/l and D.O. saturation ratio decreases to less than 50%. On the other hand, PO_4-P of the overlying O&Oi is less than 0.4 μg-at/l and D.O. saturation ratio is over 100%. So the conspicuous differences in the PO_4-P and D.O. saturation ratio between the basin water and the overlying O&Oi are formed.[10]

The water of temperature higher than 4.0°C, salinity higher than 33.3‰, PO_4-P more than 2.0 μg-at/l and D.O. saturation ratio less than 60% is shown to spread toward the outside of the bay as shown in Fig. 4, which indicates the outflow of the basin water as well as in April.

In July, the Tsugaru Warm Water (Tw), which is warmer and saltier than O&Oi and the basin water, occupies the outside of the bay replacing O&Oi[10]. As shown by the isohaline of 33.6‰, Tw enters the basin with lateral mixing from the southern side of the entrance of the bay. The temperature and salinity of the basin water rise to levels of 5°C and 33.5‰ respectively. On the other hand, PO_4-P concentration decreases to about 2.0 μg-at/l and D.O. saturation ratio is recovered to more than 60%. These changes indicate the renewal of the basin water by Tw.

In August, as shown by the isohaline of 33.8‰, the inflow path of Tw is shifted to the northern side of the entrance of the bay. Since Tw enlarges its area at mid-depth, the dichothermal structure which has been maintained from April on is transformed into a more complicated structure10). In spite of the period of warmer Tw entering, the temperature of the basin water slightly decreases to lower than 4.8°C because of the influence of the overlying cold O&Oi.

In September, the temperature and salinity in the basin water are scarcely changed from those in August, and are still lower than 5°C and 33.5‰ respectively. Contrarily, PO_4-P concentration in the basin water further increases to more than 2.4 μg-at/l and D.O. saturation ratio decreases to less than 50% which is the minimum value through the year. The outflow of the basin water along the Oshima Peninsula is shown in Fig. 5 by the isotherm of 7°C, the isohaline of 33.6‰ and the isolines of PO_4-P 2.0 μg-at/l and D.O. 65%. In this period, clear differences in the PO_4-P concentration and D.O. saturation ratio are found between the overlying Tw and the outflowing basin water along the coast of the Oshima Peninsula.10)

Attention is given to the fact that the outflow path of the basin water which was along the valley from the inside to the outside of the bay in April and June, shifts to near the Oshima Peninsula. This might be because of the difference in the mechanism of replacement of the water masses.

On September 30 and October 1, some of the stations were incompleted because of the weather conditions. But the distributions of all factors show that the basin water of temperature lower than 6°C and salinity lower than 33.5‰ is occluded in the basin. The salinity is scarcely changed in comparison with that in September, but the temperature increases about 1.0°C and PO_4-P concentration decreases to about 2.2 μg-at/l. These indicate a slight renewal of the basin water with Tw by vertical and lateral mixing.

The stagnation of the laminar basin water is clearly shown in the vertical sections of all factors10).

Late in November, the replacement of Tw with O&Oi is almost completed, and moreover the convectional mixing is developed by the cooling from the decrease in air temperature. Therefore the waters in the bay become almost homogeneous, and the temperature and salinity of the basin water increase to about 8°C and 33.9‰ respectively.10)

PO_4-P concentration of the basin water decreases to 1.9 μg-at/l and D.O. saturation ratio is recovered to 65%. Because the PO_4-P and D.O. saturation ratio in the upper waters are around 0.8 μg-at/l and 90% respectively, the differences in PO_4-P and D.O. between the laminar basin water and the others still remain10). Therefore the water in the basin can be considered as a trace of the basin water which has been undergoing transformation from April on.

2. *Variation of mean temperatures in relation to the volumes of the water masses*

Ohtani and Kido[11] defined the characteristic salinities for the water masses from the analysis on a temperature-salinity diagram, as 33.8‰ for Fw, 32.8‰ for O&Oi and 34.0‰ for Tw. And they calculated the volumes of the water masses in the bay, by means of the difference in salinity between the water masses. The results of the calculations are represented for three layers, that is, the upper layer (0–30 m), the middle layer (30–80 m) and the bottom layer (deeper than 80 m), in percentage to the volume of each layer as shown in Fig. 7. The mean salinity averaged on each plane at five depths in the bay is also presented in Fig. 7.

The mean temperatures averaged on the same planes and the monthly mean air temperatures at four weather stations around the bay as shown in Fig. 1 are presented in Fig. 8.

In February, cold O&Oi has already entered the bay from the surface, and it occupies 80% of the upper layer and 50% of the middle layer. But O&Oi does not reach the bottom layer yet and the bottom layer is still occupied by warmer Fw. And so the mean temperature increases with depth.

From April, the mean temperatures at the surface and 30 m begin to rise according to the rising mean air temperatures, and these keep rising throughout the period when O&Oi is entering. These reach the maximum in August (surface) or in September (30 m). In August, a slight fall of the mean temperature at 30 m is caused since Tw intruding into the bay at mid-depth lifts the colder waters to a shallower depth.[10] After September, the mean temperatures at the surface and 30m descend according to the dropping air temperatures.

Contrary to the changes at the upper two depths, the mean temperatures at 70 and 90 m remain constant from February through March while the bottom layer is occupied by only Fw. In April when O&Oi reaches the bottom layer, the

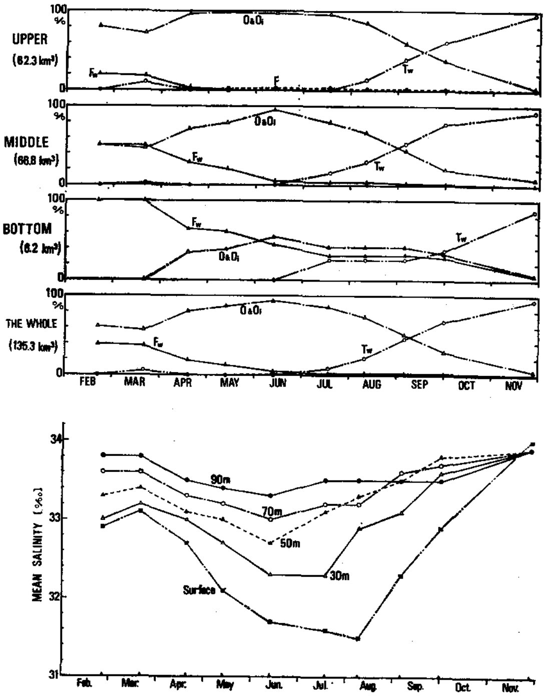

Fig. 7. (upper) The variations in volumes of the water masses in the bay, expressed in percentage to the volume of each layer. Symbols are Fw: the Winter Funka Bay Water, O&Oi: the Oyashio Water, Tw: the Tsugaru Warm Water and F: fresh water (after Ohtani and Kido). (lower) The mean salinities averaged on the planes at five depths in the bay.

mean temperatures at 70 and 90 m begin to descend, and these keep falling in proportion to the increase of O&Oi volume in the bottom layer, conversely to the increasing temperatures of the surface, 30 m and the air. In June when the volume of O&Oi reaches the maximum in all layers, these become the minimum throughout the year.

The thermocline and halocline formed between the basin water and the overlying O&Oi are maintained from February to April when both reach the sea-floor,[10)] and throughout the period when O&Oi is entering from February through June, the mean temperature at 90 m is always higher than that at 70 m. These facts indicate that the advectional outflow of the basin water as previously stated is the dominant factor in change of the hydrographic condition in the basin.

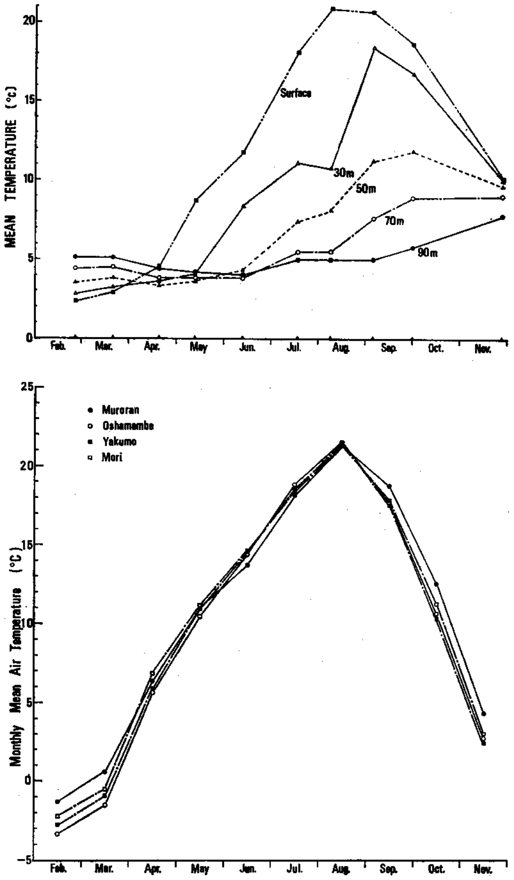

Fig. 8. (upper) The mean water temperatures averaged on the same planes as the mean salinities in Fig. 7. (lower) The monthly mean air temperatures at four weather stations around the bay shown in Fig. 1.

In July when Tw enters the bottom layer, the mean temperature at 70 and 90 m increase 1.7°C and 1.0°C respectively, according to the increases of the salinities at these depths in spite of the existence of overlying less saline O&Oi. Thus the temperature at 70 m exceeds that at 90 m.

Thereafter the temperature at 90 m stays constant while the volumes of the water masses in the bottom layer do not change until September. After September, it rises according to the increasing Tw volume in the bottom layer, and reaches the maximum in November.

The mean temperature at 70 m stays constant during the period from July to August, and the mean salinity at this depth also stays constant during this period. After August, however, the salinity begins to increase, showing the increase of Tw volume at this depth, and the mean temperature at 70 m increases more rapidly than that at 90 m.

As stated above, the mean temperature at 90 m varies according with the variation of the water-mass volumes in the bottom layer or to the mean salinity at the same depth, rather than to the mean temperatures at 70 m and other shallower depths. This means that the change of the hydrographic condition in the basin is due to lateral mixing with Tw and advection of Tw, and that the lateral mixing and the advection are superior to the vertical transfer of salts and heat by diffusion, except for winter when convectional mixing is predominant.

3. *Accumulation of nutrients and particulate organic matter in the basin water*

Yanada et al.[5)] presented the conservative PO_4-P concentration of each water mass from the relation between PO_4-P concentration and A.O.U., as 1.01 μg-at/*l* for O&Oi, 0.81 μg-at/*l* for Fw and 0.24 μg-at/*l* for Tw. Taking these values and the volumes of the water masses, the amount of non-conservative PO_4-P can be calculated by subtracting the conservative PO_4-P amount from the standing stock.

The results of the calculations made for the layer deeper than 80 m in the bay and PO_4-P standing stock in the whole bay are shown in Fig. 9.

From February through June, the PO_4-P standing stock in the basin water, in general, increases about two times and this increment is due to the increase of non-conservative PO_4-P amount. Non-conservative PO_4-P amount in February is 1.38×10^6 g-at and corresponds to 22% of the standing stock in this layer. Thereafter it increases to 8.60×10^6 g-at (60%) in June, and reaches the maximum, 9.27×10^6 g-at (67%) in August. It is considered that the rapid increase of non-conservative PO_4-P from February to June indicates active decomposition of organic matter and the abundance of organic matter in the basin water.

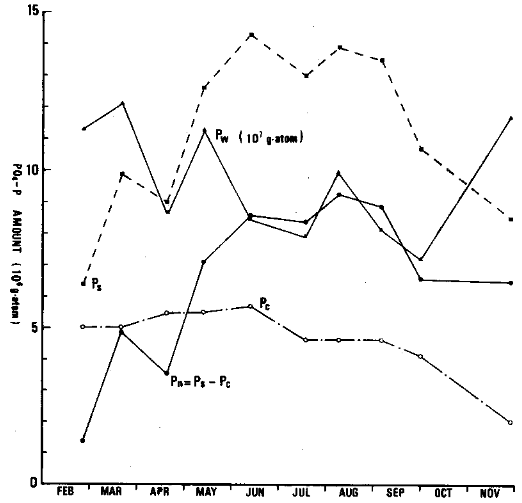

Fig. 9. The variations of PO_4-P standing stock (Ps), conservative PO_4-P amount (Pc) and non-conservative PO_4-P amount (Pn) in the layer deeper than 80 m in the unit of 10^6 g-at, and the PO_4-P standing stock in the whole bay (Pw) in the unit of 10^7 g-at.

From June to September, the standing stock and non-conservative PO_4-P amount in the basin water remain almost constant, while the horizontal transfer is dominant in the basin as stated in the previous sections. Therefore the constancy of the PO_4-P amount in the basin is considered to show that PO_4-P liberated from organic matter compensates the loss by horizontal transfer and renewal.

After September, the PO_4-P standing stock in the basin water decreases for the renewal of the basin water by lateral mixing and advection, and for the upward transport by convectional mixing after November. On the contrary, the standing stock in the whole bay in November reveals an increase of 44.8×10^6 g-at which is 64% of that at the end of September, and it becomes almost equal to the standing stock in February. This increment is almost fully due to the increase in the layer shallower than 50 m (51×10^6 g-at). The amount in the lower layer deeper than 50 m has a tendency of decrease (-6.2×10^6 g-at). Although assuming that all of the decrease in the lower layer is due to the transfer to the upper layer, the supply from the lower layer is much smaller than the increase in the upper layer.

One of the other factors which causes the increase of PO_4-P standing stock is the replacement of water masses. The PO_4-P concentration of Tw prior to entering the bay is thought to be 0.6 μg-at/l from the time-cross section at the station outside of the bay[5] and the mean concentration in the waters shallower than 50 m in the bay is about 0.3 μg-at/l at the end of September[10]. Since the volume of the layer shallower than 50 m is 97 km^3, the increment of PO_4-P by the water-mass replacement is estimated to be 29.1×10^6 g-at. Thus the sum of the supply from the lower layer (6.2×10^6 g-at) and the increase by water-mass replacement becomes 35.3×10^6 g-at, but this is also smaller than the increase in the upper layer.

Yanada[6] reported that much of particulate organic matter (POM) sunk to the layer deeper than 50 m, and according to Miyake et al.[12], the basin water is distinguished by high turbidity. And so it is considered that much POM is accumulated in the basin water. Tanaka and Tsunogai[13] supposed active vertical movement of particulate matter by convection because the vertical flux of particulate matter was unusually high in winter. Actually, according to Yanada and Maita[14], the concentration of POM in the bay increases in November, while the primary productivity in November is the smallest through the year.[15].

Considering the above results, the reason for the increase of PO_4-P standing stock in November is attributed to the following: due to the convectional mixing in winter, POM which has been accumulating in the cold basin water is transferred upward, and the temperature in the basin is increased. As the velocity of heterotrophic uptake increases exponentially with temperature[16], the POM is decomposed by microbial activity which is activated by increased temperature. And the released PO_4-P contributes significantly to the increase of PO_4-P standing stock in November.

This supposition is supported by the fact that dissolved oxygen is undersaturated in the whole bay in spite of the active convectional mixing in winter[10].

As stated above, the basin water preserves abundant nutrients and POM from spring through autumn, and the POM becomes a potential source of nutrients. At the same time POM is an important food for heterotrophic organisms[17], and especially in Funka Bay it may possibly be a food for the benthos.

Therefore the significance of the basin water in the material redistribution and ecosystem in the bay is considered to be so large that its characteristics and behaviour should be given attention in the studies on material budgets and ecology in Funka Bay.

Summary

The homogeneous and heavy Winter Funka Bay Water (Fw), which is transformed in Funka Bay from the Tsugaru Warm Water (Tw) through winter, remains in the basin of the bay as the basin water from spring through autumn, as being affected by the overlying Oyashio Water (O&Oi) or Tw. In this paper, the hydrographic and chemical characteristics of the basin water were investigated by making use of the oceanographic data obtained in 1974. The results of the studies are summarized as following.

1) From spring to summer when O&Oi enters the bay, the basin water is renewed mainly by the advectional outflow of the basin water rather than vertical diffusion, because of the thermocline and halocline formed between the basin water and the overlying O&Oi. From summer through autumn the basin water is renewed by lateral mixing with Tw along isopycnals and the advection of the basin water, but the vertical diffusion is not effective also during this period. In winter, convectional mixing is predominant in renewal of the basin water.

2) Optical and chemical studies by the other investigators suggest that much of particulate organic matter is accumulated in the basin water. And due to the decomposition of the POM, the basin water maintains nutrients of high concentrations from spring through autumn in spite of the renewals stated above. Especially in winter when Fw is formed, the nutrients released from the POM constitute the nutrients of Fw. The accumulated POM is considered to be important as a food for the benthos in the bay as well as the potential source of nutrients.

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