STAGNATION, MIXING AND RENEWAL OF THE WATER OF THE FUNKA BAY

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CONTENTS

Introduction

The Funka Bay, otherwise called the Uchiura Bay, which is located in the southwestern portion of Hokkaido opening on the North Pacific Ocean, is about 27.6 km in width at the entrance and is approximately 42.3 km in length. The greatest depth is 107 m in the central portion while it is about 80 m at the entrance of the Bay, therefore, the Bay is a basin on a small scale; however, this is of no importance because the portion deeper than the sill depth is very narrow as compared with the whole of the Bay as seen in Fig. 1 showing the bottom contours.

It has been generally known that the Bay is occupied by the water of the Oyashio current in winter, and that the lower layer is very cold even in summer while the upper layer is covered by the warm water. Under such conditions the upper layer abounds in many kinds of fish which migrate from the offsore warm water during the summer and autumn. In the lower layer, some kinds of fish which generally inhabit cold water, are caught in summer; it is of interest, however, that they are not caught after antumn but seem to move out offshore being affected by the change in the water.

Only one precise observation taken in August 1932 on board the "Shunpu Maru" (Hidaka *et al.*, 1934) gave us information about the current and the distri-

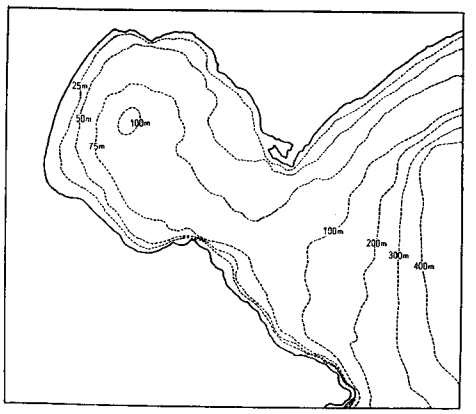

Fig. 1. Bottom contours in Funka Bay and vicinity

bution of temperature and salinity in the Bay in summer.

The author performed early hydrographic observations in the Funka Bay and its vicinity in connection with the fishery in these regions. In this paper he reports on the condition of the stagnation, mixing and renewal of the Bay water in summer and autumn mainly on the basis of data obtained in 1951.

General Feature of the Current System in the Funka Bay and its Vicinity

It is generally known that the Tsugaru Warm Current which flows out of the Tsugaru Straits flows southward along the east coast of the Sanriku District. However, the results of the observation apparently show that a part of the Tsugaru Warm Current stretches in a northerly direction toward Hokkaido and the western edge of this stretch approaches the entrance to the Funka Bay in summer.

The thickness of the Tsugaru Warm Current barely exceeds 200 m in August when the Current is predominant, and, then, the under Oyashio Current flows in the opposite direction in this region. The major portion of the Bay is shallower than 75 m, and the current near the bottom is considered to be very weak or nil. Therefore, the geopotential topography referred to the 200 decibar surface in the offshore region, and that referred to the 75 decibar surface in the Bay may represent approximately the real current respectively. The general characteristic features of the current which are obtained by means of such geopotential topography as above mentioned are shown as follows.

The stretch of the Tsugaru Warm Current flows northwestward into this region and flows northeastward off the Funka Bay. In the early summer, a coastal counterclockwise circulation is

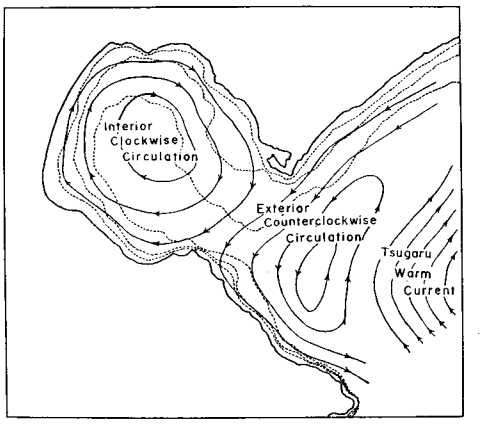

Fig. 2. Schematic representation of the current system in Funka Bay and vicinity

formed in the upper layer between this offshore Tsugaru Warm Current and the Funka Bay. The southwesterly current along the northern coast of this exterior coastal circulation has a tendency to flow southward, being restricted by the configuralion of the coast when it leaves the Chikyu-Cape, and it does not flow into the Bay. In the Bay at this time, a clockwise circulation is induced by the exterior counterclockwise circulation. These features of the current system are represented schematically in Fig. 2. In the lower layer, however, the Tsugaru Warm Current closely approaches the coast and the entrance of the Bay without forming such a counterclockwise circulation as that seen in the upper layer.

In midsummer, when the Tsugaru Warm Current prevails most strongly, the exterior coastal circulation is forced against the coast and it is observed as a narrow counter current along the coast. As a result of the predominance of the Tsugaru Warm Current, a part of the middle layer of the Current flows straight into the Bay through the northern portion of the entrance and, on the contrary, a part of the upper layer of the Bay flows out. Throughout the summer season, however, the lower layer of the Bay is stagnant and isolated from the current in the region outside the Bay.

In October, as a result of the receding of the axis of the Tsugaru Warm Current toward the east, the exterior coastal circulation becomes wider and deeper, therefore, the direction of the current in the region outside the Bay reverses in the lower layer. At this time, the lower layer of the Bay flows out of the Bay along the bottom, and the upper layer of the exterior circulation flows into the Bay.

Stagnation of the Bay Water

As seen in Fig. 3, in June the courses of the isotherms and isohalines show

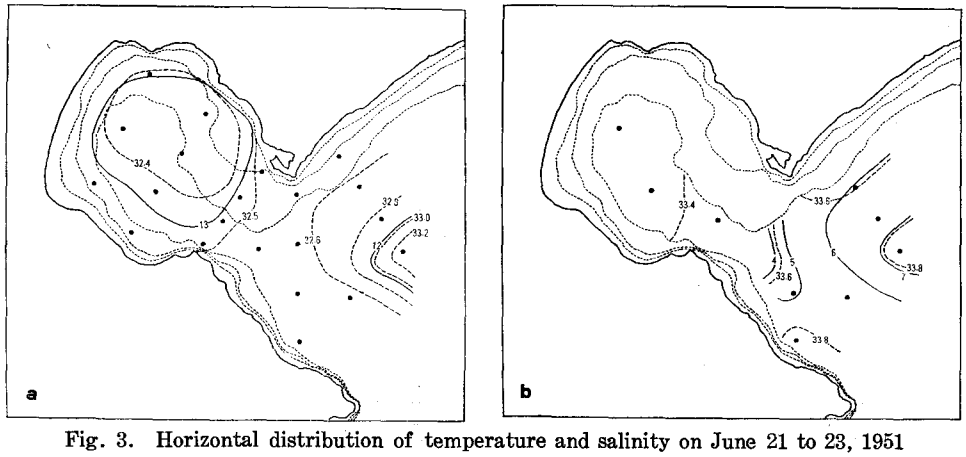

Fig. 3. Horizontal distribution of temperature and salinity on June 21 to 23, 1951
a: 10 m level b: 75 m level

that the circulation of the Bay has been formed in the upper layer, and that in the lower layer the cold and less saline water of the Bay seems to be stagnant, being enclosed by a stretch of the Tsugaru Warm Current.

In July, the patterns of the isotherms and isohalines have been considerably distorted as compared with those of the previous month. In the upper layer, as a whole, the warm and less saline water has drifted toward the south, and in the northern portion the subsurface water of a lower temperature and higher salinity has been brought upwards. In the region outside the Bay, especially, such subsurface water intrudes from the northern coast remarkably toward the south. Consequently the warm and less saline upper water of the coastal current appears to have been disturbed by this intrusion of subsurface water. The interior circulation of the Bay, though its center has shifted toward the south, has been maintained as well as in the previous month. These features may perhaps be due to the continuing northerly wind. In the lower layer, the cold and less saline water of the Bay appears to be stagnant, being almost unchanged in temperature and salinity.

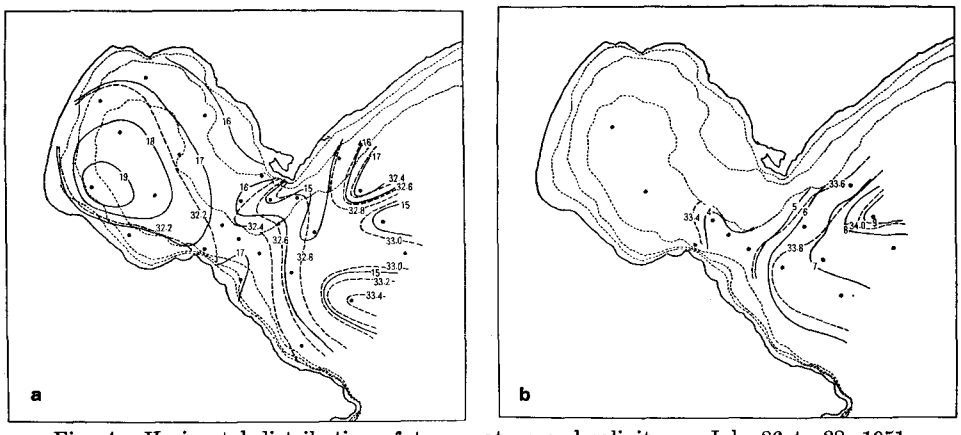

Fig. 4. Horizontal distribution of temperature and salinity on July 26 to 28, 1951
a: 10 m level b: 75 m level

Then, later in August, the middle layer of the Tsugaru Warm Current flows into the Bay as will be shown later, however, the lower layer of the Bay is stagnant throughout the summer. This water of the lower layer of the Bay is considerably colder than that in the region outside the Bay. Accordingly, the density of the former is greater than that of the latter as seen in Fig. 5. Therefore, the lower layer of the Bay must be maintained stable by the current in the region outside the Bay. Under such a condition of density distribution, estimating the boundary surface between the two waters as shown in Fig. 5 with a broken line, one can represent the dynamic boundary condition as follow:

$$2\omega \sin\varphi\rho' v' dx + g\rho' dz = 2\omega \sin\varphi\rho v dx + g\rho dz,$$

where ρ and v are the density and velocity of the water of the Tsugaru Warm Current in the region outside the Bay, and ρ', v', the density and velocity of the lower water of the Bay respectively, and where ω is the angular velocity of the earth's rotation, and φ is the latitude. From this figure, one obtains the following slope of the boundary surface:

$$i_B = \frac{dz}{dx} = 43.2 \times 10^{-4}.$$

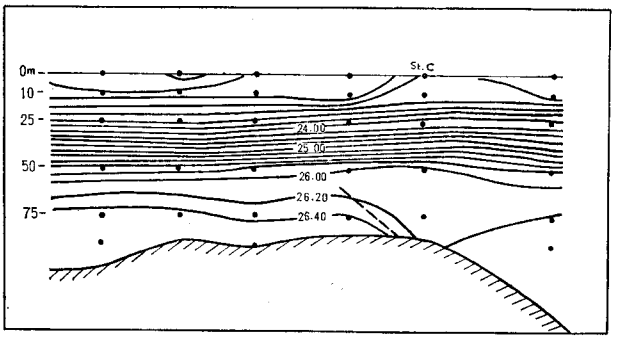

Fig. 5. Vertical profile of density in a section running from the interior (left side) toward the exterior (right side) of the Bay on September 13 and 14, 1951. St. C shows the current measurements station

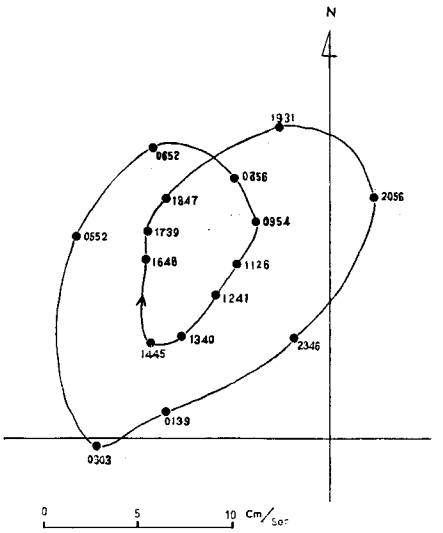

Fig. 6. Observed currents at a depth of 75 m at St. C (see Fig. 5) on September 13 and 14, 1952

The lower water at the 75 m layer in the Bay may be regarded almost at reast in consideration of the temperature and salinity distribution. Therefore, taking the values $v'=0$, $\rho=1.02615$, $\rho'=1.02645$, $\varphi=42°15'$, $\omega=0.729\times10^{-4}$ and $g=9.8$m/sec, one can obtain $v=12.6$ cm/sec. This was examined according to the direct current measurements by means of a current meter of the Ekman-Merz type in September 1952 on the same days that the hydrographic observations shown in Fig. 5 were made. For the current measurements a station was occupied near the entrance on the outside of the Bay as shown in Fig. 5. The currents observed at a depth of 75 m are shown in Fig. 6. The result of a harmonic analysis shows that the major current at the depth is 11.0 cm/sec in velocity and 321° in direction.

These two values of the velocity at the 75 m depth agree well proving that

the lower water of the Bay is stagnant and stable and that this feature may be maintained during the summer months when the Tsugaru Warm Curren prevails.

Mixing of the Bay Water

During the season when the Bay water is isolated from the current in the region outside the Bay, the upper layer is warmed by radiation and diluted by precipitation and run-off from the streams pouring into the Bay. Fig. 7 represents the temperature-salinity relations for all stations in the Bay in June and July. As seen in the figure, the salinity of the middle layer has increased a little more in July than in June despite the fact that the upper layer has been diluted and the lower layer has remained almost unchanged. This must be due to the lateral mixing with the warm and more saline water in the region outside the Bay.

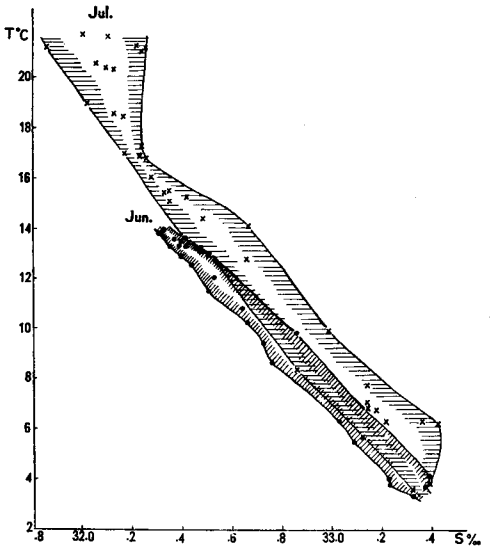

Fig. 7. Temperature-salinity relations for all stations in the Bay in June and July, 1951

Taking into account the lateral mixing, in the general expression, one can represent the change in the total heat amount of the Bay in the interval between the successive observations as follows:

$$\Delta Q=\int_{t_1}^{t_2}\int_f \rho c_p A_l \frac{\partial\theta}{\partial n}\, df dt+\int_{t_1}^{t_2}\int_F Q_s dF dt-\int_{t_1}^{t_2}\int_F Q_b dF dt-\int_{t_1}^{t_2}\int_F Q_e dF dt$$
$$-\int_{t_1}^{t_2}\int_F Q_h dF dt,$$

where Q represents the total heat amount, ρ the density of the water, c_p the specific heat, A_l the coefficient of lateral mixing, θ the temperature of the water, n the distance in the direction normal to the entrance of the Bay with the positive sign toward the outside of the Bay, and f and F represent the area of the vertical section on the entrance of the Bay and the area of sea surface of the Bay respectively, and where Q_s the radiation from the sun and sky, Q_b the back radiation from the sea surface, Q_e the heat lost by evaporation, Q_h the sensible heat given off to the atmosphere and t denotes the time of the observation.

Except the first term on the right-hand side of the above equation of the heat budget, the other terms can be calculated numerically.

i. Total heat amount of the Bay (Q).

At first, the amount of heat at each layer was obtained using a planimeter on the isotherms drawn for every degree, then the total heat amount of the Bay was calculated.

ii. Temperature gradient at the entrance of the Bay $\left(\frac{\partial\theta}{\partial n}\right)$.

Dividing the difference between the temperature of each layer at a station off the middle portion of the entrance of the Bay and the mean temperature of each corresponding layer at the entrance of the Bay by the mean distance between the station and the entrance to the Bay, the author regarded it as the temperature gradient at the entrance of the Bay.

iii. Radiation from the sun and sky (Q_s).

The average radiation which reaches the sea surface from the sky and clouds is represented by the following formula (Sverdrup *et al.*, 1946)

$$Q_s = Q_{s_0}(1-0.071C),$$

where the cloudiness C is given on the scale 0 to 10, and where Q_{s_0} represents the total radiation with a clear sky. Assuming the part of the radiation lost by reflection from the sea surface to be 4.7% (Miyazaki, 1952), on can represent the incoming radiation on the sea surface as follows:

$$Q_s = 0.953Q_{s_0}(1-0.071C).$$

iv. Effective back radiation from the sea surface (Q_b).

The effective back radiation is represented by the difference between the radiation of the sea surface and that from the atmosphere, mainly from the water vapor. In the presence of clouds the effective back radiation can be written in the empirical relation,

$$Q_b = Q_{b_0}(1-0.083C),$$

where Q_{b_0} is the back radiation at a clear sky and where C is the cloudiness. The value of Q_{b_0} is obtained from the diagram prepared by Sverdrup (1946) as a function of sea-surface temperature and relative humidity of the air.

v. Heat lost by evaporation.

The heat amount lost by evaporation at the surface is

$$Q_e = L_\theta E,$$

where L_θ is the latent heat of vaporization at the temperature of the surface and E is the amount of evaporation.

The amount of evaporation can be calculated from the formula represented by Sverdrup (1937),

$$E=\frac{K(e_w-e_a)w}{\frac{\kappa}{k_0}\ln\frac{z+z_0}{d+z_0}+dw}\,,\qquad K=\kappa\frac{0.623}{p}\rho_a\,,\qquad w=\frac{k_0u_z}{\ln\frac{z+z_0}{z_0}}=\frac{0.165}{\log\frac{z+z_0}{z_0}}u_z\,,$$

where e_w is the saturated vapor pressure at the sea-surface temperature, e_a the vapor pressure in the atmosphere, κ the coefficient of diffusion (0.235), k_0 von Kármán's constant (0.38), z the altitude of observation, z_0 the roughness parameter equal to 0.6 cm for the rough sea surface, ρ_a the density of air, p the atmospheric pressure, u_z the wind velocity, d the thickness of the diffusion layer, and where according to Sverdrup

$$d=\frac{4.12}{w}\,.$$

The salinity decreases the vapor pressure slightly, the empirical relation between vapor pressure and salinity (Sverdrup *et al.*, 1946) being

$$e_w=e_d(1-0.000537S)\,,$$

where e_d is the vapor pressure over distilled water of the same temperature.

vi. Sensible heat from the sea surface.

The amount of sensible heat given off to the atmosphere is obtained using the amount of heat used for evaporation calculated above and the Bowen ratio (Sverdrup, 1946) which represents the following relation

$$R=\frac{Q_h}{Q_e}=0.66\frac{p}{1000}\frac{\theta_w-\theta_a}{e_w-e_a}\,,$$

where θ_w and θ_a represent the temperature of the sea surface and that of the air at the height of a few meters respectively.

vii. Materials for the meteorological condition.

For the values of the total radiation with a clear sky (Q_{s_0}) were adopted those on 42°N, 60°W shown by Kimball (1928). The other meteorological materials which are necessary to calculate the values of Q_s, Q_b, Q_e and Q_h were taken from the data obtained by the Muroran Weather Station which in those days was located near the seaside facing the Funka Bay.

The results of the numerical calculation show that the heat amount gained by the lateral mixing was 26.70×10^{16} g cal while that received at the sea surface was 13.45×10^{16} g cal in the period from June 23 to July 28.

The coefficient of lateral mixing A_l is obtained, in this case, as

$$A_l=\frac{\Delta Q-Q_m}{\int_{t_1}^{t_2}\int_f \rho c_p\frac{\partial\theta}{\partial n}dfdt}\,,$$

where Q_m represents the sum of the last four terms on the right-hand side of the

equation of the heat budget. The calculation of the value amounts to 8.93×10^6.

Ichiye (1950) obtained 1.09×10^7 as a value of the coefficient of the lateral mixing in Osaka Bay. He pointed out that this value is of the same order with that obtained by assuming that the water mass transported by the tidal current causes an element of turbulence. According to Ichiye, in such case, the coefficient of the lateral mixing can be represented as $u_0^2T/2\pi^2$, where u_0 is the maximum velocity of the tidal current and T is the period of the semi-diurnal tide which is equal to 4.32×10^4 sec. Assuming the value of u_0 to be 30 cm/sec in the case of the Funka Bay, one obtains 2.10×10^6 as the value of $u_0^2T/2\pi^2$. On the other hand, Miyazaki (1952) obtained 8.43×10^5 as a value of the lateral mixing in the Tsugaru Warm Current of the Japan Sea. The value 8.93×10^6 now obtained may be accepted as valid under the influence of the tidal current and the oceanic current being rather small as compared with the values of $10^7\sim10^8$ obtained in the Pacific and Atlantic Oceans (Sverdrup, 1943).

Renewal of the Bay Water

In August, as seen in Fig. 8, the current of the upper layer has reverted to its ordinary state in the region outside the Bay, however, the upper water of the Bay flows out from the northern portion of the entrance, and in the northern portion of the Bay the lower water of lower temperature and higher salinity has ascended to the upper layer, and consequently the interior circulation has been forced toward the south. In the middle layer of a depth of 50 m, it is very noticeable that the Tsugaru Warm Current flows straight into the recess of the Bay in the northern portion. The extraordinary patterns of temperature and salinity of the upper layer in the northern portion of the Bay are due to the effect of this water flowing into the Bay. The lower water, has remained almost unchanged in temperature and salinity. At this season, the Tsugaru Warm Current flowing toward the Funka Bay becomes the strongest of the year; the velocity of the Current which is calculated at the 50 m depth relative to the 200 m depth reaches to 15.0 cm/sec while it is about 6.0 cm/sec in July.

This feature of the current is believed to continue till September because the result of observations made in September 1952 shows the feature similar to that in August above mentioned.

In October, the renewal of the Bay water takes place through all layers as seen in Fig. 9.

The warm and high saline water flows into the northern portion of the Bay from the region outside the Bay and less saline water of lower temperature of the Bay flows out of the southern portion in the upper layer. It is a most conspicuous

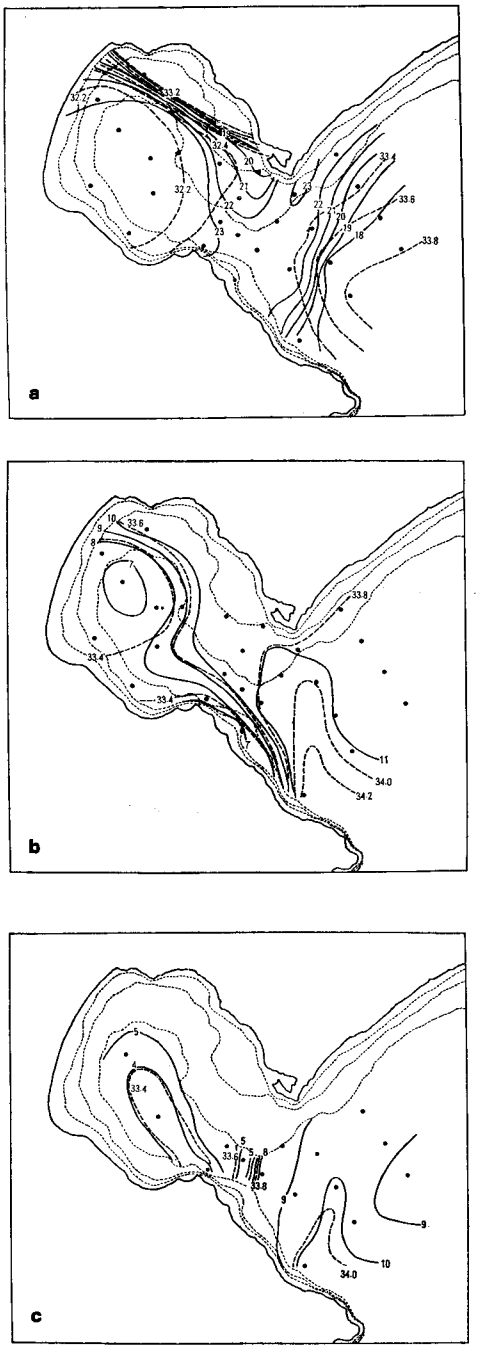

Fig. 8. Horizontal distribution of temperature and salinity on August 27 to 29, 1951
a: 10 m level b: 50 m level
c: 75 m level

feature, especially, that the lower water of the Bay flows out all over the layer of the depth. In this season, the current in the region outside the Bay flows in a southerly direction through all layers suggesting that the Tsugaru Warm Current has become weak and flows at a distance from this region. The lower water of the Bay, as pointed out before, had been maintained stable and stagnant by the Tsugaru Warm Current in the region outside the Bay during the summer. Therefore, the outflow of the lower water, as seen now, must take place according to the difference in density between the waters on the both sides of the boundary when the Tsugaru Warm Current becomes weak, and then, the current in the region outside the Bay turns in the opposite direction.

As the result of the renewal of the water, the character of the water of the Bay changes greatly in temperature and salinity after July. The amount of heat and volume of water transported by the renewal will be examined next.

The amount of heat transported into the Bay by the renewal of water in the period between the successive observations is represented as follows:

$$Q_v = -\int_{t_1}^{t_2}\int_f \rho c_p u \theta d f dt ,$$

where u is the velocity of the current normal to the entrance of the Bay with the positive sign toword the outside of the Bay. Assuming the velocity at the 75 m depth to be zero, the author calculated the values of u and then estimated

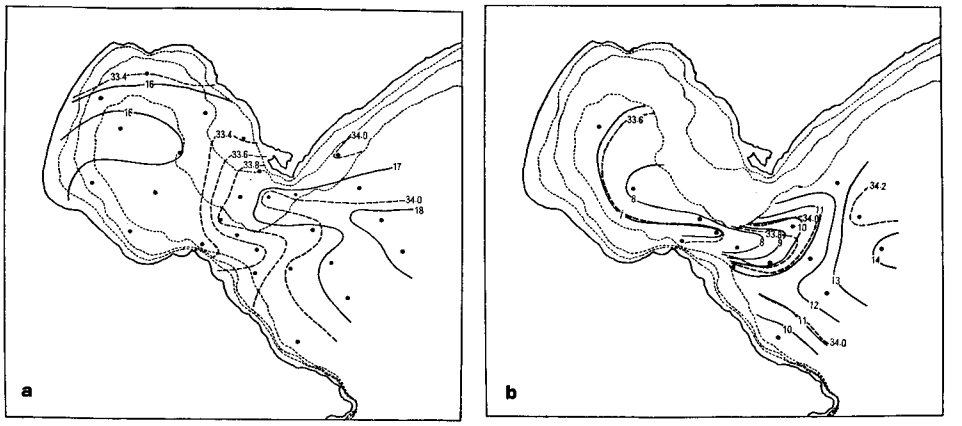

Fig. 9. Horizontal distribution of temperature and salinity on October 10 to 12, 1951
a: 10 m level b: 75 m level

roughly the value of Q_v.

The values of Q_v are shown in Table 1 together with the values of ΔQ, Q_l and Q_m obtained after June; here, Q_l represents the heat amount due to the lateral mixing through the entrance of the Bay. As a whole, the heat amount incoming or outgoing from the sea surface shows a tendency similar to the change of the total heat amount, however, the lateral mixing and the advection affect much more the change of the total amount of heat after July.

Table 1. Change of total heat amount of the Bay(ΔQ), incoming heat amount through sea surface(Q_m), heat amount due to lateral mixing(Q_l), and heat amount due to advection(Q_v, Q_v'). Q_v based on the advection at the time of observations and Q_v' on calculation using the heat budget equation

	ΔQ(10^{16} g cal)	Q_m(10^{16} g cal)	Q_l(10^{16} g cal)	Q_v(10^{16} g cal)	Q_v'(10^{16} g cal)
Jun. 23 - Jul. 28	40.15	13.45	26.70	0	0
Jul. 28 - Aug. 29	27.16	5.07	44.20	−27.97	−22.11
Aug. 29 - Oct. 11	− 4.80	− 7.93	54.60	−55.81	−51.47

The amount of heat of the Bay changed by the renewal of the water, on the other hand, can be written

$$Q_v' = \Delta Q - Q_l - Q_m.$$

Assuming the value of the coefficient of the lateral mixing to be equal to that obtained previously in the case of the summer, the author calculated the values of Q_v' in the periods between the successive observations in July, August and October. These values of Q_v' are entered in Table 1.

The amount of heat transported in the lower layer between the depths of 50 m and 75 m depends a great deal upon that of the upper portion of the layer

near the 50 m depth where the most intense inflow is encountered in August, whereas the value of Q_v is calculated with a mean value of u at the 50 m depth and that at the 75 m depth. The differences of the values of Q_v and Q_v' may be partly due to such approximate calculation as above mentioned.

The decrease of the heat amount due to the advection seems to be inconsistent with the increase of the heat amount due to the lateral mixing in August and October. This fact, however, is attributed to the effect of the outflow of the warmer water of the Bay at the upper layer instead of the inflow of the offshore water of relatively lower temperature at the middle layer in August as just mentioned above.

The values of Q_v and Q_v', however, may be assumed to agree approximately, proving to some extent the validity of the estimation of the volume transport in the interval between the successive observations. The volume transport calculated between the successive depths at the entrance to the Bay at the time of the observation is shown in Table 2. In the table, the ratio of the volume transport in a day to the volume of the Bay is entered to make it easy to estimate the number of days which an entire renewal of the water would take.

Table 2. Volume transport at the entrance of the Bay and ratio of volume transport in a day to volume of the Bay water (R)

	Aug. 28		Oct. 11	
	Inflow($10^2 m^3$/sec)	R	Inflow($10^2 m^3$/sec)	R
0 m–10 m	−147.5	−0.055	− 55.4	−0.021
10 m–25 m	−149.4	−0.040	32.9	0.009
25 m–50 m	26.1	0.005	152.2	0.029
50 m–75 m	270.8	0.081	−129.7	−0.039

The table shows that the most intense outflow of the uppermost layer and inflow of the middle layer take place in August, and that the relatively intense outflow of the lower layer occur in October. It may be expected that the renewals of the uppermost and middle layers take place within a month from August to September, and that the entire renewal of the whole water of the Bay will take place in autumn.

In the above calculation of the values of Q_v, they have been obtained on the assumption that the amount due to the advection varies linearly in the period between the successive observations, however, the agreement of the values of Q_v and Q_v' does not necessarily mean that the state has changed linearly. The fact may be not so. More frequent observations are necessary to be taken at shorter intervals to reveal the feature and condition of the renewal of the water at this season.

Summary

1. The characteristic features of the current system in the Funka Bay and its vicinity in summer and autumn were described on the basis of the observations made by the author. A part of the Tsugaru Warm Current stretches in the northerly direction toward Hokkaido, and the western edge of this stretch of the Current approaches the Bay. Between this stretch of the Tsugaru Warm Current and the Bay, a counterclockwise coastal circulation is formed in the upper layer. In the lower layer, the Tsugaru Warm Current closely approaches the coast and the entrance to the Bay. In the Bay, a clockwise circulation is induced in the upper layer by the exterior counterclockwise circulation. The lower water of the Bay, which is cold and of great density, is enclosed by the Tsugaru Warm Current and is maintained stagnant in summer. In midsummer, when the Tsugaru Warm Current prevails most strongly, the middle layer of the Current flows straight into the Bay, and the upper layer of the Bay flows out. In October, as a result of the receding of the Tsugaru Warm Current toward the east, the direction of the current in the region outside the Bay reverses in the lower layer. At this time, the lower layer of the Bay flows out, and the upper layer of the exterior circulation flows into the Bay.

2. The condition of the stagnation of the lower water of the Bay in summer was examined by direct current measurements and the slope of the boundary between the water of the Bay and that of the Tsugaru Warm Current in the region outside the Bay. The value of the current velocity obtained by direct measurements and that calculated from the dynamic boundary condition agree well, proving that the lower water of the Bay is maintained stable and stagnant.

3. The amount of heat due to the lateral mixing was calculated from the point of view of the heat budget of the Bay in the period from June to July when the Bay water is isolated from the current in the region outside the Bay. From this value, the coefficient of the lateral mixing was obtained as 8.93×10^6.

4. The amount of heat transported after July by the renewal of the water was calculated with the heat amount due to the advection at the time of observation. Furthermore, this amount of heat was obtained from the point of view of the heat budget. The two values obtained by each of the ways agree approximately, proving to some extent the validity of the volume transport. The calculated volume transport shows that it may be expected that the renewals of the uppermost and middle layers take place within a month from August to September, and that the entire renewal of the whole water of the Bay will take place in autumn.

Literature cited

Hidaka, K. *et al.* (1934): Results of the Oceanographical Observations on Board R.M.S. "Shunpu Maru" in Hunka-Wan (Volcanic Bay), Hokkaido (Aug., 1932). *Jour. Oceanogr.* **6** (2).

Ichiye, T. (1950): On the Mutual Effect of the Coastal and Off-shore Water. *Jour. Oceanogr. Soc. Jap.* **6** (2).

Kimball, H. (1928): Amount of Solar Radiation that reaches the Surface of the Earth on the Land and on the Sea, and Methods by which it is measured. *Month. Weath. Rev.* **56** (10).

Miyazaki, M. (1952): The heat budget of the Japan Sea. *Bull. Hokkaido Reg. Fish. Res. Lab.* **4**.

Sverdrup, H. U. (1937): On the evaporation from the oceans. *Jour. Mar. Res.* **1** (1).

Sverdrup, H. U. (1943): *Oceanography for Meteorologists.* Prentice-Hall, Inc. New York.

Sverdrup, H. U. *et al.* (1946): *The oceans.* Prentice-Hall, Inc. New York.