Meteorology and Oceanography in the Seto Inland Sea

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The Kobe Marine Observatory has investigated meteorology and oceanography of the Seto Inland Sea(SIS) since 1920's. In this report, we describe their characteristic features in the SIS and discuss mechanism of water exchanges between the Kuroshio and the coastal area in Kii Channel.

On the SIS, westerly winds prevail generally, and complex "land and sea bleezes" occur by means of its land configuration. Precipitation is less and sunshine duration is more than in any other region of Japan. Sea fogs of the SIS appear from March to August. Discharge from river is more in the eastern part than in the western part of the SIS. These elements control water mass generation, pollutant diffusion and biological activities in the SIS.

In the SIS, mean eastward water transport occurs chiefly by means of westerly winds. Tidal currents prevail generally and are especially significant in straits, where the current speed is rapid and vertical mixing is very strong. The sea level is highest in Bisan Seto of the SIS, where sea surface temperature and salinity are relatively low. It is suggested that Bisan Seto seems the boundary between the western and the eastern part of the SIS.

The nutrient concentration had become rich since 1930's till 1970's but thereafter it keeps the same level. In general, it is richer in the eastern part than in the western part of the SIS.

Water exchanges between the SIS and the Kuroshio take place in Bungo Channel and Kii Channel. In Kii Channel, the easternmost of the SIS, it is infered that the coastal water flows out offshore in the upper layer, and the modified Kuroshio water flows into Osaka Bay in the lower layer, as supposed from observed water temperature, salinity and dissolved oxygen sections. Such mechanism can be also thought in Bungo Channel.

1. Maritime meteorology in the Seto Inland Sea(SIS)

On the SIS, westerly winds prevail generally, and complex "land and sea breezes" occur by means of its land configuration. Especially such tendencies appear clearly on Bisan Seto and Kurushima Straits of which widths are narrow. Annual mean air temperature is about 15 °C, which is higher than on the land around the SIS. Precipitation is less than 1200 mm and sunshine duration is more than 2200 hours a year in the SIS, which is one of the least rainfall regions in Japan.

As characteristic maritime meteorological features in the SIS, land and sea breezes, and sea fogs are described as follows:

1-1 Land and sea breezes

Land and sea breezes on Hiuchi Nada are observed By the Kobe Marine Observatory (KMO) in July 30 and 31 of 1951 (KMO,1952. Fig.2). Land breezes converge and sea breezes diverge on the center of Hiuchi Nada, which connects with Harima Nada through Bisan Seto. It is seen that sea breezes from Harima Nada intrude into Hiuchi Nada and those from Hiuchi Nada do into Harima Nada. Land and sea breezes on Bisan Seto are very complex.

The local strong wind "Hijikawa Arashi" on the western Ehime Prefecture exists as a kind of land and sea breezes. Land breezes occur by means of nocturnal radiation cooling at Oozu Basin about 15 km apart from the mouth of the river Hijikawa. They blow toward the beach along the Hijikawa valley with radiation fogs. The nearer they approach the beach, the stronger they become. The wind records aboad the R/V Shumpu-Maru of the KMO are shown in fig.3 at 1 km offshore in June 12 and 13 of 1978.

1-2 Sea fogs on a fine day in the SIS

Sea fogs in the SIS appear from March to August, specially often between May and July, when air temperature is higher than sea surface temperature. Especially dense fogs occur on Bisan Seto. Fogs on a rainy day (rain fogs) appear during the significant weather and fogs on a fine day (fine fogs) do like a guerrilla. Japan Meteorological Agency has six fog observation stations in the SIS. At Megishima, Ogishima and Naoshima, islands

Marine Pollution Bulletin, Vol. 23, pp. 5–9, 1991.
Printed in Great Britain
0025-326X/91 $3.00+0.00

of Bisan Seto, frequency of fogs is shown in table 1 between 1975 and 1978. Fine fogs occupy 30 % of the total. In June 7 of 1987, this fog is observed aboad the R/V Shumpu-Maru from occurence till vanishment. The cloud of Stratus type near the summit of Megishima spread down on the sea surface and formed sea fogs. The circulation of land and sea breezes on the previous day had played a very important role in the fog formation by means of supplying and transporting moisture (Yoshikawa,1988).

Table 1 Monthly average frequency of rain fogs and fine fogs on Bisan Seto in 1985-1988 (in days).

month	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sep.	Oct.	Nov.	Dec.	year
rain fog	0.0	0.8	2.2	3.5	3.0	4.3	1.8	0.0	0.0	0.4	0.0	0.3	16.3
fine fog	0.0	0.3	0.5	1.4	1.7	1.2	2.8	0.0	0.0	0.0	0.4	0.7	9.0

2. Oceanography of the SIS

Generally the water temperature and salinity are higher, while the concentration of nutrient is lower, in the weatern part than in the eastern part of the SIS (Komura, 1983 and Yamamoto,1984). These are mostly due to the fact that there are more large rivers and the discharges of land water are much more in the eastern part than in the western part.

In the SIS, mean eastward water transport dominates chiefly by means of westerly winds. Tidal currents prevail generally, and are especially significant in straits, where the current speed is rapid and vertical mixing is very strong. Tidal residual flows generate one or two circulations with a half or one month period in a bay or a Nada (a semiclosed basin). Bisan Seto is narrower in the SIS, where sea surface temperature and salinity are relatively low. The sea level of Bisan Seto is highest in the SIS(Table 2) except in a part of Osaka Bay.

There are three kinds of currents, density current, drift current and tidal residual flow, which play an important role in the transport of materials in the SIS (Yanagi,1990). It issuggested that these kinds of currents make Bisan Seto keep high sea level with a complex dynamic mechanism and it is thought that Bisan Seto is the boundary between the eastern part and the western part of the SIS.

Table 2 Annual mean sea level of 1984-1988 at tidal stations of the SIS which are under the control of the KMO (above TP; mean sea level of Tokyo Bay, in cm).

sts.	Tosa-shimizu	Uwa-jima	Matsu-yama	Taka-matsu	Komatsu shima	shimo-noseki	Hofu	Uno	Kobe	Shira-hama
height	-9.8	-8.7	-8.3	+1.8	-2.4	-7.0	-0.3	+2.8	-0.2	-4.7

The KMO has observed oceanography of Osaka Bay since 1920's. Osaka Bay is most contaminated by pollutants from land in the SIS. Using these data, the followings are the description about the long term variations of phosphate-phosphorus concentration, and distributions of plankton which suggest sea water motions in Osaka Bay.

2-1 Long term variations of phosphate-phosphorus concentration in Osaka Bay

Watanabe(1980) analysed the changes of water temperature, salinity, dissolved oxygen and phosphate-phosphorus concentration at the innermost, at the central and at the mouth of Osaka Bay, in 1934-1935, in 1952-1953 and in 1974-1979. Adding 1985-1989 the data with them, we show the results in figs. 4-6. The phosphate-phosphorus concentration showed 0.1-0.3($\mu\ mol \cdot l^{-1}$) in 1934-1935, it became 0.1-0.7 in 1952-1953 with a little increase, and it increased to 0.3-2.3 in 1974-1979. In 1985-1989 it decreased a little to 0.3-1.6.

2-2 Plankton distributions and deduced water motion in Osaka Bay

Both zooplankton and phytoplankton were observed at 17 stations of Osaka Bay in August 1984 (Kubo,1986). Fig 7 shows the distribution of warm water chaetognath *Saggita enflata*, which denotes the path (B in fig.10) of the oceanic water which inflows to Osaka Bay from Kii Channel, flows along the west coast in the surface layer, and circulates in the center of the bay. Fig.8 shows the distribution of coastal diatom *Skeletonema costatum* at several depths (0,10,20 and 30m), which denotes the path (A infig.10) that the water in the innermost of the bay flows southward and gradually sinks along the east coast, and reaches to the bottom in the mouth of the bay. Fig.9 shows the distribution of coastal diatom *Chaetoceros curvisetus* at several depths (0,10,20 and 30m), which denotes the path (C in fig.10) of the oceanic water in the bottom layer, which inflows to Osaka Bay from Kii Channel, flows northward along the long axis of the bay and makes the upwelling due to the bottom topography near Okinose. This figure is similar to that of Fujiwara and Nakata (1990).

3. Exchanges between the Kuroshio water and the coastal water of Osaka Bay in Kii Channel

Water exchanges between the SIS and the Kuroshio take place in Bungo Channel and Kii Channel. The KMO has observed Osaka Bay along O-line and Kii Channel along C-line four times a year. The Oceanographical Division (1989) of the KMO studied this exchanges mechanism, using these data. Fig.11 shows salinity sections along O- and C-line in each season of 1987. In winter, the isohalines of 33.0 and 34.0 are situated between st.O-2 and st.O-1, and between st.C-2 and st.C-3, respectively. In spring, they are situated together near st.C-1. In summer, the isohaline of 33.0 can be seen near st.O-2 and the surface of st.C-3, and that of 34.0 can be seen above 40m depth between st.C-3 and st.C-4. In fall, the 33.0 stays in Osaka Bay and the 34.0 can be seen in the same area as in summer. Therefore, the Kuroshio water occupys the whole Kii Channel in spring. Then time proceeding, the coastal water of Osaka Bay becomes lighter and flows out offshore in the upper layer, on the other hand, the Kuroshio water flows into Osaka Bay along the bottom of Kii Channel, mixing with the coastal water.

In winter, a system of oceanic fronts appears between the Kuroshio water and the coastal water in Kii Channel. The two waters has same density, but very large differences of water temperature and salinity. When there are two waters with same density but with different temperature and salinity, and each temperature and/or salinity of the waters is changed by a certain mount with external causes such as a sudden weather variation, then the change of density is larger in the water with higher temperature and salinity. For example, the case when water temperature decreases only, is shown in fig.11. If three kinds of waters with same thermosteric anomaly ($250\times10^{-8}m^3\cdot kg^{-1}$), W1(16℃, 34.64), W2(12℃, 33.56) and W3(11℃, 33.32) in the figure decrease by 1 ℃, these anomalies become 229, 233 and 234, respectively, and if by 5 ℃, 153, 172 and 178, respectively. This means that the Kurishio water sinks down under the coastal water with lower temperature and salinity. Such a mechanism can be thought in Bungo Channel, also.

Harima Nada and Hiuchi Nada act as the innermost parts in the SIS both from Kii Channel and from Bungo Channel, respectively. Especially as Harima Nada connects with Osaka Bay, it is thought that Harima Nada is more affected by the most contaminated water of Osaka Bay.

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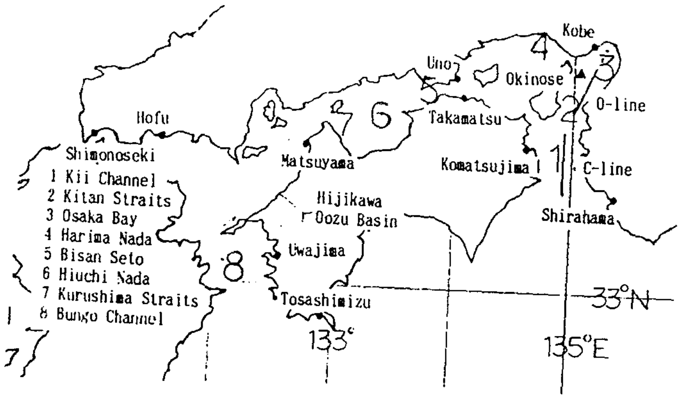

Fig.1 Position of the name of place in this paper, except Megishima Ogishima and Naoshima in Bisan Seto.

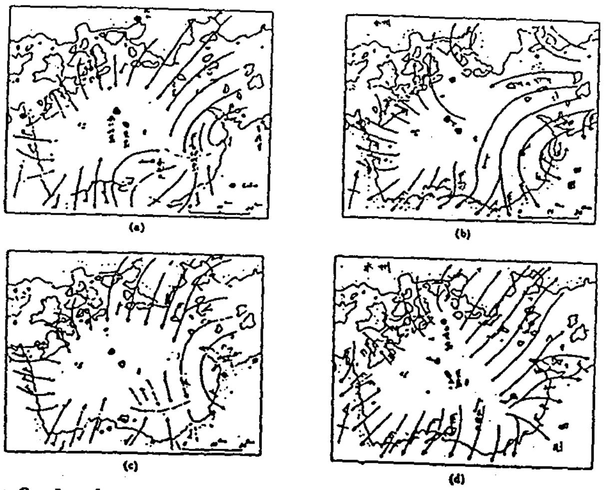

Fig.2 Land and sea breezes on Hiuchi-Nada (a) at 0500 (b) at 1200 on July 30 1951, (c) at 0500 (d) at 1200 on JUly 31 1951.

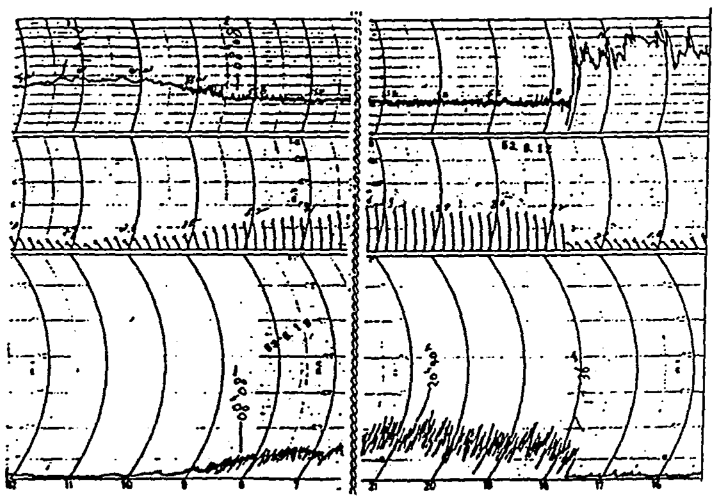

Fig.3 Wind records of "Hijikawa Arashi" on June 12-13 1978, upper;wind direction, middle; average speed, lower;instantaneous speed.

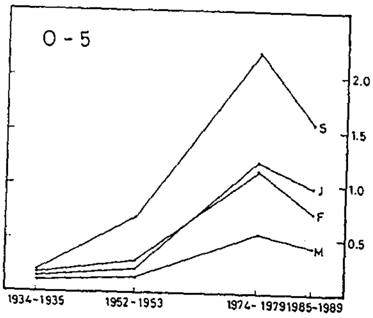

Fig.4 Integrated mean phosphate-phosphorus(μ mol l^{-1}) in February(F), May(M), July(J) and September(S) in the innermost of Osaka Bay.

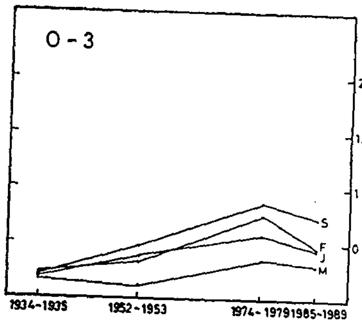

Fig.5 Same as fig.4 except the center.

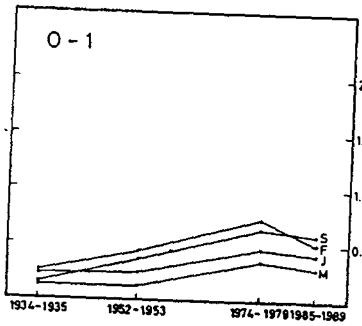

Fig.6 Same as fig.4 except the mouth.

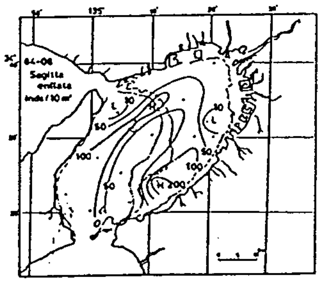

Fig.7 Distribution of *Sagitta enflata* (*inds* /10 m^3) Aug. 1984, after Kubo(1986).

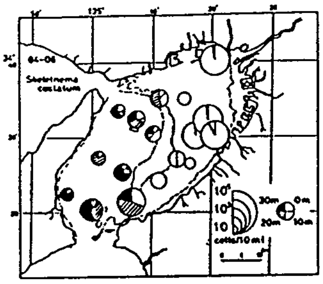

Fig.8 Distribution of *Skeletonema costatum* at several depth (*cells* /10 *ml*) Aug. 1984, after Kubo(1986).

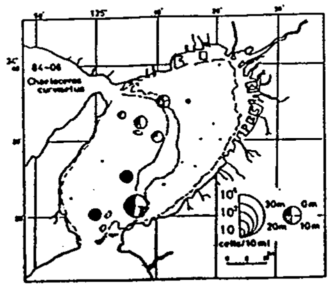

Fig.9 Same as fig.8 except *Chaetoceros curvisetus*.

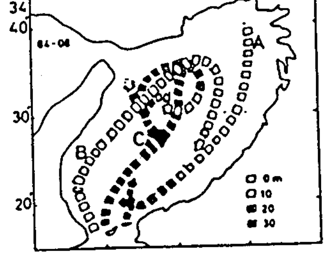

Fig.10 Water motion in Osaka Bay inferred from distributions of plankton.

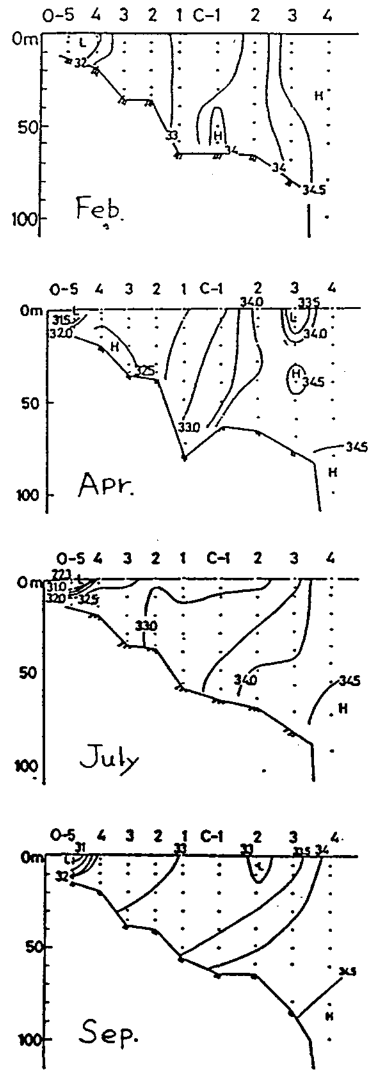

Fig.11 Seasonal salinity sections of Osaka Bay(O) and Kii Channel(C) in 1987.

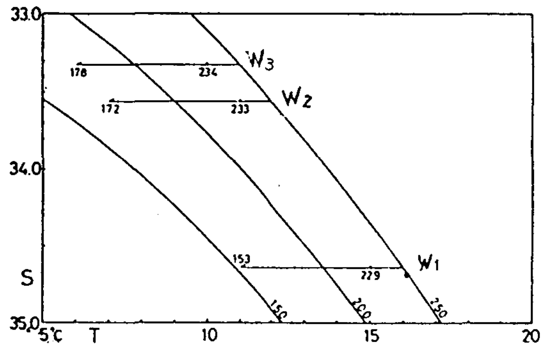

Fig.12 T-S diagram, numerals are thermosteric anomaly ($10^{-8}m^3$ kg^{-1}).