# The Causes of the Annual Variation of the Mean Sea Level along the Japanese Coast.

by

**Takaharu Nomitsu**

and

**Motojiro Okamoto.**

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ABSTRACT.

Which is the most effective and what is the relative importance, of the various causes of the annual variation of mean sea level, and how are they to be determined quantitatively? These questions are very longstanding, but have not yet been definitely solved. The authors have studied this problem in connection with the Japanese coast, and have been able to solve it quantitatively. According to their results, along the Japanese coast at least, the seasonal fluctuation of the mean sea level is chiefly produced by the variation of the sea water temperature. The variation of barometric pressure is next in importance, but not much stress need be put on the wind and all other causes.

## Introduction.

It is a phenomenon common to all parts of the world that the mean sea level changes with the seasons of a year; in some parts[1] its annual inequality reaches even one or two meters. Along the Japanese coast, the mean sea level generally has its maximum elevation in August or September, and its minimum height in January or February, the range of the inequality being 20 or 30 cms.

Though the irregularity of the sun's motion may cause the semi-annual and the annual tides, those tides theoretically will be very feeble and can not exceed about 4% of the lunar semi-diurnal tide; so the causes of the annual variation of considerable amplitude as stated above must be

1 R. Harris, Mannual of Tides, IV, 456—465(1907)

sought elsewhere. Now it is the generally accepted view that the annual change is chiefly what is called the "meteorological tide", which is caused by changes of the atmospheric pressure, wind, temperature of the sea water, precipitation, evaporation, oceanic current, etc. Hitherto, however, there no method has been devised to analyse and calculate quantitatively the effect of those elements, so opinion is divided as to which one of these causes is the most effective and what is the relative importance of each cause.

Of course, the relative importance of these causes must be different according to the local conditions. As regards shallow inland seas or long narrow bays, E. Piccard[1] found that the annual variation of mean sea level at Kronstadt near the mouth of Finnland Bay goes together with the change of precipitation in the neighbourhood. Ed. Brückner[2] noticed that the mean sea level at Odessa and of the Asow Sea in the Black Sea rises about 20 cms. in May or June on account of the increase in Spring of the quantity of water in the rivers in the southern parts of Russia. H. Lentz[3] pointed out that the annual fluctuation of mean sea level along the German coast of the Baltic Sea is largely affected by the wind. According to O. Krümmel,[4] the annual variation of sea level along the German, Danish, and Swedish coasts of the Baltic Sea ranges between 10 and 20 cms., and it is caused by precipitation, wind and barometric pressure. Krümmel also states that the sea level along the coast of Aden Bay has about 25 cms. as its annual inequality and it may be explained as the influence of the monsoon. Notwithstanding that in all the said papers the investigators merely compared the variation of the sea level with that of the element believed to be its cause and found no more than that they run parallel to each other, it can be well understood that the sea level of shallow inland seas with narrow mouths or very narrow bays, as in the above examples, may be remarkably affected by the wind and tributary land water.

On the other hand, how will it be on the coast of the open sea in general? It is the effect of barometric pressure that was recognized universally from early times as an important cause of the seasonal fluctuation of sea level. According to Sir C. Close's review[5] of the earlier investigations on this point, M. Daussy, already in 1831, studied the

1 Beitr. zur phys. Geogr. des Finn. Golfs, 111(1903).
2 Meteor. Zeitschr., 297(1886).
3 Fluth und Ebbe, und die Wirkungen des Winds auf den Meeresspiegel, 120(1879).
4 Handbuch der Ozeanographie, I, 56(1907).
5 Geographical Journal, **52**, 51 (1918).

effect of barometric pressure on sea level at Brest, and Sir J. Lubbock, Sir James Loss, W. Ferrel, and others followed him. In Japan, Dr. F. Omori[1] compared the level fluctuations at several tide-stations under our Military Survey Department with the variations of barometric pressure in the neighbourhoods.

But the real variations of the sea level can never be explained satisfactorily by the change of barometric pressure only. For instance, the effect of the barometric pressure at the tidal stations investigated by Dr. Omori was only 30 to 40 % of the actual level variation. Dr. Nagaoka[2] paid attention to the influence of the sea water temperature and said that it appeared to him that the fluctuation of sea water temperature would lead to annual variation of the sea level. After this suggestion, Omori[3] again discussed the effect of water temperature. Both these investigations, however, are based on data of the temperature of the sea surface only, and not on the really observed data of subsurface temperature. Moreover, though it is obvious that the water must stand at a lower level where the density is great and at a higher in regions of low density, currents from higher level to lower are produced in order to diminish the level difference, as soon as an inclination of the level is generated. Thus the difference of level caused by the difference of density in open seas must generally be smaller than that in the case of statical equilibrium as in a communicating tube. Then, what ratio should they hold? Unless this point is made clear, no discussion can have much weight. For these reasons, the papers of Dr. Nagaoka and Dr. Omori are not decisive as to whether the water temperature variation is really the chief cause of annual fluctuation of mean sea level, but merely suggestive. Indeed, from early times it has been noticed by many learned men, Zöppritz, Mohn, etc., that the sea water temperature has some connection with the sea level, and it seems to be acknowledged that the water temperature variation should lead to some annual change of sea level. As for the importance of this influence, however, it appears to have been made light of. Krümmel[4] said:

"Meere mit erheblichen Temperaturschwankungen vom Winter zum Sommer werden periodisch ihr Niveau heben und senken. Aber es handelt sich dabei nur um unbedeutende Wirkungen."

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1 Publications of the Earthquake Investigation Committee, **18**, 23(1904); The Bulletin of the Imp. Earthquake Inves. Committee, **2**, 35(1908).

2 Proc. of the Tokyo Mathematico-physical Society, **4**, 382(1908).

3 Bulletin of the Imp. Earthquake Inves. Committee, **5**, 39(1911).

4 Handbuch der Ozeanographie, I, 35(1907).

R. Harris[1] insisted that the effect of water temperature variation must be so small that its annual inequality could not reach even 0.1 foot, and that the most important cause of annual variation of sea level throughout the earth would be the mechanical action of the wind. But his argument is too weak to be agreed with. He wrote:

"As a rule the water at most tidal stations stands highest in summer or autumn and lowest in the winter or spring. This suggests that the annual fluctuation may be due to the alternate heating and cooling of the ocean waters, causing alternate expansion and contraction of the volumes.........

"While it is undoubtedly true that the surface of the water in high latitudes stands on a slightly higher level than in low latitudes, and is higher in the early autumn than in the early spring, it can be easily seen that this annual fluctuation can not be considerable, i, e., it can scarcely be a measurable quantity. Suppose the surface of the water at a point in high latitudes to be 0·1 foot above the surface at a point 8000 miles away in the opposite hemisphere. The instantaneous slope will be 2 one-billionths. And so the accelerating force per unit mass will be $2g$ divided by one billion. But this acting through, say, 3 months will give rise to a velocity of 0·52 foot per second at the surface. If the assumed distance were less than 8000 miles, this velocity would be increased in proportion. As no such alternation of surface flow from one hemisphere to the other has been observed, it is practically certain that the results due to annual temperature changes in the water can not cause an annual inequality in sea level with a range as great as 0·1 of a foot and so this portion of it may be neglected."

In this estimate of Harris, the viscosity of sea water was neglected. It is, however, a well known fact that the kinetic eddy viscosity for a current of vast scale and incessantly disturbed by winds and waves, as in the ocean surface, is extraordinarily great; and so Harris' estimate is of little weight. Moreover, his insistence on the winds being the chief cause of sea level fluctuation was based only upon the fact that, in most places, the seasonal variations of the sea level are in harmony with the wind.

Reflecting upon the foregoing descriptions, we see that the former explanations as to the causes of the annual variation of mean sea level are almost all merely verbal or qualitative but not quantitative except that as to the effect of barometric pressure, and so naturally investigators keep to their own opinions and never endorse the views of others. Thus,

1 Mannual of Tides, IV, 455, 466 (1907).

in spite of this problem being very old, it may be said to be unsettled yet.

Now, in May of last year (1925), our Military Survey Department[1] published the results of determination of mean sea levels at the twelve tide-stations observed for the past twenty five years, from 1900 to 1924. The present authors were struck with the regular appearance nearly a simple harmonic, which the twenty five years mean of the annual variation of sea level assumes, and commenced to analyse it quantitatively and to determine the relative importance of its causes. The results are described below.

## I. General Plan and Data of the Present Investigation.

Even if we except the effect of astronomical tide, the sea level is affected directly or indirectly by atmospheric pressure, wind, water temperature, precipitaion, evaporation, oceanic current, sunshine, clouds, humidity, etc., that is, almost all meteorological elements. If we classify and arrange them suitably, we can reduce them to the following five as the causes of sea level fluctuation.

(I) Internal Causes:

- ( i ) Change in the quantity of the water itself due to precipitation, tributary land water, and evaporation.
- (ii) Density variation
  - (a) due to temperature variation caused by change of the sun radiation, wind, oceanic current, etc.
  - (b) due to salinity variation caused by the changes in precipitation, tributary land water, evaporation, oceanic current, etc.

(II) External Causes:

- (iii) Barometric pressure variation.
- (iv) Mechanical action of the wind.
- (v) Coriolis' force due to the earth's rotation, acting on the oceanic current.

'Internal Cause' means such as can be reduced to a change in water itself and 'External Cause' such as exists necessarily outside of the water.

In order to analyse quantitatively the annual variation of the mean sea level along the Japanese coast, the present authors calculate first the effects of barometric pressure and of water density, which are the most

1 中等海水面測定作業成績概要 (大正十四年五月)

important of the causes and can be calculated easily and determinately. Then, subtracting both these effects from the actual variation of sea level, they go on to discuss the residue as the influences of the wind and Coriolis' force. Though it is impossible to treat the latter influences in a general way, they can be estimated, as will be seen later, quantitatively, albeit roughly.

The influence of the change in the quantity of sea water itself, caused by precipitation, tributary land water, and evaporation of sea water, is the only one which we can not determine directly. But it may be supposed that this influence would perhaps be inappreciable in the case of small islands, such as our country, where no large river can be found and which are situated in a wide open sea. After subtracting the calculated fluctuations due to all those causes except the change in the quantity of water from the actual variation of sea level, we can see whether this presupposition is true or not.

As to the data used, the monthly means of the levels at 12 tide stations are supplied by the publication of the Military Survey Department[1] as already mentioned, and the corresponding barometric pressures at the nearest meteorological stations are taken from the reports of the Central Meteorological Observatory.[2] The data of water temperatures and salinities we owe to the Central Fishery Institute.[3]

The reports of the Institute contain abundant data of sea water temperature and salinity, but unfortunately the subsurface measurements in the seas abjacent to the tidal stations are few and irregular and to get complete sets of subsurface data throughout the year is much more difficult. Thus, of the 12 tidal stations, we can find only six having subsurface data with regard to the neighbouring seas for 4 or 5 years (from 1919 to 1922 or 1923) appropriate to our present object.

The 12 tidal stations, the 12 meteorological observatories, and the 6 lines of subsurface measurements are shown in the following table and map.

Finally, regarding the winds and currents on the sea surface, we consulted the various publications of the Japanese Hydrographic Department.[4]

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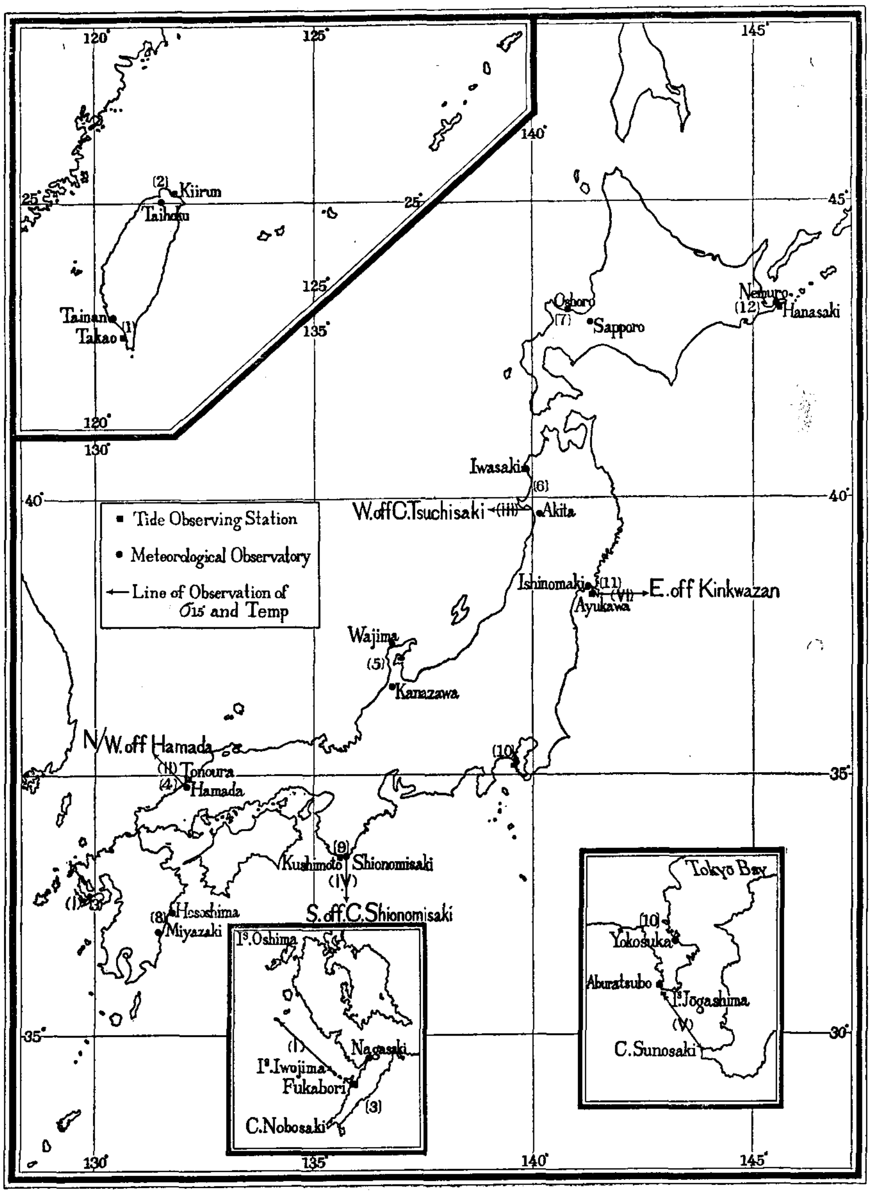
1 The Results of Determination of Mean Sea Levles (1925).

2 The Annual Reports (1914—1923).

3 The Reports of the Fundamental Fishery Investigations (1919—1923).

4 Meteorological Charts of the Sea adjacent to Japan (1918);
Current Charts of the North Pacific Ocean (1918);
Hydrographic Magazine, **2**, **7**, **36**, **38** (1922, 1923, 1925, 1926).


Tide Observing Station
Meteorological Observatory
Line of Observation of $\sigma_{15}$ and Temp
Kiirun
Taihoku
Tainan
Takao
Iwasaki
Akita
W.off C.Tsuchisaki
Ishinomaki
Ayukawa
E.off Kinkwazan
Oshoro
Sapporo
Nemuro
Hanasaki
Wajima
Kanazawa
N/W.off Hamada
Tonoura
Hamada
Kushimoto
Shionomisaki
S.off C.Shionomisaki
Hososhima
Miyazaki
I^s.Oshima
I^s.Iwojima
Nagasaki
Fukabori
C.Nobosaki
Tokyo Bay
Yokosuka
Aburatsubo
I^s.Jogashima
C.Sunosaki

| Tidal Stations | Meteor. Stations | Lines of Subsurface Measurements | |
|---|---|---|---|
| 1. Takao | Tainan | .......................... | |
| 2. Kiirun | Taihoku | .......................... | |
| 3. Fukabori | Nagasaki | I. Iwôjima to I. Ôshima | (i) |
| 4. Tonoura | Hamada | N/W off Hamada | (ii) |
| 5. Wajima | Kanazawa | .......................... | |
| 6 Iwasaki | Akita | W. off C. Tsuchisaki | (iii) |
| 7. Oshoro | Sapporo | .......................... | |
| 8. Hososhima | Miyazaki | .......................... | |
| 9. Kushimoto | Shionomisaki | S. off C. Shionomisaki | (iv) |
| 10. Aburatsubo | Yokosuka | I. Jôgashima—C. Sunosaki | (v) |
| 11. Ayukawa | Ishinomaki | E. off Kinkwazan | (vi) |
| 12. Hanasaki | Nemuro | .......................... | |

## II. The Effect of the Barometric Pressure.

### § 1. *The Pressure Factor.*

It is evidently true that the sea water stands higher with low barometric pressure and lower with a high barometer. If the sea water is in a state of statical equilibrium with regard to the atmospheric pressure, the equivalent change of the sea level corresponding to an atmospheric pressure change of 1 mm. Hg., that is, the so-called "pressure factor" should take the value :

$$\frac{\text{Specific gravity of mercury}}{\text{Specific gravity of sea water}}=13.2.$$

Almost all the values of the pressure factor in the open sea given by former investigators approximate to the above value; but in some localities, the estimates range from 7 to 18. Though the factor may thus appear to be somewhat uncertain, it may be noted that places where the factor has a very small value are situated up a river or along the coast of an inland sea having a narrow mouth; on the other hand, the factor may perhaps be notably great if the proper vibration of a bay and the change of the atmospheric pressure have nearly a coincident period. Hence the abnormal values of the pressure effect can be satisfactorily explained. Now, as we are going to deal with a large open sea where the water can move freely and with an annual fluctuation which runs very gradually, it can undoubtedly be taken that the actual pressure factor should be equal to the statical one mentioned above. Recently Mr. S. Ogura[1] investigated the pressure factor for the coast of small isolated-islands in the western part of the North Pacific Ocean. His results give a clear justification of the above remark.

For these reasons, we adopt the value 13·2 as the pressure factor in the following calculations.

## § 2. *The Calculations.*

We can assume the monthly mean of the sea levels as the so-called mean sea level.

At first we take the ten years' mean of the monthly means of sea levels at the twelve tidal stations (from 1914 to 1923). Next we take the corresponding ten years' mean of the monthly means of atmospheric pressure at the nearest meteorological observatories, and multiplying these by the presure factor, calculate the effect of the atmospheric pressure on the mean sea level. Then we subtract the influence of the barometric pressure from the actual mean sea level.

The results of the calculations are as in table I and the annexed figures.

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1 Japanese Journal of Astronomy and Geophysics, **2**, 1 (1925).

Table I.

〔1〕 Takao (Tainan). 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −13.0 | −12.4 | −6.3 | −5.4 | +0.6 | +5.4 | +10.8 | +13.6 | +12.1 | +6.4 | −1.4 | −11.0 | 26.6 |
| Baro. Press. (mm. Hg.) | 764.8 | 762.7 | 762.1 | 759.7 | 757.2 | 755.7 | 754.9 | 753.6 | 756.0 | 759.6 | 761.8 | 763.2 | 11.2 |
| Effect of Baro. Press. (cm) | −7.3 | −4.5 | −3.7 | −0.5 | +2.8 | +4.8 | +5.8 | +7.6 | +4.4 | −0.4 | −3.3 | −5.2 | 14.9 |
| Residual (cm) | −5.7 | −7.9 | −2.6 | −4.9 | −2.2 | +0.6 | +5.0 | +5.9 | +7.7 | +6.8 | +1.9 | −5.8 | 15.6 |

〔2〕 Kiirun (Taihoku). 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −13.7 | −12.7 | −12.0 | −6.0 | +2.5 | +9.6 | +15.8 | +17.7 | +14.1 | +3.3 | −5.4 | −12.9 | 31.4 |
| Baro. Press. (mm. Hg.) | 767.0 | 764.4 | 763.7 | 760.5 | 757.7 | 755.4 | 754.2 | 753.5 | 756.9 | 761.4 | 764.1 | 765.5 | 13.5 |
| Effect of Baro. Press. (cm) | −8.8 | −5.3 | −4.4 | −1.3 | +3.6 | +6.1 | +8.2 | +9.1 | +4.6 | −1.3 | −4.9 | −6.3 | 17.9 |
| Residual (cm) | −4.9 | −7.4 | −7.6 | −4.7 | −1.1 | +3.5 | +7.6 | +8.6 | +9.5 | +4.6 | −0.5 | −6.6 | 17.1 |

Table I (Continued).

〔3〕 Fukabori (Nagasaki). 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −17·0 | −16·2 | −14·4 | −8·9 | +0·9 | +5·4 | +13·2 | +19·9 | +18·0 | +8·6 | +1·4 | −10·9 | 36·9 |
| Baro. Press. (mm. Hg.) | 767·0 | 764·9 | 764·3 | 761·7 | 758·7 | 756·2 | 756·7 | 755·5 | 758·8 | 762·7 | 765·7 | 766·5 | 11·5 |
| Effect of Baro. Press. (cm) | −8·5 | −4·4 | −3·6 | −0·1 | +3·8 | +7·2 | +6·5 | +8·1 | +3·7 | −1·5 | −6·1 | −6·5 | 16·6 |
| Residual (cm) | −8·5 | −11·8 | −10·8 | −8·8 | −2·9 | −1·8 | +6·7 | +11·8 | +14·3 | +10·1 | +7·5 | −4·4 | 25·6 |

〔4〕 Tonoura (Hamada). 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −14·4 | −17·9 | −17·7 | −12·2 | −3·5 | +7·3 | +15·7 | +20·6 | +15·9 | +9·4 | +3·0 | −6·5 | 38·5 |
| Baro. Press. (mm. Hg.) | 765·5 | 764·1 | 763·8 | 761·3 | 758·3 | 755·9 | 756·4 | 755·9 | 759·4 | 762·8 | 764·9 | 765·2 | 9·6 |
| Effect of Baro. Press. (cm) | −5·8 | −4·0 | −3·6 | −0·3 | +3·7 | +6·9 | +6·2 | +6·9 | +2·3 | −2·3 | −5·0 | −5·4 | 12·7 |
| Residual (cm) | −8·6 | −13·9 | −14·1 | −11·9 | −7·2 | +0·4 | +9·5 | +13·6 | +13·6 | +11·7 | +8·0 | −1·1 | 27·7 |

Table I (Continued).

[5] Wajima (Kanazawa). 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −4·7 | −11·9 | −13·7 | −13·2 | −7·3 | +1·7 | +9·8 | +15·3 | +11·8 | +6·5 | +5·4 | +0·1 | 29·0 |
| Baro. Press. (mm. Hg.) | 764·2 | 763·2 | 763·5 | 761·6 | 758·8 | 756·8 | 757·3 | 756·3 | 759·4 | 762·1 | 764·3 | 764·1 | 8·0 |
| Effect of Baro. Press. (cm) | −4·3 | −2·9 | −3·3 | −0·8 | +2·9 | +5·6 | +4·9 | +6·3 | +2·1 | −1·5 | −4·4 | −4·1 | 10·6 |
| Residual (cm) | −0·4 | −9·0 | −10·4 | −12·4 | −10·2 | −3·9 | +4·9 | +9·0 | +9·7 | +8·0 | +9·8 | +4·2 | 22·1 |

[6] Iwasaki (Akita). 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −5·2 | −14·4 | −14·1 | −12·3 | −5·8 | +3·9 | +10·0 | +15·0 | +11·0 | +5·9 | +5·3 | +0·6 | 29·4 |
| Baro. Press. (mm. Hg.) | 761·6 | 762·4 | 762·4 | 761·4 | 758·8 | 756·7 | 757·3 | 756·7 | 759·9 | 762·6 | 763·8 | 762·1 | 7·1 |
| Effect of Baro. Press. (cm) | −1·5 | −2·5 | −2·5 | −1·2 | +2·3 | +5·0 | +4·2 | +5·0 | +0·8 | −2·8 | −4·4 | −2·1 | 9·4 |
| Residual (cm) | −3·7 | −11·9 | −11·6 | −11·1 | −8·1 | −1·1 | +5·8 | +10·0 | +10·2 | +8·7 | +9·7 | +2·7 | 22·1 |

Table I (Continued).

〔7〕 Oshoro (Sapporo). 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −3·9 | −10·6 | −11·6 | −8·9 | −2·2 | +3·5 | +8·6 | +11·9 | +8·7 | +3·1 | +1·9 | −0·5 | 23·5 |
| Baro. Press. (mm. Hg.) | 759·7 | 761·2 | 760·7 | 759·9 | 758·0 | 756·2 | 756·9 | 756·9 | 760·1 | 762·2 | 762·1 | 759·7 | 6·0 |
| Effect of Baro. Press. (cm) | −0·3 | −2·3 | −1·6 | −0·5 | +2·0 | +4·4 | +3·4 | +3·4 | −0·8 | −3·6 | −3·4 | −0·3 | 8·0 |
| Residual (cm) | −3·6 | −8·3 | −10·0 | −8·4 | −4·2 | −0·9 | +5·2 | +8·5 | +9·5 | +6·7 | +5·3 | −0·2 | 19·5 |

〔8〕 Hososhima (Miyazaki). 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −14·5 | −11·0 | −12·1 | −8·0 | −0·9 | +6·2 | +8·1 | +14·5 | +14·1 | +10·9 | +1·7 | −8·5 | 29·0 |
| Baro. Press. (mm. Hg.) | 766·3 | 764·2 | 763·9 | 761·6 | 758·7 | 756·6 | 757·1 | 755·8 | 758·7 | 762·4 | 765·3 | 765·8 | 10·5 |
| Effect of Baro. Press. (cm) | −6·5 | −3·7 | −3·3 | −0·3 | +3·6 | +6·4 | +5·8 | +7·4 | +3·6 | −1·3 | −5·2 | −5·8 | 13·9 |
| Residual (cm) | −8·0 | −7·3 | −8·8 | −7·7 | −4·5 | −0·2 | +2·3 | +7·1 | +10·5 | +12·2 | +6·9 | −2·7 | 21·0 |

Table I (Continued).

〔9〕 Kushimoto (Shionomisaki). 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −12·3 | −10·2 | −14·2 | −8·1 | −1·1 | +5·8 | +6·4 | +13·6 | +12·5 | +10·9 | +2·7 | −5·7 | 27·8 |
| Baro. Press. (mm. Hg.) | 763·9 | 763·0 | 763·2 | 761·6 | 758·7 | 756·7 | 757·7 | 756·4 | 759·1 | 762·2 | 764·4 | 763·7 | 8·0 |
| Effect of Baro. Press. (cm) | −4·0 | −2·8 | −3·0 | −0·9 | +2·9 | +5·6 | +4·3 | +6·0 | +2·4 | −1·7 | −4·7 | −3·7 | 10·7 |
| Residual (cm) | −8·3 | −7·4 | −11·2 | −7·2 | −4·0 | +0·2 | +2·1 | +7·6 | +10·1 | +12·6 | +7·4 | −2·0 | 23·8 |

〔10〕 Aburatsubo (Yokosuka) 1914—1923.

| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −6·1 | −6·2 | −9·7 | −8·1 | −2·1 | +2·1 | +3·2 | +8·7 | +8·9 | +7·4 | +2·6 | −0·1 | 18·6 |
| Baro. Press. (mm. Hg.) | 762·1 | 761·8 | 762·2 | 761·4 | 758·8 | 757·1 | 757·8 | 757·1 | 760·2 | 762·1 | 763·8 | 762·0 | 6·7 |
| Effect of Baro. Press. (cm) | −2·1 | −1·7 | −2·3 | −1·2 | +2·3 | +4·4 | +3·6 | +4·4 | +0·4 | −2·1 | −4·4 | −2·0 | 8·8 |
| Residual (cm) | −4·0 | −4·5 | −7·4 | −6·9 | −4·4 | −2·3 | −0·4 | +4·3 | +8·5 | +9·5 | +7·0 | +1·9 | 16·9 |

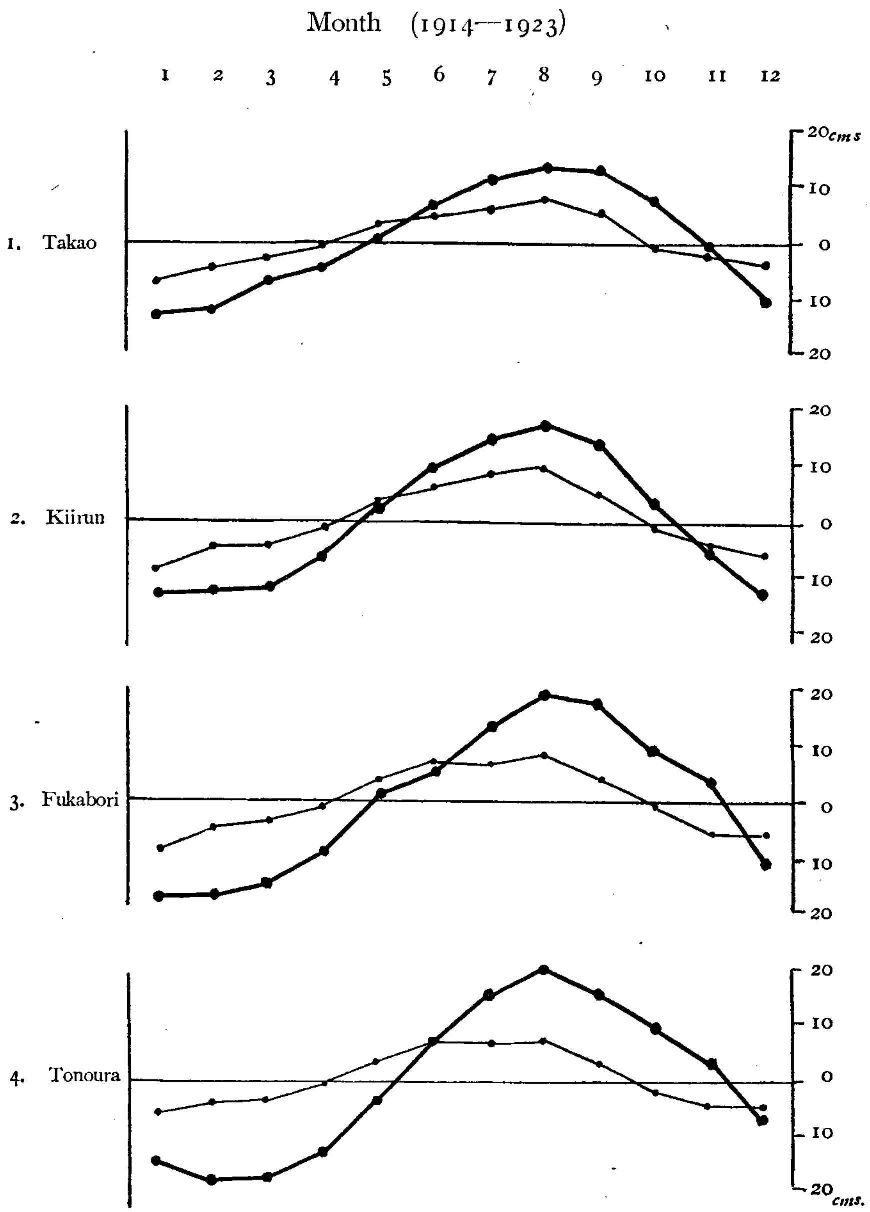
Table I (Continued).

〔11〕 Ayukawa (Ishinomaki). 1914—1923.

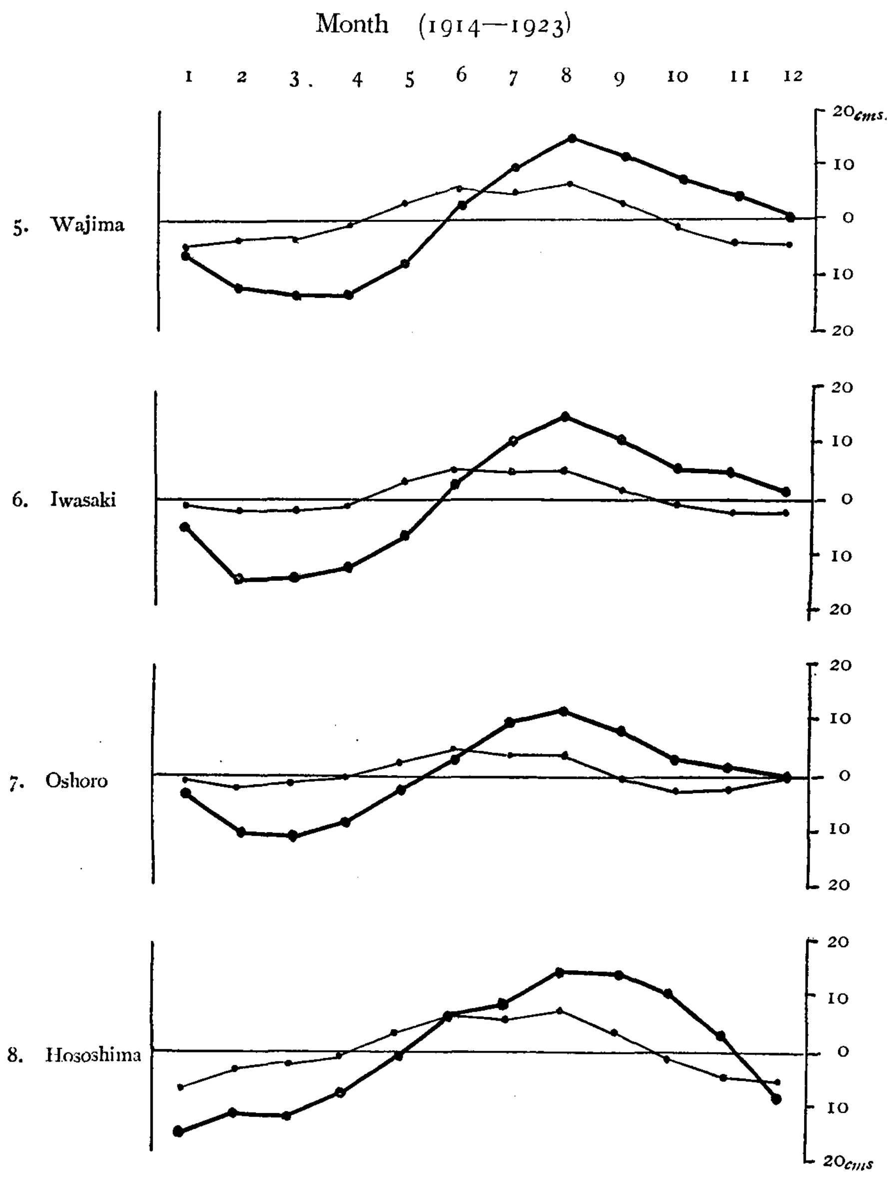
| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | −3·4 | −7·8 | −11·9 | −11·4 | −6·1 | −0·5 | +4·4 | +10·5 | +10·6 | +7·8 | +4·8 | +2·5 | 22·5 |
| Baro. Press. (mm. Hg.) | 761·8 | 761·7 | 762·4 | 761·6 | 759·2 | 757·2 | 757·9 | 757·4 | 760·4 | 762·9 | 762·8 | 761·9 | 5·7 |
| Effect of Baro. Press. (cm) | −1·6 | −1·5 | −2·4 | −1·3 | +1·8 | +4·5 | +3·6 | +4·3 | +0·3 | −3·1 | −2·9 | −1·7 | 7·6 |
| Residual (cm) | −1·8 | −6·3 | −9·5 | −10·1 | −7·9 | −5·0 | +0·8 | +6·2 | +10·3 | +10·9 | +7·7 | +4·2 | 21·0 |

〔12〕 Hanasaki (Nemuro). 1914—1923.

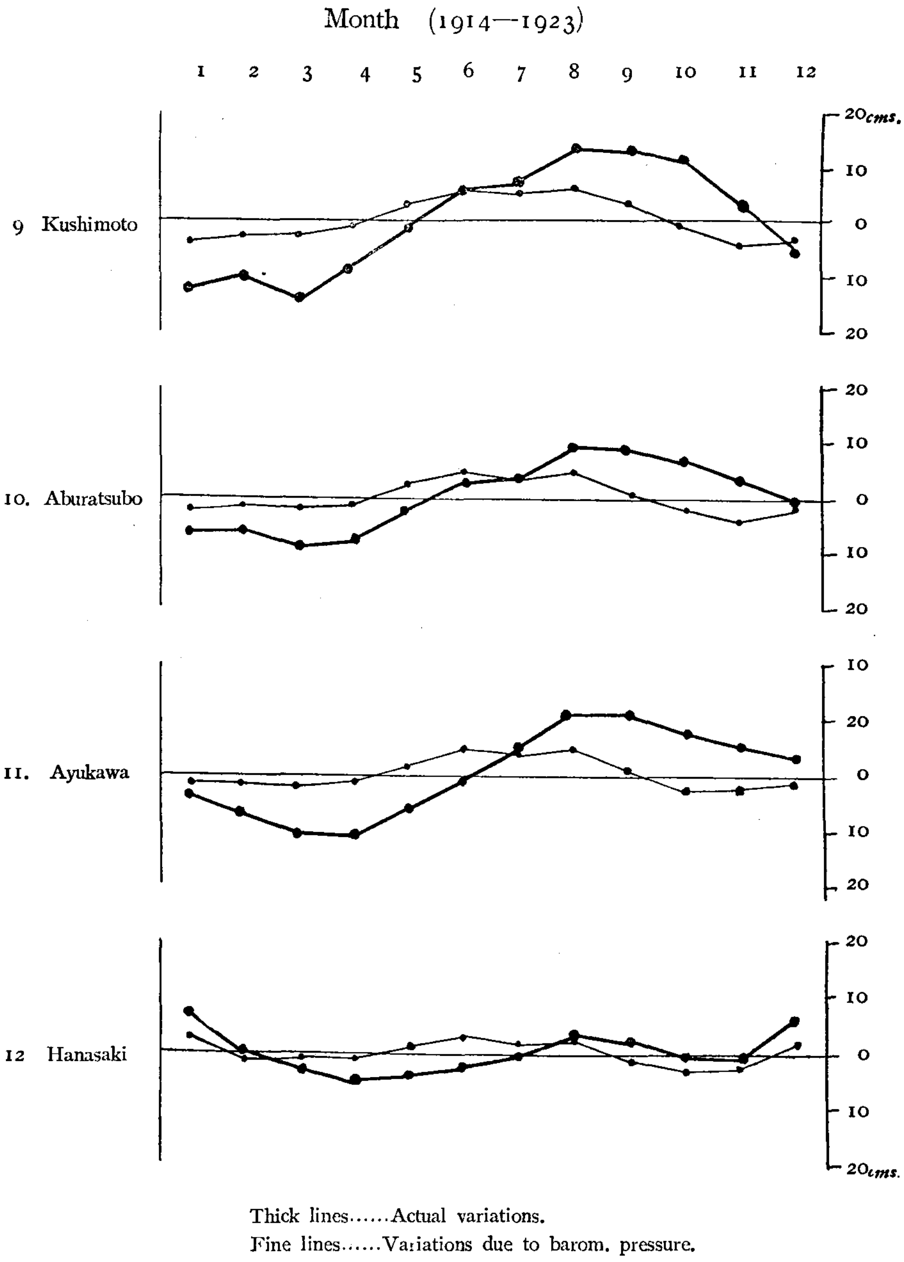
| Variation \ Month | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Actual Sea Level (cm) | +6·9 | −0·5 | −3·4 | −5·5 | −4·6 | −2·7 | −0·6 | +3·4 | +2·0 | −0·5 | −1·1 | +6·4 | 13·5 |
| Baro. Press. (mm. Hg.) | 757·9 | 760·5 | 760·0 | 760·1 | 759·0 | 757·4 | 758·3 | 758·0 | 760·8 | 762·2 | 762·2 | 758·2 | 4·8 |
| Effect of Baro. Press. (cm) | +2·3 | −1·2 | −0·5 | −0·8 | +0·8 | +2·9 | +1·7 | +2·1 | −1·6 | −3·4 | −3·4 | +1·9 | 6·3 |
| Residual (cm) | +4·6 | −0·7 | −2·9 | −4·8 | −5·4 | −5·6 | −2·3 | +1·3 | +3·6 | +2·9 | +2·3 | +4·5 | 10·2 |




Thick lines......Actual variations.
Fine lines......Variations due to barom. pressure.




Thick lines......Actual Variations.
Fine lines......Variations due to barom. pressure.




Thick lines......Actual variations.
Fine lines......Variations due to barom. pressure.

Let us here note the essential points in the above results.

1) The Range of Annual Variation due to Barometric Pressure.

The effect of the barometric pressure alone is not sufficient to account for even half the annual variation of sea level. This fact is numerically demonstrated by the following table.

| Place | | (I) Annual inequality of Actual M. S. L. | (II) Annual inequality of Effect of B. P. | $\frac{(II)}{(I)}$ |
|---|---|---|---|---|
| Tide Station | Met. Obs. | | | |
| 1. Takao | Tainan | 26·6 cms. | 14·9 cms. | 0·58 |
| 2. Kiirun | Taihoku | 31·4 〃 | 17·9 〃 | 0·57 |
| 3. Fukabori | Nagasaki | 36·9 〃 | 16·6 〃 | 0·45 |
| 4. Tonoura | Hamada | 38·5 〃 | 12·7 〃 | 0·33 |
| 5. Wajima | Kanazawa | 29·0 〃 | 10·6 〃 | 0·36 |
| 6. Iwasaki | Akita | 29·4 〃 | 8 0 〃 | 0·27 |
| 7. Oshoro | Sapporo | 23·5 〃 | 8·0 〃 | 0·34 |
| 8. Hososhima | Miyazaki | 29·0 〃 | 13·9 〃 | 0·48 |
| 9. Kushimoto | Shionomisaki | 27·8 〃 | 10·7 〃 | 0·39 |
| 10. Aburatsubo | Yokosuka | 18·6 〃 | 8·8 〃 | 0·43 |
| 11. Ayukawa | Ishinomaki | 22·5 〃 | 7·6 〃 | 0·34 |
| 12. Hanasaki | Nemuro | 13·5 〃 | 6·3 〃 | 0·47 |

The ratio

$$\frac{\text{the annual inequality of the sea level due to barometric pressure}}{\text{the annual inequality of the actual mean sea level}}$$

takes the values of from 0·27 to 0·58.

2) The Phase of the Variation due to the Barometric Pressure.

The maximum effect of the barometric pressure appears in June, July, or August and the minimum in December or January. On the other hand, we see that the actual sea water stands at its highest level in August, and at its lowest level in January at Formosa, in February at Kyushu, and in March at the northern end of Japan.

Hence those two variations everywhere show a phase difference of one or two months, but we recognise only the roughly parallelism that both of them are at their maximum in summer and their minimum in winter.

3) The Residue after subtracting the Effect of Baro etric Pressure from the Actual Mean Sea Level.

The residue after the barometric pressure effect is subtracted from the actual sea level variation is about 3/4 of the total fluctuation.

The maximum of residual variation appears in September and its minimum in January at South Japan (Formosa), in February at Kyûshû, and is delayed as it goes to the north. Now, it is to be noted that the variation in the temperature of the water is quite parallel to this variation, and so the effect of change in density is perhaps remarkably greater.

## III. The Effect of Change in Density.

§ 1. *The Effect of the Water Temperature and Salinity.*

The differences in the temperature and the salinity of the water can be reduced to the difference in density. As was stated in the introduction, in order to calculate the effect of the density variation, it is necessary to know the ratio between the difference in level caused by the difference in density in the open sea where the water can flow freely and that in the case of statical equiliblium.

One of the present authors[1] has discussed this question theoretically in his papar "on the so-called Grenzfläche in the current due to the difference of density." According to the result, in the case where the same inequality of density extends throughout the total sea water from surface to bottom, the real level difference should be only 3/8 to 4/8 of the statical one; in the other case, where the difference in density exists in the superficial layer only, for instance, in a layer of 1/10 or so of the total depth, the actual level difference must be almost equal to the statical one.

Now, while the actual ocean on the earth ha a mean depth of 4000 metres, local differences in the density of the water exist only in the upper stratum to a depth of 400 or 500 metres, below which the water is almost uniform throughout the whole ocean. The annual fluctuation of the water density, however, does not extend to such depths, commonly only to 200 or 300 metres. Hence, for the open sea coast, we may generally calculate the effect of density upon sea level variation as if in the case of statical equilibrium.

§ 2. *The Method of the Calculation.*

(i) We have data giving the water temperatures and salinities in the layers at depths of 0, 50, 100, and 150 or 200 metres in sea water.

From these data, we take possibly many years' means of the monthly mean temperatures and salinities, and find the densities corresponding to both the mean temperatures and the salinities with Knudsen's table.

1 T. Nomitsu: These Memoirs, **10**, 111 (1926).

It may be noticed that our data are the results of observations made only once in each month and that the dates of observations are different every year. We therefore take the mean of the really observed dates of the same month in the different years as the assumed date of observation in that month.

(ii) The inequality in density leads to a variation in specific volume. Let the specific volume be $V_t$ and the density $\rho_t$, then

$$V_t=\frac{1}{\rho_t}=\frac{1}{1+\frac{\sigma_t}{1000}}$$

where $\sigma_t=(\rho_t-1)\times 1000.$

As the density inequality of sea water is of order of 1/1000, we may put

$$V_t \doteqdot 1-\frac{\sigma_t}{1000}$$

Let two specific volumes $V_t$ and $V_t'$ correspond to $\sigma_t$ and $\sigma'_t$ respectively, then

$$\varDelta V=V_t'-V_t=\frac{\sigma_t-\sigma'_t}{1000}.$$

If we fix on a suitable density which is slightly greater than all of the obtained densities and find the differences between this standard and the other densities, we get the differences between the specific volumes corresponding to the standard and the other densities.

(iii) In order to get the total of the density effect, we must integrate the specific volume variation for the depth, namely $\varDelta$V, along the depth of the sea wat r. If we trace curve showing the relation between the range of the density variation (i. e. of the specific volume) and the depth of the water, we can determine the dep h at which the variation becomes negligibly small. Here, using Simpson's rule, we integrate the value of $\varDelta$V from the surface to the depth where the density variation is approximately zero. The values obtained by the foregoing calcula ions are the heights referred to the sea level when the total sea water is assumed to have the standard density which we have fixed at first. Thus we can get the annual variation of sea level due to the change in the density of the water.

## § 3. *Results of Calculations.*

The results are summarised in table II and the annexed graphs.

## Table II.

〔3〕 Fukabori (Nagasaki). (i) I. Iôjima—I. Ôshima. 1919—1922.

| Month | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Density($\sigma_t$) Variation at Depth | $0^m$ | 25·39 | 25·93 | 25·72 | 25·59 | 24·81 | 24·02 | 22·46 | 21·71 | 22·05 | 23·28 | 23·90 | 24·72 | 4·22 |
| | $50^m$ | 25·57 | 25·95 | 25·85 | 25·84 | 25·42 | 24·77 | 23·85 | 23·15 | 22·82 | 23·60 | 24·23 | 24·96 | 3·13 |
| | $100^m$ | 25·67 | 26·03 | 25·88 | 26·00 | 25·74 | 25·51 | 25·15 | 24·87 | 24·77 | 24·87 | 24·96 | 25·05 | 1·26 |
| | $150^m$ | 25·94 | 26·21 | 26·02 | 26·13 | 25·98 | 25·88 | 25·63 | 25·64 | 25·62 | 25·55 | 25·61 | 25·57 | 0·66 |
| Effect of Density (cm) | | −10·6 | −15·7 | −13·7 | −13·4 | −8·2 | −1·5 | +9·6 | +16·8 | +18·8 | +12·4 | +5·2 | −1·7 | 34·5 |
| Effect of Baro. Press. (cm) | | −5·1 | −4·1 | −2·8 | −0·4 | +3·5 | +6·3 | +4·6 | +6·6 | +2·5 | −1·5 | −4·3 | −5·8 | 11·7 |
| Sum of Effects of Density and Baro. Press. (cm) | | −15·7 | −19·8 | −16·5 | −13·8 | −4·7 | +4·8 | +14·2 | +23·4 | +21·3 | +10·9 | +0·9 | −7·5 | 43·2 |
| Actual Sea Level (cm) | | −20·0 | −14·5 | −14·8 | −12·1 | −2·6 | +7·6 | +15·0 | +20·1 | +17·2 | +11·8 | +1·9 | −9·2 | 40·1 |
| Residual (cm) | | −4·3 | +5·3 | +1·7 | +1·7 | +2·1 | +2·8 | +0·8 | −3·3 | −4·1 | +0·9 | +1·0 | −1·7 | |

Table II (Continued).

[4] Tonoura (Hamada). (ii) N/W off Hamada. 1919—1923.

| Month | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Density ($\sigma_t$) Variation at Depth | 0m | 25.30 | 25.71 | 25.81 | 25.66 | 25.20 | 24.51 | 22.36 | 21.68 | 21.64 | 23.05 | 23.77 | 24.60 | 4.17 |
| | 50m | 25.27 | 25.77 | 25.92 | 25.76 | 25.41 | 25.13 | 24.05 | 23.67 | 23.14 | 23.39 | 23.79 | 24.64 | 2.78 |
| | 100m | 25.36 | 25.89 | 26.01 | 25.91 | 25.85 | 25.39 | 24.66 | 24.70 | 24.36 | 24.77 | 24.73 | 24.91 | 1.65 |
| | 150m | 25.81 | 26.06 | 26.15 | 26.08 | 26.03 | 25.80 | 25.68 | 25.91 | 26.07 | 25.44 | 25.54 | 25.74 | 0.71 |
| Effect of Density (cm) | | −7.8 | −13.9 | −15.5 | −13.8 | −9.2 | −0.9 | +9.2 | +11.2 | +15.8 | +14.0 | +8.1 | −0.5 | 31.3 |
| Effect of Baro. Press. (cm) | | −5.8 | −4.2 | −4.0 | −0.5 | +4.0 | +7.9 | +5.3 | +6.9 | +2.8 | −1.6 | −4.4 | −6.2 | 14.6 |
| Sum of Effect of Density and Baro. Press. (cm) | | −13.6 | −18.1 | −19.5 | −14.3 | −5.2 | +7.0 | +14.6 | +18.1 | +18.6 | +12.4 | +3.7 | −6.7 | 38.1 |
| Actual Sea Level (cm) | | −14.8 | −17.1 | −17.6 | −10.4 | −2.2 | +7.8 | +15.6 | +18.5 | +14.9 | +10.8 | +2.6 | −8.0 | 36.1 |
| Residual (cm) | | −1.2 | +1.0 | +1.9 | +3.9 | +3.0 | +0.8 | +1.0 | +0.4 | −3.7 | −1.6 | −1.1 | −1.3 | |

Table II. (Continued)

[6] Iwasaki (Akita). (iii) W. off C. Tsuchisaki. 1919—1923.

| Month | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Density ($\sigma_t$) Variation at Depth | 0m | 25·91 | 26·46 | 26·51 | 25·69 | 25·69 | 24·31 | 23·68 | 22·35 | 22·12 | 23·15 | 23·84 | 24·98 | 4·39 |
| | 50m | 26·07 | 26·59 | 26·61 | 26·18 | 26·26 | 25·87 | 25·76 | 24·43 | 24·33 | 24·48 | 24·21 | 25·18 | 2·40 |
| | 100m | 26·09 | 26·62 | 26·56 | 26·25 | 26·47 | 26·25 | 26·33 | 25·36 | 25·45 | 25·48 | 25·27 | 25·36 | 1·35 |
| | 200m | 26·37 | 26·73 | 26·87 | 26·56 | 26·46 | 26·30 | 26·77 | 26·25 | 26·40 | 26·49 | 26·52 | 26·45 | 0·62 |
| Effect of Density (cm) | | −8·4 | −18·0 | −16·5 | −8·5 | −6·5 | −1·5 | +0·5 | +16·6 | +13·7 | +12·4 | +11·7 | +3·3 | 34·6 |
| Effect of Baro. Press. (cm) | | −1·8 | −2·8 | −2·8 | −1·2 | +2·4 | +5·5 | +2·8 | +4·8 | +0·9 | −2·1 | −2·8 | −2·7 | 8·3 |
| Sum of Effects of Density and Baro. Press. (cm) | | −10·2 | −20·8 | −19·3 | −9·7 | −4·1 | +4·0 | +3·3 | +21·4 | +14·6 | +10·3 | +8·9 | +0·6 | 42·2 |
| Actual Sea Level (cm) | | −6·4 | −14·6 | −15·0 | −10·4 | −5·3 | +2·0 | +10·4 | +14·8 | +9·6 | +7·6 | +7·4 | +0·1 | 29·8 |
| Residual (cm) | | +3·8 | +6·2 | +4·3 | −0·7 | −1·2 | −2·0 | +7·1 | −6·6 | −5·0 | −2·7 | −1·5 | −0·5 | |

Table II (Continued).

〔9〕 Kushimoto (Shionomisaki). (iv) S. off C. Shionomisaki. 1919—1923.

| Month | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Density ($\sigma_t$) Variation at Depth | 0m | 24·65 | 24·96 | 25·07 | 24·43 | 24·06 | 23·38 | 22·40 | 21·55 | 22·30 | 22·97 | 23·40 | 23·97 | 3·52 |
| | 50m | 24·70 | 24·99 | 25·17 | 24·75 | 24·39 | 23·89 | 23·07 | 22·55 | 22·71 | 22·99 | 23·36 | 23·99 | 2·62 |
| | 100m | 24·76 | 25·10 | 25·23 | 24·84 | 24·68 | 24·43 | 23·90 | 23·84 | 23·90 | 23·94 | 23·84 | 24·21 | 1·39 |
| | 200m | 25·24 | 25·43 | 25·48 | 25·33 | 25·12 | 24·96 | 24·80 | 24·75 | 25·06 | 24·98 | 24·99 | 25·01 | 0·73 |
| Effect of Density (cm) | | −11·5 | −17·2 | −19·0 | −12·6 | −4·4 | +4·9 | +14·3 | +18·3 | +13·2 | +10·3 | +3·0 | +1·5 | 37·3 |
| Effect of Baro. Press. (cm) | | −4·0 | −2·8 | −3·6 | −1·0 | +3·3 | +6·4 | +2·6 | +5·8 | +2·4 | −0·7 | −3·6 | −4·6 | 11·0 |
| Sum of Effects of Density and Baro. Press. (cm) | | −15·5 | −20·0 | −22·6 | −13·6 | −1·1 | +11·3 | +16·9 | +24·1 | +15·6 | +9·6 | −0·6 | −3·1 | 46·1 |
| Actual Sea Level (cm) | | −12·6 | −10·9 | −14·8 | −6·7 | +0·2 | +8·0 | +7·4 | +11·1 | +12·2 | +11·5 | +0·8 | −6·9 | 27·0 |
| Residual (cm) | | +2·9 | +9·1 | +7·8 | +6·9 | +1·3 | −3·3 | −9·5 | −13·0 | −3·4 | +1·9 | +1·4 | −3·8 | |

Table II (Contiuned).

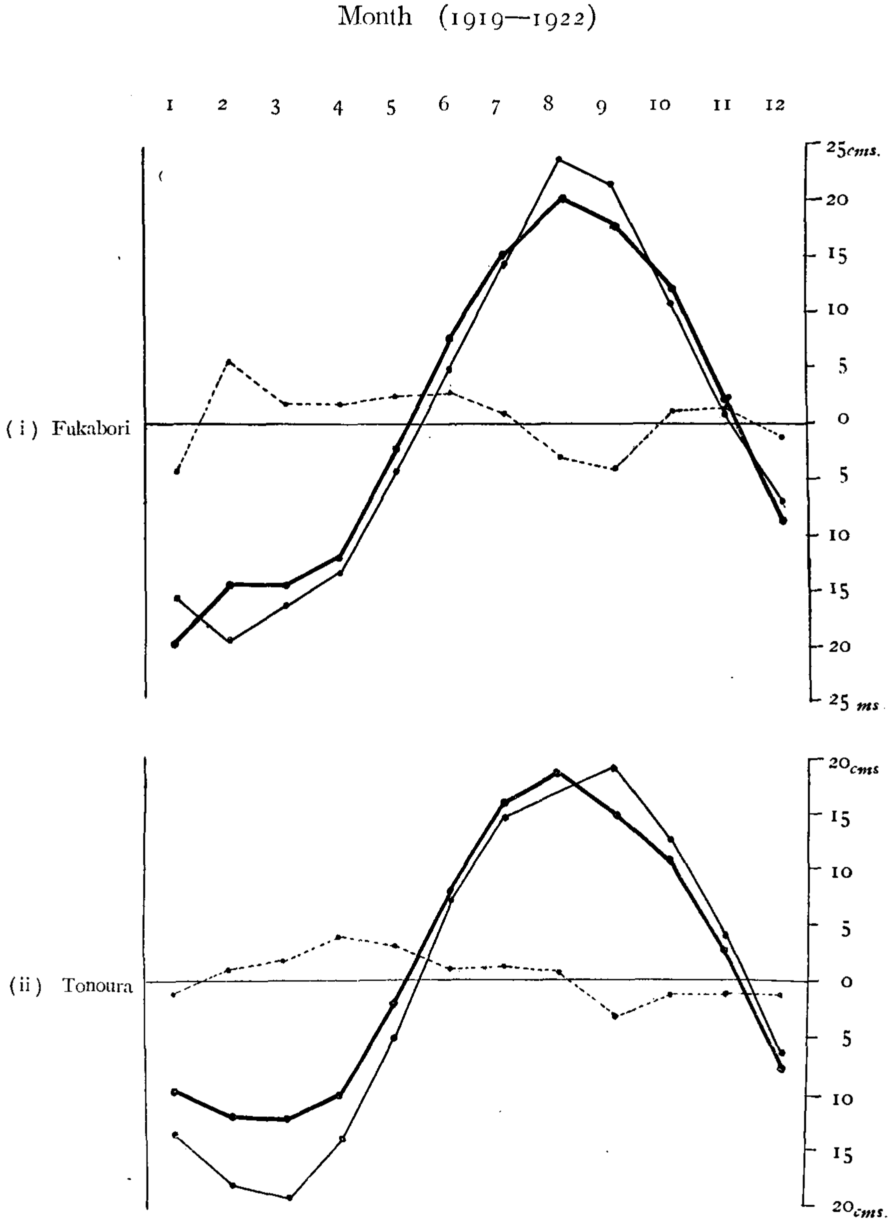
[10] Aburatsubo (Yokosuka). (v) I. Jôgashima—C. Sunosaki. 1919—1923.

| Month | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Density ($\sigma_t$) Variation at Depth | 0m | 25·40 | 25·31 | 25·44 | 24·70 | 24·06 | 23·55 | 22·85 | 21·81 | 21·27 | 23·20 | 24·11 | 24·87 | 4·17 |
| | 50m | 25·36 | 25·40 | 25·49 | 25·34 | 25·14 | 24·89 | 24·76 | 24·67 | 23·75 | 23·69 | 24·24 | 25·11 | 1·80 |
| | 100m | 25·54 | 25·59 | 25·68 | 25·54 | 25·59 | 25·44 | 25·60 | 25·51 | 24·97 | 24·95 | 24·88 | 25·44 | 0·80 |
| | 200m | 25·73 | 25·92 | 26·02 | 25·96 | 25·91 | 25·74 | 26·02 | 25·99 | 26·00 | 25·98 | 25·77 | 26·05 | 0·29 |
| Effect of Density (cm) | | −5·7 | −7·3 | −9·1 | −7·5 | −4·0 | −0·3 | +0·2 | +3·5 | +12·5 | +12·3 | +8·2 | −0·3 | 21·5 |
| Effect of Baro. Press. (cm) | | −2·1 | −2·0 | −2·8 | −1·5 | +2·8 | +4·6 | +2·2 | +4·2 | +0·5 | −1·5 | −2·9 | −2·0 | 7·5 |
| Sum of Effects of Density and Baro. Press.(cm) | | −7·8 | −9·3 | −11·9 | −9·0 | −1·2 | +4·3 | +2·4 | +7·7 | +13·0 | +10·8 | +5·3 | −2·3 | 24·9 |
| Actual Sea Level (cm) | | −6·4 | −6·7 | −10·2 | −7·9 | −1·6 | +4·3 | +3·5 | +5·3 | +9·7 | +9·0 | +1·8 | −1·3 | 19·9 |
| Residual (cm) | | +1·4 | +2·6 | +1·7 | +1·1 | −0·4 | 0 | +1·1 | −2·4 | −3·3 | −1·8 | −3·5 | +1·0 | |

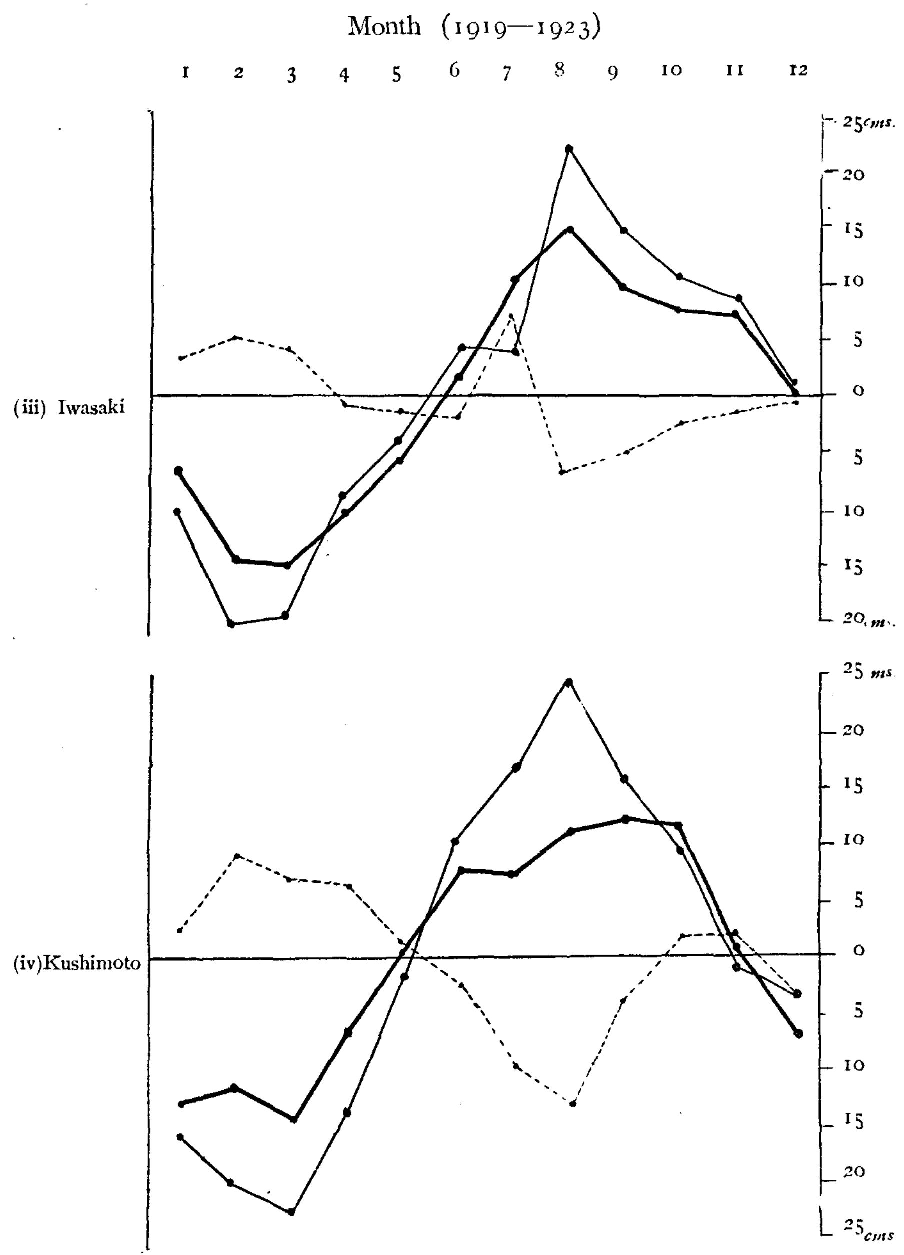
Table III. (Continued)

〔11〕 Ayukawa (Kinkwazan). (vi) E. off Kinkwazan. 1919—1922.

| Month | | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | Range |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Density ($\sigma_t$) Variation at Depth | 0m | 26·49 | 26·68 | 26·84 | 26·81 | 26·03 | 25·57 | 24·59 | 23·38 | 23·85 | 24·57 | 25·00 | 25·64 | 3·46 |
| | 50m | 26·49 | 26·74 | 26·94 | 26·94 | 26·51 | 26·24 | 25·56 | 25·23 | 24·98 | 24·83 | 25·04 | 25·76 | 2·11 |
| | 100m | 26·58 | 26·86 | 26·87 | 26·71 | 26·65 | 26·54 | 26·04 | 25·50 | 25·09 | 25·28 | 25·34 | 25·89 | 1·78 |
| | 200m | 26·54 | 26·59 | 26·96 | 27·13 | 27·06 | 26·80 | 26·21 | 25·98 | 25·68 | 25·92 | 25·82 | 26·09 | 1·45 |
| Effect of Density (cm) | | −9·7 | −15·7 | −20·8 | −21·4 | −17·6 | −4·5 | +9·4 | +20·0 | +24·1 | +19·2 | +17·7 | +2·9 | 45·5 |
| Effect of Baro. Press. (cm) | | −1·7 | −0·7 | −2·2 | −1·9 | +2·1 | +4·9 | +2·2 | +4·4 | −0·3 | −2·4 | −2·9 | −1·7 | 7·1 |
| Sum of Effects of Density and Baro. Press. (cm) | | −11·4 | −16·4 | −23·0 | −23·3 | −15·5 | +0·4 | +11·6 | +24·4 | +23·7 | +16·8 | +14·8 | +1·2 | 47·7 |
| Actual Sea Level (cm) | | −4·5 | −9·0 | −12·0 | −11·3 | −4·8 | +0·6 | +3·5 | +9·5 | +10·4 | +8·5 | +5·8 | +2·2 | 22·4 |
| Residual (cm) | | | | | | | | | | | | | | |




Thick lines......Actual variations.
Fine lines......Variations due to the fluctuations of the baro. pressure and water density.
Dotted lines......Residual variations.

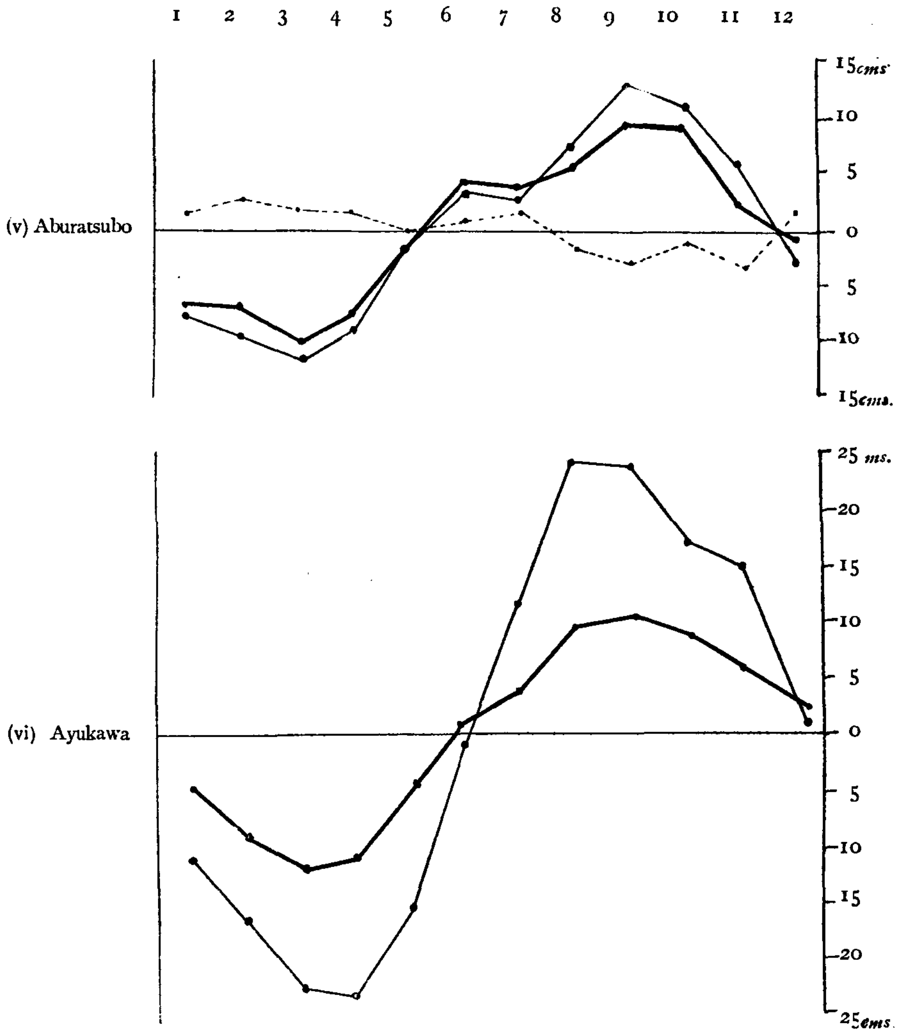



Thick lines... ..Actual variations.

Fine lines......Variations due to the fluctuations of the baro. pressure and water density.

Dotted lines......Residual variations

Month (1919—1923)




Thick lines......Actual Vaiiations.
Fine lines......Variations due to the fluctuations of the baro. pressure and water density.
Dotted lines......Residual variations.

Let us here note the essential point in the results of calculations.

1) The Range and Phase of Level Variation due to Change in Density.

First of all, the ranges of level variation are:

| Place of Tidal Station | : Observation of Temp. and $\sigma_{15}°$ | (I) Range of the Actual Variation | (II) Range of Variation due to Density | $\frac{(II)}{(I)}$ |
|---|---|---|---|---|
| (i) Fukabori | : Ôshima-Iwôjima | 40·1 cms. | 34·5 cms. | 0·86 |
| (ii) Tonoura | : N/W off Hamada | 36·1 〃 | 31·3 〃 | 0·89 |
| (iii) Iwasaki | : W. off Tsuchisaki | 29·8 〃 | 34·6 〃 | 1·17 |
| (iv) Kushimoto | : S. off Shionomisaki | 27·3 〃 | 37·3 〃 | 1·37 |
| (v) Aburatsubo | : Jôgashima-Sunosaki | 19·9 〃 | 21·5 〃 | 1·08 |
| (vi) Ayukawa | : E. off Kinkwazan | 22·4 〃 | 45·5 〃 | 2·05 |

From this table, we can see that the change in density accounts for most of the actual variation at the five positions except at Ayukawa.

The variation calculated as due to change in density at Ayukawa is very large as compared with the actual variation of mean sea level. Off Ayukawa, as a warm current (Kuroshio) and a cold current (Oyashio) intermingle each other, there is a conspicuous difference in density in a short distance and the difference extends from the surface to a very deep layer, almost to the bottom there, According to Nomitsu's theory[1] as to the "Grenzfläche", when the difference in density extends throughout a great part of the water depth, the actual difference in sea level caused by difference in density should be about half the statical one. This would explain the peculiarity at Ayukawa.

Next the maximum and minimum of sea level come out as follows:

| Tidal Station | Maximum (cms) | | Minimum (cms) | |
|---|---|---|---|---|
| | Actual Variation | Variation due to Density | Actual Variation | Variation due to Density |
| (i) Fukabori | +20·1 (VIII) | +18·8 (IX) | −20·2 (I) | −15·7 (II) |
| (ii) Tonoura | +18·5 (VIII) | +15·8 (IX) | −17·6 (III) | −15·5 (II) |
| (iii) Iwasaki | +14·5 (VIII) | +16·6 (VIII) | −15·0 (III) | −18·0 (II) |
| (iv) Kushimoto | +12·2 (IX) | +18·3 (VIII) | −14·8 (III) | −19·0 (III) |
| (v) Aburatsubo | + 9·7 (IX) | +12·5 (IX) | −10·2 (II) | − 9·1 (II) |
| (vi) Ayukawa | +10·4 (IX) | +24·1 (IX) | −12·0 (III) | −20·8 (III) |

1 Loc. cit.

Here I, II, III,.........mean January, February, April,.........respectively. Thus we see that the phase difference between the actual and the calculated sea level variations is very small.

2) The Relative Importance of the Effect of Salinity and of Water Temperature Change separately.

As the influence of temperature and that of salinity upon the density are not independent of each other, the effects of the two factors on sea level variation can not be completely separated and so we have determined both effects conjoinly. But it is desirable to know their relative importance and therefore to separate them even approximately. For this purpose, we first assume the sea water at a certain place to have invariable salinity throughout the year equal to the yearly mean value of real salinity at that place, and calculate the effect of the temperature change alone. Subtracting this from the effect of the two factors conjointly, we get the effect of the salinity change alone. In order to show the relative importance of the temperature and the salinity change separately, we pick up from our calculations the amplitudes of sea level variation due to them.

| Place | (I) Variation due to Density | (II) Variation due to Temp. only. | $\frac{(II)}{(I)}$ | (III) Variation due to Sal. only | $\frac{(III)}{(I)}$ |
|---|---|---|---|---|---|
| (i) Fukabori | 34·5 cms. | 26·3 cms. | 0·76 | 9·5 cms. | 0·36 |
| (ii) Tonoura | 31·3 〃 | 25·0 〃 | 0·80 | 11·9 〃 | 0·38 |
| (iii) Iwasaki | 34·6 〃 | 34·6 〃 | 1·00 | 8·9 〃 | 0·26 |
| (iv) Kushimoto | 37·3 〃 | 37·4 〃 | 1·00 | 6·6 〃 | 0·18 |
| (v) Aburatsubo | 21·5 〃 | 20·2 〃 | 0·94 | 4·5 〃 | 0·21 |
| (iv) Ayukawa | 45·5 〃 | 39·0 〃 | 0·86 | 14·7 〃 | 0·32 |
| | | mean | 0·88 | mean | 0·29 |

3) The Effects of the Changes in Water Density and Barometric Pressure conjointly——Residue after subtracting them.

If we add the effects of density and barometric pressure calculated above, we see that, except in the case of Ayukawa, the result approaches very near the actual sea level in the whole run of variation throughout the year. Thus the annual variation of mean sea level can, for the most part, be taken as the effects of the change in density and of the variation in barometric pressure.

Precisely speaking, however, there still remains a residue, if we subtract the effects of barometric pressure and density change from the actual variation of mean sea level. The residues at Fukabori, Tonoura, and Aburatsubo are very small and those at Iwasaki and Kushimoto are somewhat conspicuous.

But the sign of the residue is plus from winter to spring and minus from summer to autumn, and we see an obvious regularity in the mode of variation of the residue, for which some reasons will be sought in the following chapters.

## IV. The Effect of the Wind.

§ 1. *The General Idea.*

It is generally accepted that the sea level is raised along the leeward and lowered along the windward coast. Of course, the quantitative effect of wind upon the sea level must differ very much according to the geographical features, the nature of the wind, and other circumstances, and there is perhaps no hope of getting a general law on this matter, the existing investigations of Colding[1] and Jeffreys[2] being only for very special cases.

Roughly speaking, however, we may classify the sea surfaces affected by the wind into the following two kinds.

(i) The first kind is a basin which is comparatively small in size and where the wind blows uniformly over the whole area. In this case, the sea water drifted on to the leeward coast can not run away laterally, but sinks down into the lower layers, and flows back horizontally on the bottom layer, in order to neutralize the level inclination.

Colding's experimental formula, based on observations in the Baltic Sea, can be used only in such cases.

Colding's formula states:

$$\zeta = 0{\cdot}000000763 \, \frac{L}{H} \, W^2 \sin^2 \alpha,$$

where $\zeta$ is the difference of sea levels at the windward and the leeward coast (in metres),

$L$, the distance between the two coasts (in metres),

$H$, the mean depth (in metres),

$W$, the wind velocity (metres/sec.),

$\alpha$, the angle between the wind and the coast line.

(ii) The second kind is an ocean of vast extent where the wind blows either over only small parts of the ocean surface so that the water can easily escape laterally along the leeward coast, or over the whole ocean but changing in direction from place to place so as to facilitate a complete circulation of the water on the sea surface.

1 Kgl. Danske Vidensk. Selsk. Skrifter, **1**, 272 (1880).

2 Phil. Mag. **46**, 114 (1923).

In such a case, the difference in level due to the wind will be comparatively small, because on the leeward side the sea water would run away before it accumulated to any great extent and on the windward side, water would be supplied from all around as soon as it was blown away by the wind. These considerations lead us to the view that the influence of wind on the annual variation of mean sea level must be rather small, which is contrary to Harris' opinion.

With regard to Japan, the coast of the Japan Sea wil belong to the first class, and the Pacific coast to the second class.

§ 2. *Estimation of the Effect of the Wind on the Japanese Coasts.*

Generally speaking, the prevailing wind over the seas adjacent to Japan is north westerly in winter and south easterly in summer.

Hence, on the Pacific coast, the effect of the wind ought to lower the level in winter and to raise it in summer. But we have seen that the reverse is the case, that is, the residue left after subtracting the effects of barometric pressure and of density inequality from the actual variation of the mean sea level is higher in winter and lower in summer. Hence, the effcet of the wind along the Pacific coast may perhaps be so feeble as to be unnoticeable compared with the effect of Coriolis' force.

On the contrary, on the Japan Sea side the residual variation obtained in the preceding chapter coincides with that required by the wind effect. Now noting that the prevailing wind over the Japan Sea is almost uniform throughout the whole surface, we will apply here Colding's formula.

According to the Meteorological Charts of the Seas adjacent to Japan published by our Admiralty and the Atlas of the Pacific Ocean by the Deutsche Seewarte, we may assume the wind velocity over the Japan Sea as below:

| Seasons (Months) | Winter (I,II,III,) | Spring (IV,V,VI,) | Summer (VII,VIII,IX) | Autumn (X,XI,XII) |
|---|---|---|---|---|
| Wind velocity (vector mean) | 6·2 *m/sec.* *N.* 20° *W.* | 1·3 *m/sec* *S.* 40° *E.* | 3·0 *m/sec.* *S.* 50° *E.* | 4·8 *m/sec.* *N.* 15° *E.* |

Assuming that $L=9\times10^5$ metres and $H=1530$ metres, we get the cerresponding level variation as follows :

| Seasons | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|
| Level variation | +1·3 *cms* | −0·5 *cm* | −0·9 *cm* | +0·3 *cm* |

## V. The Effect of Coriolis' Force.

§ 1. *The Method of Estimation.*

Every moving body on the earth is affected by the earth's rotation and this effect is equivalent to the action of a deflecting force proportional to the velocity of the moving body. Let $v$ denote the velocity of the moving body in latitude $\lambda$, then the deflecting force i. e., Coriolis' force per unit mass is

$$2v\omega \text{Sin}\,\lambda,$$

where $\omega$ represents the angular velocity of the earth's rotation (0·0000729 radian per second).

Now it is very difficult to determine what current would be generated and what influence would be affected upon the sea level by Coriolis' force, when the wind or other current-producing force is given. But if we have actually measured and know the state of the existing current, we can easily determine the effect of current upon sea level due to Coriolis' force. As for a free current which has escaped outside of the direct action of the current-producing force, the lateral equilibrium of the current gives the relation.

$$\text{Coriolis' force} - \text{Centrifugal force} = g.\ \text{Sin}\,\gamma$$

where $\gamma$ is the angle of level inclination across the current from right to left, and $g$ is the gravity acceleration.

Hence, if the path, width, and velocity of the free current are known by actual measurements, we can calculate the inclination $\gamma$ at any place. Then the total difference in level between the two sides of the current zone will be obtained as follows:

$$\text{The level diff.} = \Sigma \sin\gamma\Delta\,\text{b},$$

where $\Delta$b is the elementary width of current zone having the velocity $v$ and $\Sigma$ means the sum of the values throughout the whole current zone.

In like manner, the sea level fluctuation due to the seasonal change of the oceanic current can be determined, provided that the current variations are known in detail.

§ 2. *Results of Estimation.*

Owing to the great difficulty of current measurement, even the various publications of the Hydrographic Department give us very insufficient data and so we can only very roughly estimate Coriolis' effect.

Along the side of Japan Sea, the Tsushima Current, a branch of the Kuroshio, flows north-east with a breadth of 30—50 sea-miles, and its average velocity determined by current-bottles is as below:

| Season (Months) | Winter (I,II,III) | Spring (IV,V,VI) | Summer (VII,VIII,IX) | Autumn (X,XI,XII) |
|---|---|---|---|---|
| Current Velocity | 8–9 mls/day | 7–8 mls/day | 8–10 mls/day | 5–7 mls/day |

This corresponds to a seasonal level variation of the following amount:

| Season | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|
| Level Variation | +1·2 cms. | −0·4 cms. | +1·6 cms. | −2·4 cms. |

Along the Pacific coast runs the strong Kuroshio current and near the Kushimoto tidal station it has the following velocity and breadth.

| Season | | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|---|
| Current Velocity | Left 20 mls wide | 15 | ? | 20 | ? |
| | Central 20 〃 wide | 37 mls/day | 38 mls/day | 48 mls/day | 41 mls/day |
| | Right 20 〃 wide | 20 | ? | 22 | 22 |
| Mean | | 24 mls/day | 25 mls/day | 30 mls/day | 27 mls/day |

The corresponding variation of sea level should be:

| Season | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|
| Sea Level variation | +5·0 cms. | +2·8 cms. | −7·1 cms. | −0·8 cm. |

Lastly, let us compare these calculated effects of wind and Coriolis' force with those residues of sea level variation obtained in Chapter III.

On the Japan Sea side.

| Season | | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|---|
| Residual variation | Tonoura | +0·6 cms. | +2·5 cms. | −0·8 cms. | −2·3 cm. |
| | Iwasaki | +4·6 〃 | −1·4 〃 | −1·5 〃 | −1·6 〃 |
| mean | | +2·6 cms. | +0·5 cms. | −1·2 cms. | −1·9 cms. |
| Coriolis' effect (calc.) | | +1·2 | −0·4 | +1·6 | −2·4 |
| Wind effect (calc.) | | +1·3 | −0·5 | −0·9 | +0·3 |
| Sum | | +2·5 | −0·9 | +0·7 | −2·1 |

On the Pacific Side.

| Season | Winter | Spring | Summer | Autumn |
|---|---|---|---|---|
| Residual variation at Kushimoto | +6·6 cms. | +1·6 cms. | −8·6 cms. | −0·2 cm. |
| Current effect (calc.) | +5·0 cms. | +2·8 cms. | −7·1 cms. | −0·8 cm |
| Wind effect | ? | ? | ? | ? |

## Conclusions.

Reflecting on the results obtained in the foregoing chapters, we arrive at the following conclusions.

( i ) Of the various causes of annual variation of mean sea level, the most effective is the influence of water density change due to inequalities in its temperature and salinity.

( ii ) The effect of atmospheric pressure comes second in importance.

The above two effects conjointly approximate very near to the actual fluctuation of sea level.

(iii) The effect of the wind is commonly very slight, a conclusion which is in opposition to the opinion of Harris. On the Japan Sea side, the annual inequality due to wind effect reaches scarcely 5 cms., and along the coast on the Pacific side too it is far behind the effect of Coriolis' force.

( iv ) The effect of Coriolis' force is also very small for the coast of the Japan Sea, but it is not so small for the Pacific coast where there is a strong oceanic current.

( v ) The effect of change in the quantity of the water itself is negligible as presupposed.

It may be useful to remark here that, for the sea level fluctuation in a short period, say one or several days, the circumstances will be quite different. As the temperature and salinity of sea water remain nearly unchanged for several days, the short period variation of sea level due to the density change cannot be marked. On the other hand, the barometric pressure and the wind at most places fluctuate greatly from time to time, and therefore the sea level fluctuation in a short period must generally be governed by these two factors, especially by the barometric pressure. Mr. Ogura's investigation[1] upon the pressure factor may be taken to verify this point.

1 Loc. cit.

Nevertheless, in a region where the variations of barometric pressure and the wind are very feeble, as in the equatorial calm zone, even a small effect of water density variation can not be neglected compared with the effect of barometric pressure and wind. The abnormally great value of the pressure factor obtained by Ogura for the equatorial region is perhaps due to his neglect of the effect of density.