Effect of ocean tides on gravity tides in Japan: the case of $M_2$ tide

T. Tanaka* Department of Geophysics, University of New England, Armidale, New South Wales, Australia 2351

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Summary. The effects of ocean tides on the $M_2$ tidal changes of gravity observed at several stations in Japan have been estimated by applying the Green's function given by Farrell in 1972. Gravity tides observed by using an Askania Gs-11 gravimeter (No. 111) from 1957 to 1959 (ICY) are generally small compared with theoretical values expected from the Gutenberg-Bullen Earth model. Though results from recent observations by new Askania gravimeters and a LaCoste & Romberg gravimeter show better agreement with the theoretical values, the differences remaining are not negligible. A significant alteration of the ocean tidal model near Japan is required in order to explain such differences.

Introduction

Earth tides observed at places near the seas are usually greatly disturbed by ocean tides. Since Japan is surrounded by seas, the oceanic effects form a fairly large percentage of the observed Earth tides, so that the estimate of such is essential for the interpretation of observed results. Comparisons of observed with theoretical Earth tides give information about the Earth structure when ocean tides are well known, and conversely about ocean tides when the Earth structure is well known (Farrell 1973).

In Japan, many observations of gravity tides were carried out by Nakagawa (1962) at 10 stations from 1957 to 1959 (ICY), using an Askania gravimeter Gs-11 (No. 111). The location of the observation stations is shown in Fig. 1. Similar observations of gravity tides have been carried out at Kyoto (Station No. 1) and Mizusawa (No. 7). The observation at Kyoto employing a new Askania gravimeter Gs-15 (No. 217) has continued uninterrupted for more than three years (Nakagawa et al. 1975).

The oceanic effect on the gravity tides observed at these stations was briefly treated by Nakagawa (1962), who considered only the gravitational attractions due to the sea water masses within a radial range of 1° from each station. Satô (1975) has recently calculated the oceanic effects on gravity tides at Mizusawa by using a tidal chart based on that compiled by Ogura (1933) and the Green's function given by Farrell (1972a). In his calculation the seas

* Present address: Disaster Prevention Research Institute, Kyoto University, Uji, Kyoto, Japan.
within a range of 30° from Mizusawa have been taken into consideration. In this article we estimate the oceanic effects on the $M_2$ gravity tides at these 10 stations due to all oceans, and compare these with the observed results.

Calculation and result

We use the Green's function obtained by Farrell (1972a) to calculate the oceanic effects on these stations. The Hendershott $M_2$ tidal model (Hendershott 1973) given for $6 \times 6^\circ$ Mercator grids is used for the global ocean tidal model. In order to reduce the integration error, detailed ocean tidal data together with a use of finer grids are necessary for seas adjacent to Japan. In such regions we modify the Hendershott model, applying the co-range and co-tidal charts compiled by Ogura (1933) for the neighbouring seas to Japan. Fig. 2 shows the resulting co-tidal chart used for the seas near to Japan. For oceans outside the thick line in Fig. 2 the Hendershott model is used. The seas close to each station within the thick line are divided into smaller rectangles. Since some of the stations are very close to the nearest coasts (for example about 100 m in the case of Naze, Station No. 5), the smallest size of the grid becomes $0.0045 \times 0.0045^\circ$. The condition of mass conservation for the total sea water of
the Hendershott model is taken into consideration (Farrell 1972b). In this case, the Hendershott model is altered by about 10 per cent, and the amplitude in the north-western part of the Pacific Ocean depicted in Fig. 2 decreases by 10–20 per cent. Since this alteration causes a discrepancy in the amplitude and phase from the observed coastal tides along Japan, we use the unchanged co-tidal chart for the seas close to Japan (within the seas surrounded by the thick line in Fig. 2).

Oceanic effects at each station thus obtained are shown in Table 1. The largest effect is at Naze (No. 5) where it reaches a maximum of 7.9 μgal. From the results in Table 1 and the location of stations shown in Fig. 1, it may be presumed that the oceanic perturbation in the $M_2$ gravity tide exceeds 2 μgal at all places in Japan.

The ratio of an observed tidal amplitude of gravity on the real Earth to the theoretical one on a perfectly rigid Earth is called ‘tidal factor of gravity’ and denoted by $G$. $G$ is expressed by the formula $G = 1 - (3/2)k + h$, using Love's numbers $h$ and $k$. Similarly the lag of an observed tidal phase behind the theoretical one expected on the rigid Earth is called ‘phase lag’ and denoted by $\kappa$. Fig. 3 shows the corrected tidal factor of gravity, $G$, and the phase lag, $\kappa$, obtained by subtracting the oceanic effects estimated from the results observed by Nakagawa (1962) during the IGY. Though $G$ and $\kappa$ were given for two different methods of analysis (Lecolazet's and Doodson–Lennon's methods), the mean values of the two are
Table 1. Oceanic effect on the $M_s$ gravity tides in Japan.

<table>
<thead>
<tr>
<th>No.</th>
<th>Station</th>
<th>Attraction term</th>
<th>Elastic term</th>
<th>Total effect</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Amplitude (μgal)</td>
<td>Phase (°)</td>
<td>Amplitude (μgal)</td>
</tr>
<tr>
<td>1</td>
<td>Kyoto</td>
<td>1.3</td>
<td>5.8</td>
<td>2.0</td>
</tr>
<tr>
<td>2</td>
<td>Matsushiro</td>
<td>1.1</td>
<td>2.6</td>
<td>1.6</td>
</tr>
<tr>
<td>3</td>
<td>Omaezaki</td>
<td>2.3</td>
<td>-2.2</td>
<td>3.0</td>
</tr>
<tr>
<td>4</td>
<td>Shionomisaki</td>
<td>3.3</td>
<td>3.9</td>
<td>3.5</td>
</tr>
<tr>
<td>5</td>
<td>Naze</td>
<td>2.4</td>
<td>10.1</td>
<td>5.5</td>
</tr>
<tr>
<td>6</td>
<td>Nemuro</td>
<td>0.8</td>
<td>-30.2</td>
<td>1.9</td>
</tr>
<tr>
<td>7</td>
<td>Mizusawa</td>
<td>0.9</td>
<td>-6.1</td>
<td>1.5</td>
</tr>
<tr>
<td>8</td>
<td>Kanozan</td>
<td>1.5</td>
<td>1.6</td>
<td>2.6</td>
</tr>
<tr>
<td>9</td>
<td>Tottori</td>
<td>1.3</td>
<td>4.3</td>
<td>1.6</td>
</tr>
<tr>
<td>10</td>
<td>Aso</td>
<td>1.8</td>
<td>12.4</td>
<td>3.0</td>
</tr>
</tbody>
</table>

tentatively used in the present discussion. The points numbered from 1 to 10 represent the results. For the Gutenberg–Bullen A (G–B) Earth model the value of $G$ is expected to be 1.16 and $\kappa$ zero (Farrell 1972a). As seen in the figure only the $G$ values of Omaezaki (No. 3) and Nemuro (No. 6) are fairly close to the theoretical value 1.16, and those for all other stations are small, and the $\kappa$ values are positive.

In Fig. 3 are also plotted the results from recent observations at Kyoto and Mizusawa. The points 11 and 12 are the recent results observed at Kyoto by using the Askania Gs-11 (No. 111), the time intervals of analysis being 383 and 98 days, respectively (Nakagawa 1974). The point 13 is obtained from the recent result observed at Kyoto by a new Askania gravimeter Gs-15 (No. 217), where a data length of more than 850 days was used for the analysis (Nakagawa 1974). Presently, the most reliable $G$ value and $\kappa$ at Kyoto are considered to be 1.200 and $+2.95^\circ$ (Nakagawa et al. 1975). After the oceanic correction has been made, these values become 1.135 and $2.6^\circ$, respectively, and are given by the point 13.

The two points 71 and 72 in Fig. 3 represent the results from recent observations at Mizusawa. The former corresponds to the result obtained from the average value of 17 sets of monthly analysis of the data observed by an Askania gravimeter Gs-12 (No. 197) for the

Figure 3. Tidal factor of gravity and phase lag of $M_s$ obtained by correcting the oceanic effects. Numbers are the station numbers shown in Table 1 and Fig. 1. Points 11, 12 and 13 are recent results at Kyoto, and 71 and 72 are also recent results at Mizusawa (see the text).
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five years from 1967 to 71. The latter corresponds to the result from a 21-day-analysis of the data by a LaCoste & Romberg gravimeter G-305 (Nakai 1974).

Discussion

As apparent in Fig. 3, these recent results give fairly large $G$ values, which are closer to the value of 1.16, than those observed by the Askania Gs-11 (No. 111) during the IGY. The reliability of the recent results is higher than that of the results obtained during the IGY due to the length of data and better calibration. Since the time change of the $G$ value of such a large scale seems to be improbable, we may conclude that the low $G$ value observed by the Askania Gs-11 (No. 111) is due to some instrumental origins such as the problem of calibration. In 1968 a simultaneous observation of Earth tides with four Askania gravimeters, that is, two Askania Gs-11 gravimeters including No. 111 and two Askania Gs-12 gravimeters, and two LaCoste & Romberg gravimeters were made by the Working Group for Comparing the Gravimeters in Japan (1969) during a period of 79 days. The results of the Gs-11 gravimeters from this observation gave smaller $G$ values compared with other gravimeters. Though a problem with the galvanometer for recording is mentioned as one of the reasons of the small $G$ value of the Gs-11 gravimeter (No. 111), this tendency is inferred to be inherent.

We can get the $G$ value of 1.14 and the phase lag of 1 - 2° by averaging the recent observations at Kyoto and Mizusawa. The difference in the amplitude from the G–B model corresponds to 1 μgal, which is about 2 per cent of the observed $M_2$ amplitude. This discrepancy seems to be somewhat large to be neglected as a simple error of estimate. Three probable causes for the discrepancy are: observational errors including the calibration error, uncertainty of the ocean tides and deviation of the real Earth structure from the G–B model.

As to the latest result obtained by the Askania Gs-15 (No. 217) at Kyoto (point 13, Fig. 3), the observational error is considered to be far smaller than 2 per cent because of the uninterrupted long-term careful observation under excellent conditions (Nakagawa et al. 1975). The calibration error in the result from the Askania Gs-12 (No. 197) at Mizusawa (point 71, Fig. 3) is considered to reach a few per cent according to Nakai (1974). The result from the LaCoste & Romberg G-305 (point 72, Fig. 3) is reported to be tentative owing to the short term (21 days) of analysis, though the precision of its calibration is estimated to be about 0.5 per cent (Nakai 1974). Therefore there remains a slight uncertainty in the results at Mizusawa. However, the common tendency of the small $G$ value and the positive phase lag observed by different instruments at both the stations suggests that it is not due to observational errors alone.

The uncertainty in the ocean tides is a possible cause of the discrepancy. If we try to attribute the discrepancy wholly to an inadequacy of the ocean tidal model, a considerable alteration of the co-tidal chart is required. As shown in Table 1, the calculated oceanic effects at Kyoto and Mizusawa are 3.3 and 2.4 μgal, respectively, in which the effects from the seas close to Japan (bounded by the thick line in Fig. 2) occupy half of the total effects and those from the rest of the north-western Pacific Ocean a quarter. When the Hendershott model is used unchanged (i.e. without the condition of the water-mass conservation), the oceanic effects on the two stations are calculated as 4.9 and 4.1 μgal, respectively, which increases the discrepancy between the observed and theoretical gravity tides. Therefore a better agreement may be attainable by assuming a fairly small amplitude compared with the present ocean tidal model in the north-western part of the Pacific Ocean. A good agreement with the observed $G$ values can be obtained by halving the tidal amplitude in seas close to Japan (in the region within the thick line in Fig. 2). In this case, the oceanic effects at Kyoto and Mizusawa are 2.23 μgal cos ($\omega t - 12.0^\circ$) and 1.14 cos ($\omega t + 10.6^\circ$), respectively, and the
correction for these oceanic effects gives the $G$ value of 1.156 for the point 13 (Kyoto) in Fig. 3 and 1.164 for the point 72 (Mizusawa), which agree well with the theoretical value on the G–B model.

Variations in the calculated oceanic loading effect can be caused by a deviation of the real Earth structure from the G–B model. In this case, however, there appear no significant differences among the oceanic effects obtained by the three different Earth models given by Farrell (1972a). Therefore the acceptable Earth structures represented generally as laterally homogeneous models are considered to be insufficient to explain the discrepancy. The lateral heterogeneity in the Earth structure (i.e. the underthrusting oceanic plates underneath the Japan Islands) might cause an oceanic effect differing from the present estimate. However, this effect is considered to be too small to explain the discrepancy (Zurn, Beaufort & Slichter 1976).

Satô (1975) has lately proposed a slightly larger observed $G$ value of 1.21 from a recent analysis of data by the LaCoste & Romberg G-305 at Mizusawa. In this case, the oceanic correction by applying the co-tidal chart in Fig. 2 unchanged gives 1.16. Accordingly, the modification of tidal amplitudes proposed above should be restricted within the seas south of the main Island of Japan in order to satisfy the conditions at Kyoto and Mizusawa, if the result by Satô is adopted.

Conclusion

The tidal factors of gravity $G$ observed at 10 stations in Japan from 1957 to 1959 (IGY) by using the Askania gravimeter Gs-11 (No. 111) are generally small compared with the theoretical $G$ for the G–B model Earth. This is considered to be due to instrumental errors. Recent observations at Kyoto and Mizusawa still give small $G$ values when the Hendershott tidal model and the co-tidal chart shown in Fig. 2 are used for the oceanic correction. One solution can be obtained by halving the tidal amplitudes around Japan (in the region within the thick line in Fig. 2). In this case, we must assume that the tidal amplitude decreases rapidly with the distance from the coast in order to conform the amplitude in deep seas to that actually observed along the coast. Lately a slightly larger $G$ value is proposed for Mizusawa. If the observed $G$ value at Mizusawa is about 1.21, it is consistent with the Earth tides on the G–B model Earth together with the oceanic effect using the Hendershott tidal model and co-tidal chart shown in Fig. 2; in this case the modification mentioned above should be restricted within the seas close to Kyoto, namely south of the main Island of Japan. However, it should be emphasized that even the recent observations from Kyoto and Mizusawa have given large differences in the observed $G$ and $K$ values of $M_2$ between different instruments, namely up to 5 per cent and 2° in the case of Kyoto and 2 per cent and 1° for those at Mizusawa. Clearly, further experimental investigations are required before we can come to any definite conclusions regarding modifications to the north-western Pacific tidal charts.

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References


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