Unusually High Mean Sea Level in September 1971
Along the South Coast of Japan

3. Numerical Experiments on the Unusual High
Sea Level along the South Coast of Japan—

by

Masamori Miyazaki

Meteorological Research Institute, Tokyo

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Abstract

This study aims to simulate the unusual rise of sea level in September, 1971, by the barotropic motion on the continental shelf to the south of Japan based on storm surge equations. We chose two numerical models. In the first model, we only considered the effects of Typhoon 7123. In the second model, the approach of the Kuroshio axis was taken into account. Results of computations show that the long-lasting rise of sea level is only possible in the second model. The continental shelf wave moving to the west was also simulated in that model.

1. Introduction

It was one of the few tentative conclusions of the Research Committee that the unusual rise of sea level in September, 1971, is probably related to the approach of the Kuroshio axis to the south coast of Japan. Another factor in raising sea level might be the passage of Typhoon 7123 from west to east nearly along the coast. The passage of a typhoon could generate long-term variations of the mean sea level on the continental shelf with or without the approach of the Kuroshio, and the path of the Kuroshio could also be affected by the typhoon.

Moreover, in the mareogram (original or daily mean) at each tidal station, peaks of sea level seem to move westwards along the coast with speeds of a few meters per second. They seem to correspond to continental shelf waves whose periods are comparable to the inertia period.

In order to make these points clearer, ENDO (1972) made some numerical experiments in which the western part of the oceanic subtropic gyre corresponding to the Kuroshio and its extension was simulated by the barotropic assumption. His computations for an ocean with a continental slope show that a typhoon passing northwards along the coast line over the land will raise the coastal sea level. He also found a counterclockwise vortex moving southwards on the slope with a speed of
2-3 m/sec after the main disturbance had passed away with the typhoon. However, his area of consideration was too broad to simulate the motion on the continental shelf, and the effects of bottom stress which he disregarded would be important in the shallow region.

In the present study, we deal with the whole area of continental shelf to the south of the Japanese Pacific coast. Variations of sea level induced by Typhoon 7123 were first computed for a period of about eleven days. In the next model, boundary conditions are a little modified. Corresponding to the approach of the Kuroshio to the Boso Peninsula, a profile of sea-level elevation is assumed at the southern edge of the area in question, and similar computations are made by taking the typhoon effects into account.

Of course, our main purpose is to ascertain whether long-term variations of the mean sea level are induced along the coast or not. We are based on basic storm-surge equations, and the nonlinearity is only considered in bottom friction terms.

2. Plan of computation

The area covered in our computation is shown in Fig. 1. It extends from the east coast of Kyushu to the Boso Peninsula. The mesh size is 8' in latitude (14.82 km), and the total number of meshes is 72x16. In Fig. 1, the track of Typhoon 7123, and contours of depths 100 m, 1000 m and 2000 m are also indicated.

Computations are made for 270 hours from the evening of 28 August. Distributions of wind and atmospheric pressure are computed by the usual method of composition. For the first three days, parameters of the typhoon are given by observations, and afterwards the typhoon is supposed to move to the east with a constant speed and depth as it runs far away from the area of computation.

In the first model, the sea level at the southward edge of the computing area is assumed to be at a hydrostatic balance. In the second model, the sea level there is assumed to rise more than the hydrostatic response linearly with time for the first three days, and then the increment is assumed to become constant. The total amount of the increment is assumed to be largest at the eastern edge, and to decrease exponentially to the west.

3. Basic equations

In Fig. 1, we choose the origin at the south-west edge, x axis shorewards, and y axis eastwards parallel to the coast. Denoting the x and y component of the volume transport by M and N, the elevation of sea level by h, and the water depth by D, then the basic equations of storm surge are

\[
\begin{align*}
\frac{\partial M}{\partial t} + fN &= -gD \frac{\partial}{\partial x}(h-h_0) + \tau_z^{(x)} - \tau_b^{(x)} \\
\frac{\partial N}{\partial t} - fM &= -gD \frac{\partial}{\partial y}(h-h_0) + \tau_z^{(y)} - \tau_b^{(y)} \\
\frac{\partial h}{\partial t} &= - \frac{\partial M}{\partial x} - \frac{\partial N}{\partial y} \tag{1}
\end{align*}
\]

in which f is the Coriolis parameter, g is the acceleration due to gravity, h_0 is the
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Fig. 1. Computed area.
hydrostatic estimate of the sea-water elevation, and $\tau_s, \tau_b$ are tangential stresses exerted on the sea surface and bottom, respectively, $\tau_s$ and $\tau_b$ are represented as functions of wind velocity $W$ and (vertical mean) sea water velocity $V$ as follows:

$$\begin{align*}
\tau_s &= \rho_a \gamma_s^2 |W| W \\
\tau_b &= \rho_w \gamma_b^2 |V| V - 5\gamma_w \tau_s
\end{align*}$$

(2)

where $\rho_a, \rho_w$ are densities of the air and the sea water, and $\gamma_s, \gamma_b$ are drag coefficients at the sea surface and bottom. The second formula in (2) is derived by Reid (1957).

4. Boundary conditions

We suppose a natural coast toward which the water depth decreases to zero. Then boundary conditions at the coast will be

$$S(M, N) = 0$$

(3)

The condition at the outer edge of the computing area is different from case to case. In the first model we suppose

$$h = h_0$$

(4)

at the outer edge. In the second model, we take

$$h = h_0 + h_1 e^{K(y - y_0)}$$

(5)

in which

$$\begin{align*}
h_1 &= Ht & 0 \leq t < T \\
&= HT & T \leq t
\end{align*}$$

(6)

Constants $y_0, K, H$ and $T$ are given as follows:
- $y_0$ ... the $y$ coordinate of the eastern edge of the computing area,
- $K \cdots 0.105/\Delta S$, or a factor which makes the last term of (5) 0.9 times the value at the next eastward grid,
- $T \cdots$ three days,
- $H \cdots 0.01 \text{ cm/minute}$.

5. Computations of forcing terms

As for the pressure distribution, a symmetric pattern is generally assumed. In the present case, Fujita’s formula is used.

The wind around the center of the typhoon is supposed to be the composition of the field wind and the symmetric wind. The former is proportional to the movement of the typhoon, the latter to the gradient wind. The coefficients are 0.58 and 1.0 in our case, respectively. In the symmetric wind, we also assume a constant inflow angle of 15°.

These coefficients are slightly different from those assumed in previous storm surge simulations in inland bays. The wind speed in an open sea is generally larger than that in an inland bay and the inflow angle is also smaller in an open sea.
Thus we finally take

\[
\begin{align*}
    h_0 &= a \left[ 1 + \left( \frac{r}{r_0} \right)^2 \right]^{-\frac{1}{2}} \\
    W_x &= C_1 V_s e^{-\alpha x} - C_2 \left[ C_4 (r^2 + r_0^2)^{-\frac{3}{2}} - \frac{f}{2} \right] (0.2588x - 0.9659y) \\
    W_y &= C_1 V_s e^{-\alpha y} - C_2 \left[ C_4 (r^2 + r_0^2)^{-\frac{3}{2}} - \frac{f}{2} \right] (0.9659x + 0.2588y)
\end{align*}
\]

where \( x, y \) is the coordinate relative to the typhoon center, \( r \) is the distance from the typhoon center, \( a \) is the depth of the typhoon in mb, \( r_0 \) is a parameter defining the radius of the maximum wind, \( V_s, V_s \) are \( x, y \) components of the typhoon movements, \( C_1, C_2 \) constants 0.58 and 1.0, \( C_3 = 5 \times 10^{-8} \), and \( C_4 = \left( \frac{ar_0}{\rho a} \right)^{\frac{1}{2}} \times 10^{3/2} \).

6. Finite-difference equations

The computational scheme is exactly the same as that used in the storm surge computations in the Gulf of Mexico (Miyazaki, 1965). This is one of the centered

![Fig. 2a. Computed variations of the coastal sea level (Case 1).](image-url)
The staggered method in which \((M, N, D)\) and \((h)\) are given at alternative mesh points and alternative time step.

If we take

\[
M' = M \frac{\Delta t}{\Delta s}, \quad N' = N \frac{\Delta t}{\Delta s}
\]

the finite-difference prediction equations will be

\[
\begin{align*}
(M')^i_{n+1} &= A(M')^i_{n+2} - 2B(N')^i_{n+2} + CX^i_{n+1} - BY^i_{n+1} \\
(N')^i_{n+1} &= 2B(M')^i_{n+2} + A(N')^i_{n+2} + BX^i_{n+1} + CY^i_{n+1}
\end{align*}
\]

\[
h^{i+1}_{n+1} = h^{i+1}_{n+1} - (M')^{i+1}_{n+1} + (M')^{i+1}_{n+1} - (N')^{i+1}_{n+1} + (N')^{i+1}_{n+1}
\]

where

\[
A = \frac{1 - \beta^2 - \alpha^2}{(1 + \beta)^2 + \alpha^2}, \quad B = \frac{\alpha}{(1 + \beta)^2 + \alpha^2}, \quad C = \frac{1 + \beta}{(1 + \beta)^2 + \alpha^2}
\]

\[
\alpha = \frac{f}{2}, \quad \beta = \frac{1}{2} \sqrt{M^2 + N^2 / D^2}
\]

Fig. 2b. Computed variations of the coastal sea level (Case 1).
and \( \Delta_i, \Delta_j \) mean centered differences in \( i \) and \( j \) directions, respectively.

7. Results of computation (I) — the case of typhoon only

Fig. 2 (a), (b) show computed time variations of sea level at several stations along the coast. The number for each curve shows the \( j \)-coordinate. At every station, a peak appears as the typhoon approaches and passes. These peaks move eastwards as the typhoon moves, and their magnitudes decrease to the east since the typhoon declined after it hit Kyushu.

However, we have little increase or decrease of sea level on the average after the main peak has passed by. Oscillations with periods of 20 and 22 hours are clearly present at stations in the western part. Since the period of inertia motion is 21.7 hours (latitude 33.5°N) in our case, these periodic variations seem to correspond to continental shelf waves. Variations of total kinetic and potential energies in the computed area also indicate these periods (Fig. 3).

However, it is not clear whether these waves move to the east or west, or do

\[
X_{n-1}^{i,j} = \left( \frac{\tau_{x}^{(y)}}{\tau_{x}^{(y)}} \right)_{n-1}^{i,j} - g D_{n}^{i,j} \left( \frac{\Delta x}{\Delta y} \right)_{n-1}^{i,j} \left( h_{n-1}^{i,j} - (h_{n-1})_{n-1}^{i,j} \right)
\]

\[
Y_{n-1}^{i,j} = \left( \frac{\tau_{y}^{(y)}}{\tau_{y}^{(y)}} \right)_{n-1}^{i,j} - g D_{n}^{i,j} \left( \frac{\Delta y}{\Delta y} \right)_{n-1}^{i,j} \left( h_{n-1}^{i,j} - (h_{n-1})_{n-1}^{i,j} \right)
\]

Fig. 3. Time variations of the total kinetic and potential energies (Case 1).
not move at all. The artificial setting of the east and west boundaries would sometimes create artificial waves of reflection, which could conceal what actually takes place. Especially, it will be unfortunate that a wide continental shelf spreads to the west of the computing area. So difficulties will occur in the western part more frequently when the main disturbance is present in the western part. The setting of the eastern boundary would cause less problems.

Variations with smaller periods are present in the western part, but no predominant periods. This is likely to be due to local topography.

It will be concluded from the above results that the unusual rise of sea level in September, 1971 are hardly to be explained by this model, although some features of continental shelf waves can be reproduced. In other words, we have no significant changes of the mean sea level after the main disturbance accompanied with a typhoon has passed, nor any proof of waves slowly moving to the west.

8. Results of computation (II) — the case in which the approach of the Kuroshio is taken into account

Variations of the computed mean sea level at several coastal stations are shown in Fig. 4. In order to filter out short-term variations, these curves are represented by twelve-hourly running means of computed values.

![Fig. 4. Computed variations of the coastal sea level (Case 2, 12-hourly running mean).](image-url)
These curves clearly indicate that the sea level first rises at each station with the approach of the typhoon, and falls after it has passed. But after some hours it again rises, reaches a secondary maximum level, and then finally tends to a finite value. The time of secondary maxima moves from east to west with an average speed of 3.2 m/sec. This is likely to correspond to observation. However, in the western part, variations in the later stage are very small and hardly distinguishable.

Speaking qualitatively, the above results are in good agreement with the observed facts on the unusual rise of sea level. The relative changes of the mean sea level in the later stage are at most about 10 cm, but this is one half the maximum rise by the Kuroshio at the outer edge of the continental shelf.

Lastly, we must check on the case in which typhoon effects are disregarded in the second model, or we only have the approach of the Kuroshio to the south-east edge of the continental shelf. We did not make direct computations for this case. But, as far as linearity holds (approximately, strictly speaking), this case will be computed by single differences of two results of computation. The results show no maxima. The mean sea level at each station only rises gradually and then tends to a finite value.

References

ENDO, M., 1972: Time variations of the westward intensified current (2)—Responses against the typhoon. Lecture at the spring general meeting of the Japan Meteorological Society, May, 1972.


1971年9月の本州南岸の異常潮位について

宮崎正衛

この数値実験の目的は本州南岸の陸だた上に台風23号のモデルを走らせる、また陸だた南縁において黒潮接岸に相当する潮流上昇をあたえて、だって1971年9月の場合のような持続的な異常潮位が沿岸で起こるかどうかを確かめるためである。計算に当ってはいわゆる潮流、高潮の基礎方程式をprimitive methodにより線形積分してゆく方式をとったが、非線形項は海底摩擦についてのみ考えられている。

計算の結果によると、台風の影響だけを考えたのでは今回のような異常潮位は説明でき難しい。しかし、陸だたの南縁において黒潮の接岸に相当する潮流上昇（東に高く、西に向って指数関数的に減少する。）を台風の影響のほかに考えると、はっきり異常潮位が定性的に説明される。すなわち台風による直接の影響が過ぎ去ったのち、東から西に向けてゆっくりとした速度で進行する第2のピークが見られるのである。