An Investigation on the Variations of Sea Level due to Meteorological Disturbances on the Coast of the Japanese Islands (VI) — Storm Surges on the Coasts of the Inland Sea and Osaka Bay —

by

Ichiro Isozaki

Meteorological Research Institute, Tokyo
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Abstract

Storm surges on the coasts of the Inland Sea and Osaka Bay are investigated by use of hourly readings of tidal records for the ten years from 1953 to 1962. Remarkable storm surges on these coasts are caused by typhoons which take paths somewhat west of the station independent of the local topographical characteristics. The storm surges on the coast of Osaka Bay grow remarkably when the strong wind in a typhoon area excites the inflow of water to the bay through the Kii Straits. The storm surges on the coast of the Inland Sea grow notably when the strong wind in a typhoon area excites the flow of water into the Sea through the Bungo Straits. On the other hand, the interaction between the surges in the Inland Sea and Osaka Bay, which takes place near Akashi Straits, is not so significant.

These features are examined by numerical tests. The results obtained coincide fairly well with the observations. Moreover, information about the flow of water under severe meteorological conditions, which have not yet been observed, are obtained.

1. Introduction

The coast of Osaka Bay has been suffering most frequently and severely from the storm surges due to typhoons. Since 1900, three extraordinarily destructive storm surges, the height of which exceeded 200 cm, have occurred at Osaka Harbor: the surge associated with the Muroto Typhoon on Sept. 21, 1934 which had a maximum surge height of 310 cm and caused a flood over an area of 4.5 km², the surge caused by Typhoon Jane on Sept. 3, 1950 with a maximum height of 237 cm, and the one caused by Typhoon Nancy on Sept. 16, 1961 with a maximum height of 280 cm. General features of the storm surge in Osaka Bay have been given by many authors (WADACHI and HIRONO, 1954; MIYAZAKI, 1957; OKUYAMA and UNOKI, 1958; Kobe Marine Observatory, 1961).

The coast of the Inland Sea also suffers often from storm surges. There, the
height of the surge is somewhat lower than at the innermost coast of Osaka Bay, and no storm surge with more than 200 cm height has been observed.

The Inland Sea, which consists of four sea areas of Suho-nada, Iyo-nada, Bingo-nada and Harima-nada, has very complicated topographical features with a number of small islands, and three straits; Bungo Straits, Kammon Straits and Akashi Straits, which connect the Inland Sea with the Pacific Ocean, the East China Sea and Osaka Bay respectively. So the movement of sea water associated with storm surge is very complex and has not been well understood on account both of scanty observation and the complicated topography. General features of them were described by KUNIYASU (1961).

In Japan, the empirical formula

\[ H = a \Delta p + b W^2 \cos \theta \]  

(1.1)

is usually used for description and prediction of storm surge, where \( \Delta p \) is the fall of atmospheric pressure from the normal, \( W \) the wind velocity, \( \theta \) the angle between the wind direction and the direction in which the wind set-up is most effective (usually, the direction normal to the coast or the direction of the bay axis), \( H \) the surge height, and \( a \) and \( b \) the numerical constants. Owing to the fact that this formula is derived under the assumption that the storm surge occurs quasi-statically, it cannot be applied to the storm surge in the Inland Sea and Osaka Bay where the complicated dynamical effects may prevail. Indeed, the values of the constants \( a \) and \( b \) obtained by many authors differ considerably from one another because of the difference of used data.

To understand the phenomenon of storm surge more precisely, it is necessary to know how sea level changes respond dynamically to the meteorological conditions that vary with time and space. WADACHI (1938) considered dynamically the storm surge at Osaka Bay associated with the Muroto Typhoon. Later, MIYAZAKI (1951) calculated the storm surge caused by meteorological disturbances which progressed over the Kii Straits and Osaka Bay without changing its shape and speed. The growth mechanism of the storm surge was clarified to some extent by their work, but the results were not satisfactory enough to be of practical use because their computations were only one-dimensional.

For practical purposes, accordingly, the problem must be solved two-dimensionally taking the outer ocean and the actual topography into consideration. The recent advance in the high speed electronic computer has made it possible to some degree to calculate the storm surge under severe meteorological conditions which change violently with time and space, taking the actual complicated topographical features into consideration. The usefulness of these numerical computations was testified by HANSEN (1956), who computed satisfactorily the storm surge on the North Sea, and PLATZMAN (1958), who computed the level of Lake Michigan. In this country, the numerical computation of storm surge in several bays including the Inland Sea and Osaka Bay has actively been made by the Japan Meteorological Agency in order to improve the method of forecasting and to offer basic data for coast protection (Marine Division, JMA and Third Regional Port and Harbor Construction Bureau, 1961, 1964; Marine Division, JMA and Fourth Regional Port and Harbor Construction Bureau, 1962, 1965).
The purpose of this report is, in the first place, to investigate the local characteristics of the abnormal sea-level rise on the coasts of the Inland Sea and Osaka Bay in more detail by analyzing the observed tidal records. Next, we would like to calculate numerically the elevation and flow of storm surge caused by the model Typhoon Vera as it progresses along different courses, and to study the effects of the typhoon conditions on the storm surge of the Inland Sea and Osaka Bay.

2. General description of the storm surge

2.1 Data processing

Hourly readings of the sea level at eleven tide gage stations on the coasts of the Inland Sea and Osaka Bay are used in this analysis. Locations of the tide gage stations are showing in Fig. 1 and Table 1. Komatsujima, Wakayama and Shimozu are on

Table 1. List of the tide gage stations.

<table>
<thead>
<tr>
<th>Station</th>
<th>North Lat.</th>
<th>East Long.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wakayama</td>
<td>34° 13'</td>
<td>135° 26'</td>
</tr>
<tr>
<td>Shimozu</td>
<td>34° 06'</td>
<td>135° 09'</td>
</tr>
<tr>
<td>Komatsujima</td>
<td>33° 59'</td>
<td>134° 37'</td>
</tr>
<tr>
<td>Sumoto</td>
<td>34° 20'</td>
<td>134° 54'</td>
</tr>
<tr>
<td>Osaka</td>
<td>34° 39'</td>
<td>135° 25'</td>
</tr>
<tr>
<td>Kobe</td>
<td>34° 41'</td>
<td>135° 11'</td>
</tr>
<tr>
<td>Uno</td>
<td>34° 29'</td>
<td>133° 59'</td>
</tr>
<tr>
<td>Takamatsu</td>
<td>34° 21'</td>
<td>134° 03'</td>
</tr>
<tr>
<td>Matsuyama</td>
<td>33° 52'</td>
<td>132° 43'</td>
</tr>
<tr>
<td>Uwajima</td>
<td>33° 14'</td>
<td>132° 33'</td>
</tr>
<tr>
<td>Shimonoseki</td>
<td>33° 58'</td>
<td>130° 57'</td>
</tr>
</tbody>
</table>
the coast of Kii Straits and Sumoto, Kobe and Osaka are on the coast of Osaka Bay. Uwajima and Shimonoseki face the Bungo Straits and Kammon Straits respectively, and Matsuyama, Takamatsu and Uno are on the coast of the Inland Sea. The period covered by the data used is the ten years from 1953 to 1962.

The height of the meteorological tide or storm surge was obtained by subtracting predicted astronomical tides from the observed ones. In predicting the astronomical tide, thirty tidal constants obtained in the previous report (Isozaki, 1968) were used and the monthly mean sea level was assumed to coincide with the mean of the observed sea level.

2.2 Notable storm surges

The number of atmospheric disturbances which caused remarkable storm surges at any one of the tide gage stations on the coasts in question was seventeen in ten years. Table 2 gives the maximum height of surge in each case at respective stations. Fifteen of the seventeen storm surges mentioned in Table 2 were generated by typhoons, and two were due to extratropical cyclones. The maximum height of the storm surge associated with the extratropical cyclone was less than 100 cm.

As will be seen in Table 2, four typhoons caused storm surges higher than 100 cm at any one of the tide gage stations. Among them, Typhoon Nancy which progressed northeastward along the west coasts of the Kii Straits and Osaka Bay on Sept. 16, 1961 caused the severest storm surge in Osaka Bay. The maximum surge height observed at Osaka Harbor at that time was 241 cm, which is next to the height of 310 cm caused by the Muroto Typhoon on Sept. 21, 1934, and the coastal area along the track were struck by the storm surges with severe damage especially around Osaka Bay. The maximum surge height was about 150 cm on the coast of Kii Straits and was 163 cm at Nagoya Harbor. The coast of the Sea of Harimanada, eastern part of the Inland Sea, was also attacked by a storm surge of about 100 cm.

Typhoon Marie which passed in a northeastern direction on the western part of the Inland Sea on the morning of Sept. 26, 1954 caused an abnormal sea-level rise on the coasts along the Inland Sea and Osaka Bay. Its height exceeded 100 cm nearly the whole length of the coastal line and reached 132 cm, 123 cm, and 132 cm at Osaka, Matsuyama and Kure respectively.

Typhoon Della which passed in a north-northeastern direction on the central part of the Inland Sea on the afternoon of Sept. 29, 1960 caused a remarkable storm surge on the eastern part of the Inland Sea and innermost part of Osaka Bay. The highest sea-level rise of the surge above normal was 108 cm, 106 cm, 102 cm and 102 cm at Kobe, Osaka, Uno and Takamatsu respectively. It was small and did not exceed 50 cm on the western part of the Inland Sea.

Typhoon Louise, which crossed Kyushu from south to north and entered the Japan Sea on the morning of Sept. 30, 1955, caused a severe storm surge on the western Inland Sea. The highest surge reached 150 cm on the coast of the Suho-nada, 100 cm at Matsuyama and 132 cm at Kure.
Table 2. Maximum surge heights taken from hourly tidal record (cm).

<table>
<thead>
<tr>
<th>Date</th>
<th>Typhoon name</th>
<th>Wakayama</th>
<th>Shimozu</th>
<th>Komatsujima</th>
<th>Sumoto</th>
<th>Osaka</th>
<th>Kobe</th>
<th>Uno</th>
<th>Takamatsu</th>
<th>Matsu- yama</th>
<th>Uwajima</th>
<th>Shimonoseki</th>
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<tbody>
<tr>
<td>June 7-8, 1953</td>
<td>Tess</td>
<td>38</td>
<td>31</td>
<td>34</td>
<td>42</td>
<td>75</td>
<td>63</td>
<td>50</td>
<td>50</td>
<td>49</td>
<td>38</td>
<td>48</td>
</tr>
<tr>
<td>Sept. 25, 1953</td>
<td>Grace</td>
<td>37</td>
<td>—</td>
<td>49</td>
<td>—</td>
<td>36</td>
<td>30</td>
<td>45</td>
<td>38</td>
<td>26</td>
<td>36</td>
<td>15</td>
</tr>
<tr>
<td>Aug. 18-19, 1954</td>
<td>June</td>
<td>57</td>
<td>61</td>
<td>50</td>
<td>51</td>
<td>66</td>
<td>61</td>
<td>66</td>
<td>72</td>
<td>50</td>
<td>52</td>
<td>66</td>
</tr>
<tr>
<td>Sept. 14, 1954</td>
<td>Marie</td>
<td>74</td>
<td>48</td>
<td>58</td>
<td>69</td>
<td>132</td>
<td>105</td>
<td>93</td>
<td>99</td>
<td>123</td>
<td>79</td>
<td>57</td>
</tr>
<tr>
<td>Sept. 30, 1955</td>
<td>Louise</td>
<td>37</td>
<td>29</td>
<td>43</td>
<td>44</td>
<td>52</td>
<td>51</td>
<td>82</td>
<td>84</td>
<td>100</td>
<td>74</td>
<td>77</td>
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<tr>
<td>Oct. 4, 1955</td>
<td>Marge</td>
<td>26</td>
<td>22</td>
<td>34</td>
<td>34</td>
<td>29</td>
<td>27</td>
<td>40</td>
<td>37</td>
<td>52</td>
<td>42</td>
<td>—</td>
</tr>
<tr>
<td>Aug. 17, 1956</td>
<td>Babs</td>
<td>49</td>
<td>42</td>
<td>32</td>
<td>48</td>
<td>71</td>
<td>71</td>
<td>82</td>
<td>75</td>
<td>79</td>
<td>45</td>
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<tr>
<td>Sept. 10, 1956</td>
<td>Emma</td>
<td>40</td>
<td>35</td>
<td>36</td>
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<td>46</td>
<td>48</td>
<td>59</td>
<td>58</td>
<td>56</td>
<td>35</td>
<td>96</td>
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<tr>
<td>Sept. 7, 1957</td>
<td>Bess</td>
<td>37</td>
<td>33</td>
<td>32</td>
<td>—</td>
<td>47</td>
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<td>47</td>
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<td>53</td>
<td>49</td>
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<tr>
<td>Dec. 13, 1957</td>
<td>Flosse</td>
<td>38</td>
<td>37</td>
<td>36</td>
<td>—</td>
<td>65</td>
<td>54</td>
<td>49</td>
<td>48</td>
<td>34</td>
<td>21</td>
<td>50</td>
</tr>
<tr>
<td>Aug. 25, 1958</td>
<td>Ellen</td>
<td>47</td>
<td>52</td>
<td>54</td>
<td>49</td>
<td>—</td>
<td>51</td>
<td>48</td>
<td>—</td>
<td>28</td>
<td>—</td>
<td>—</td>
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<tr>
<td>Aug. 8-9, 1959</td>
<td>Sarah</td>
<td>39</td>
<td>41</td>
<td>46</td>
<td>—</td>
<td>51</td>
<td>50</td>
<td>42</td>
<td>41</td>
<td>35</td>
<td>37</td>
<td>33</td>
</tr>
<tr>
<td>Sept. 17, 1959</td>
<td>Vera</td>
<td>28</td>
<td>24</td>
<td>25</td>
<td>—</td>
<td>38</td>
<td>42</td>
<td>38</td>
<td>49</td>
<td>40</td>
<td>19</td>
<td>48</td>
</tr>
<tr>
<td>Sept. 26, 1959</td>
<td>Della</td>
<td>74</td>
<td>86</td>
<td>66</td>
<td>—</td>
<td>106</td>
<td>108</td>
<td>102</td>
<td>92</td>
<td>46</td>
<td>50</td>
<td>37</td>
</tr>
<tr>
<td>Sept. 16, 1961</td>
<td>Nancy</td>
<td>168</td>
<td>—</td>
<td>144</td>
<td>142</td>
<td>241</td>
<td>164</td>
<td>85</td>
<td>88</td>
<td>40</td>
<td>41</td>
<td>40</td>
</tr>
</tbody>
</table>
2.3 Path of atmospheric disturbances which caused remarkable storm surges

The tracks of meteorological disturbances which caused remarkable storm surges at respective stations are shown in Figs. 2a–k. The circle on each track is the position of the center of the storm when the highest surge was observed. The tracks of the

(Fig. 2-a)
Fig. 2. Tracks of typhoon and cyclone which caused remarkable storm surges at each station. The circle on each track is the position of the storm center when the highest surge is observed at respective stations.
seventeen atmospheric disturbances in question are given in Fig. 21.

One of the most interesting facts is that a remarkable storm surge occurs when a typhoon passes near or some distance away to the west of respective stations no matter how they are situated with reference to the sea. This suggests that the role of the local wind set-up is in general minor in the growth of storm surge at these stations. The strong wind in a typhoon area which excites the flow of water into Osaka Bay through the Kii Straits seems to cause a remarkable storm surge on the bay. On the other hand, the notable storm surge on the Inland Sea coast seems to be caused
by a typhoon which takes such a course that the strong wind associated with it accelerates the flow of water into the Sea through the Bungo Straits. Of course, the atmospheric pressure fall will play an important part in the storm surge.

The tracks of twelve typical typhoons are represented in Fig. 3. The successive positions of the center of a typhoon are connected by a straight line with the station at which the highest surge is observed simultaneously. Generally, the storm surge
becomes highest a few hours after the typhoon approached nearest when its path is near the station. And the highest surge appears at the nearest approach of the typhoon when its path lies northeastward far west of the station.

For the case of Typhoon Nancy, the peak of storm surge appeared a few hours after the passage of the typhoon on the coast of Osaka Bay and the Sea of Harimana, at about the same time of the typhoon passage over the Kii Straits, and several hours before the arrival of the typhoon at the western Inland Sea. In the case of Typhoon Vera, which caused the severest storm surge on the coast of Ise Bay, the maximum surge height on the coast of Osaka Bay and the Sea of Harima-nada appeared several hours after the typhoon approached nearest. On the other hand, the storm surge associated with Typhoon Tess, which took a course quite similar to that of Typhoon Vera, reached highest several hours before the arrival of the typhoon on these coasts. This discrepancy may be explained by the fact that Typhoon Vera had in its system a vast area of strong southwesterly wind behind the center which induced the flow of water into Osaka Bay.

2.4 Characteristics of growth and decay of the storm surge

Four typical typhoons which took characteristic paths are selected from the seventeen meteorological disturbances in question, to clarify the nature of the storm surge generated when a typhoon progresses along different courses. These are Typhoons Marie on Sept. 26, 1954, Emma on Sept. 10, 1956, Vera on Sept. 26, 1959 and Nancy on Sept. 16, 1961, the tracks of which run, as seen in Fig. 3, about northeastward and are nearly parallel with certain distances from one another.

Fig. 4 shows the time variation of storm surge elevation at Osaka and Wakayama which is caused by the four typhoons mentioned above, as the representative storm surge on Osaka Bay and the Kii Straits respectively. The time scale is adjusted so as to place the origin at the time of nearest approach of the typhoon, and the positions on the abscissa to the left and the right of origin represent the time before and after the passage of the typhoon respectively. The time of maximum surge height appears, in general, about two hours after the typhoon approaches nearest.

When a typhoon passes east of the station, as seen in case of Typhoon Vera, the sea level at Osaka is lowered by the effect of strong northeasterly off-shore wind before the storm center approaches the station. As soon as the typhoon passes and the wind shifts to the southwest, the sea level rises suddenly. These phenomena may be explained by the conditions that the bay is shallow in depth and that its mouth is open southward. At that time, the sea level at Wakayama did not fall before the arrival of the storm center because the water depth of the Kii Straits is large enough.

In general, the sea level begins to rise about 20 hours before the time of nearest approach of a typhoon, and returns to normal about 10 hours after the passage of a typhoon and then falls slightly under normal. When a typhoon passes far west of the station, as in the case of Typhoon Emma, the sea level rises gradually toward the peak and then falls gradually having relatively small surge height and long surge duration.
Fig. 5 shows the time variation of storm surge elevation at the stations Takamatsu, Matsuyama, Shimonoseki and Uwajima. The difference in the nature of the storm surge due to the difference of typhoon courses is somewhat vague. The maximum of surge height at Takamatsu appears about a few hours after the passage of a typhoon. The main part of the sea-level rise at Matsuyama, Shimonoseki and Uwajima takes place before the arrival of a typhoon and the maximum surge appears just at or somewhat later than the time of nearest approach of the typhoon. In general, the sea level begins to rise about 20 hours before the arrival of a typhoon and returns to normal about 4~8 hours after its passage, and then falls slightly under normal. The low sea level after the passage of a typhoon is most prominent at Shimonoseki as will be suggested by Fig. 9. The decay of storm surge is faster on the Inland Sea than on Osaka Bay.

Fig. 4. Time variation of storm surges caused by the typical typhoons at Osaka and Wakayama.
3. **Numerical tests**

By use of the high speed electronic computer, it has become possible to some degree to calculate the storm surge under severe meteorological conditions which change violently with time and space, taking the actual complicated topography into consideration. According to a comparison between observation and calculation, we may say that numerical analysis is considerably reliable, at least to the first approximation. Our knowledge, however, still remains scanty as to the behavior of storm surge and forces acting upon it such as wind stress and bottom friction. In addition, the ability of the computer is limited. Accordingly, it should be borne in mind that the results of our computation may be corrected in some point in future, though the correction is reasonably supposed not to be so great.

So we performed computations on the storm surge in the Inland Sea and Osaka.
Bay following the same procedure as was taken in the previous report (UNOKI, ISOTAKI and OTSUKA, 1964). In the experiments conducted by the Japan Meteorological Agency over the area in question, the area is divided into three parts; Osaka Bay, the central and the western part of the Inland Sea. It is difficult to define the conditions at the boundary between the respective areas over which the experiments were carried out separately. So in the present tests, the computation is carried out over the whole area of the Inland Sea and Osaka Bay.

3.1 Procedure of computation

Basic equations

The equations of motion on the rotating earth are

\[
\frac{\partial u}{\partial t} + u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} + w \frac{\partial u}{\partial z} - fu = -\frac{1}{\rho_w} \frac{\partial p}{\partial x} + \frac{\mu}{\rho_w} \frac{\partial^2 u}{\partial z^2}
\]

(3.1)

\[
\frac{\partial v}{\partial t} + u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} + w \frac{\partial v}{\partial z} + fu = -\frac{1}{\rho_w} \frac{\partial p}{\partial y} + \frac{\mu}{\rho_w} \frac{\partial^2 v}{\partial z^2}
\]

(3.2)

\[
\frac{\partial w}{\partial t} + u \frac{\partial w}{\partial x} + v \frac{\partial w}{\partial y} + w \frac{\partial w}{\partial z} = -\frac{1}{\rho_w} \frac{\partial p}{\partial z} + g
\]

(3.3)

where \(x\) and \(y\) and \(z\) are the rectangular coordinates with \(x-y\) plane on the undisturbed sea surface and \(z\)-axis directed downward. \(u, v\) and \(w\) the corresponding components of the velocity of the water particle, \(f\) the Coriolis parameter, \(\rho_w\) the density of water, \(p\) the pressure, \(g\) the acceleration of gravity and \(\mu\) the coefficient of vertical eddy viscosity. The horizontal eddy viscosity is neglected, but the dissipation of energy due to its action is taken into consideration by smoothing the calculated values at respective grid points. On the other hand, the equation of continuity is

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0
\]

(3.4)

Integrating the above equations over depth from the surface \(Z = -\zeta\) \((x, y, t)\) to the bottom \(z = h\) \((x, y)\) and neglecting the terms of higher order, we have

\[
\frac{\partial M_x}{\partial t} = -g(h + \zeta) \frac{\partial \zeta}{\partial x} + g(h + \zeta) \frac{\partial \zeta_0}{\partial y} + \frac{\tau_x^{(v)}}{\rho_w} - \frac{\tau_x^{(z)}}{\rho_w} + fM_y - (h + \zeta) \left\{ \frac{\partial \bar{u}^2}{\partial y} + \frac{\partial \bar{v}}{\partial y} \right\}
\]

(3.5)

\[
\frac{\partial M_y}{\partial t} = -g(h + \zeta) \frac{\partial \zeta}{\partial y} + g(h + \zeta) \frac{\partial \zeta_0}{\partial y} + \frac{\tau_y^{(v)}}{\rho_w} - \frac{\tau_y^{(z)}}{\rho_w} - fM_x - (h + \zeta) \left\{ \frac{\partial \bar{u} \bar{v}}{\partial x} + \frac{\partial \bar{v}^2}{\partial y} \right\}
\]

(3.6)

\[
\frac{\partial \zeta}{\partial t} = \frac{\partial M_x}{\partial x} + \frac{\partial M_y}{\partial y}
\]

(3.7)

where \(\zeta\) is the elevation of the sea surface above the still water level, \(h\) the depth of the basin, \(\bar{u}\) and \(\bar{v}\) the components of the vertically-averaged flow \(\bar{V}\), and \(\zeta_0\) the equilibrium height of the sea surface corresponding hydrostatically to the fall of atmospheric pressure. \(\tau_x^{(v)}\) and \(\tau_y^{(v)}\) are the components of the surface stress due to wind \(\tau_v\), and \(\tau_x^{(z)}\) and \(\tau_y^{(z)}\) the components of the bottom friction \(\tau_b\). \(M_x\) and \(M_y\) are them components of the volume transport, expressed as
As to the surface stress by wind and the bottom friction our knowledge remains still imperfect and vague although a great deal of discussion has been made. Accordingly, for the present, they are given as follows,

\[ \tau_x = \rho_a \gamma^2 w |w|, \quad \tau_y = \rho_a \gamma^2 v |v| - 2 \tau_z \]  \quad (3.10), (3.11)

where \( \rho_a \) is the density of air, \( w \) the wind vector at an anemometer height and \( \gamma^2 \) the coefficient of surface stress. For \( \gamma^2 \) various values have been reported (Wilson, 1959), but no value valid at high wind speed has been established yet. Here we adopt the value \( 2.6 \times 10^{-3} \). \( \gamma^2 \) is the coefficient of bottom friction and we used for it the same value as \( \gamma^2 \). \( \beta \) is a constant and determined as 0.35 empirically.

Meteorological condition In this experiment, the storm surges caused by the model Typhoon Vera when it attacks the Inland Sea and Osaka Bay are obtained numerically. The atmospheric pressure distribution in a typhoon area is assumed to be represented by Fujita's formula,

\[ p_r = p_\infty - \frac{a}{\sqrt{1 + (r/r_o)^2}} \]  \quad (3.12)

where \( p_r \) and \( p_\infty \) are the atmospheric pressure (sea level value) at a distance \( r \) and at infinity from the typhoon center respectively. \( a \) and \( r_o \) are constants dependent on the structure of the typhoon. For the case of Typhoon Vera, \( a = 70 \text{ mb}, \quad r_o = 75 \text{ km and } p_\infty = 1010 \text{ mb} \).

We next suppose that the wind distribution in a typhoon consists of two component fields. One is the wind field symmetrical with respect to the typhoon center, in which the wind crosses the isobar to the left at an angle of 30° with a speed proportional to the pressure gradient. The other is the basic wind field, the speed of which is presumed to depend on the speed of the typhoon and decreases exponentially with the distance from its center.

As the boundary condition we have

\[ M_x = 0 \quad \text{at the coast} \]  \quad (3.13)

\[ \zeta = m \zeta_o \quad \text{at the mouth of a bay} \]  \quad (3.14)

where \( m \) is a constant which is provisionally introduced on account of a lack of information about surges outside the bay, which may be decided empirically.

Programming In order to solve the Eqs. (3.5), (3.6) and (3.7) numerically they have to be approximated by difference equations, and the time integration can then be made stepwise for each grid point. Fig. 6 shows the grid points at which the water depth is given and the elevation and the components of volume transport are calculated. Putting

\[ S_x = M_x \frac{\Delta t}{\Delta s}, \quad S_y = M_y \frac{\Delta t}{\Delta s} \]  \quad (3.15)
where $\Delta t$ and $\Delta s$ are the time step and the mesh width used in numerical integration respectively, Eqs. (3.5) – (3.7) can be broken down as follows:

$$S_x^{i,j}(t + \Delta t) = S_x^{i,j}(t) - \frac{g}{2} \left( \frac{\Delta t}{\Delta s} \right)^2 \left\{ \zeta_x^{i,j}(t + \frac{\Delta t}{2}) + \zeta_x^{i-1,j}(t + \frac{\Delta t}{2}) + h_x^{i,j} + h_x^{i,j+1} \right\}$$

$$ \times \left\{ \zeta_x^{i,j}(t + \frac{\Delta t}{2}) - \zeta_x^{i-1,j}(t + \frac{\Delta t}{2}) \right\} + A_x^{i,j}$$  \hspace{1cm} (3.16)

$$S_y^{i,j}(t + \Delta t) = S_y^{i,j}(t) - \frac{g}{2} \left( \frac{\Delta t}{\Delta s} \right)^2 \left\{ \zeta_y^{i,j-1}(t + \frac{\Delta t}{2}) + \zeta_y^{i,j}(t + \frac{\Delta t}{2}) + h_y^{i,j} + h_y^{i+1,j} \right\}$$

$$ \times \left\{ \zeta_y^{i,j-1}(t + \frac{\Delta t}{2}) - \zeta_y^{i,j}(t + \frac{\Delta t}{2}) \right\} + A_y^{i,j}$$  \hspace{1cm} (3.17)

$$\zeta^{i,j}(t + \Delta t) = \zeta^{i,j}(t) - S_x^{i+1,j}(t + \frac{\Delta t}{2}) + S_x^{i,j}(t + \frac{\Delta t}{2}) - S_y^{i,j}(t + \frac{\Delta t}{2})$$

$$- S_y^{i,j}(t + \frac{\Delta t}{2})$$  \hspace{1cm} (3.18)

Here, $A_x^{i,j}$ and $A_y^{i,j}$ contain the acceleration terms and the external forces such as the atmospheric pressure gradient force, the wind stress on the water surface, the bottom friction and the Coriolis force, and are calculated every ten minutes.

The stability of the finite difference equation has been studied by Platzman (1958) and others. For central time difference, Platzman shows that the condition

$$\frac{\Delta s}{\Delta t} > \sqrt{\frac{2g}{h_{\max}}}$$  \hspace{1cm} (3.19)
has to be fulfilled, where \( h_{\text{max}} \) is the maximum depth in the integration area. As the values of \( \Delta s \) and \( \Delta t \) are, in the present case, 5 km and 120 sec, we limit the water depth to 85 meters or less.

### 3.2 Classification of the experiments

Fig. 7 shows the grid system for the Inland Sea and Osaka Bay over which numerical computation is carried out. The grid size, \( \Delta s=5 \text{ km} \), is too large to represent the complicated coastal topography of the Inland Sea, but we cannot use a smaller grid size because of the limitation of the computer's ability. But the general situation of the storm surge is represented in the computations.

There are many straits in the Inland Sea and Osaka Bay. Among them, the principal ones which will appreciably affect the storm surge are shown in Table 3. The three straits of Akashi, Naruto and Kammon are assumed respectively to be closed by a breakwater with an opening, the cross section of which is nearly equal to that of the real straits, because the width of these straits is too small to be represented by the grid system of 5 km width.

<table>
<thead>
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<tr>
<td>11.2</td>
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</tbody>
</table>

First, the storm surges caused by the model typhoon as it progresses along the six different courses shown in Fig. 8 with a speed of 73 km/hr are computed. Here,
Fig. 8. Tracks of typhoons assumed in the numerical computation of storm surges on the Inland Sea and Osaka Bay.

the course A is similar to that of Typhoon Emma, the course C to that of Typhoon Marie, the course D to that of Typhoon Bess, the course E to that of Typhoon Nancy and the course F to that of Typhoon Vera.

Next, the storm surges caused by the model typhoon as it progresses along the course E with different velocities of 80, 60, 50 and 40 km/hr are computed. Lastly, the storm surge caused by the model typhoon as it progresses along the course E with a speed of 73 km/hr is computed omitting the effect of surface wind stress. Table 4 shows the estimated peak values of storm surges at the several stations for the eleven cases mentioned above.

As an example of the computation for the model typhoon progressing along the course E with a speed of 73 km/hr, the sea level distribution at $t=12^\circ$, when the typhoon has passed Osaka Bay, is shown in Fig. 9. In this figure, the sea level rises abnormally at the innermost part of Osaka Bay and falls at the western part of the Inland Sea. These situations are similar to those of Typhoon Nancy.
3.3 Effect of the typhoon path on storm surge

Fig. 10a shows the time variation of the storm surges at the stations on the coast of Osaka Bay and the Kii Straits when the model typhoon progresses along the six different courses shown in Fig. 8 at a speed of 73 km/hr. The severest storm surge is caused by the typhoon which progresses along the course E, and the peak values are 289 cm and 239 cm at Osaka and Kobe respectively. The next severest occurs when the course D is followed. In every case the maximum surge height at respective stations appears a few hours after the passage of the typhoon, and the sea level returns normal six or eight hours after. In the case of the course F, the sea level falls at Osaka and Kobe before the arrival of the typhoon, but not at the other stations. These features coincides with those shown in Fig. 4. Nevertheless, the second peak which appeared at Komatsujima and Wakayama about 4 hours after the passage of a typhoon in the cases of the courses, D, E and F is obscure in the observations.
Fig. 10b shows the time variation of the storm surges at the stations on the coast of the Inland Sea and the Bungo Straits which are caused by the model typhoon as it progresses along the six different courses in question. Remarkable storm surge occurs in the eastern and central part of the Inland Sea in the cases of the courses B and C, and the surge in the western part grows remarkably in the cases of the courses A and B. The maximum surge heights at Kure, Matsuyama, Shimonoseki and Takamatsu are 234 cm, 210 cm, 182 cm and 191 cm respectively. The mode of growth and decay of the storm surge is generally coincident with those shown in Fig. 5.
Fig. 11a, b show the relation between the maximum surge height and the distance of the typhoon track from the station. The maximum surge height is attained by the typhoon which passes at a certain distance west of the station, and decreases as the...
Fig. 11a, b. Relation between the maximum surge height and the distance of the station from the typhoon path.
path leaves that course to the right or left. This is due to the fact that the distribution of wind in the typhoon area is not symmetrical, having the area of the strongest wind to the right of the typhoon center.

Fig. 12 shows the positions of the model typhoon when the surge reached the maximum level at the respective stations for the typhoon courses A and E. The successive positions of the storm center are connected by a straight line with the station at which the highest surge is observed simultaneously. In case of the typhoon course A, generally, the maximum surge height appears a few hours after the typhoon approaches nearest, and the retardation time becomes larger at the eastern stations. In the case of the course E, the maximum surge appears after the passage of the typhoon on the coast of Osaka Bay and the Sea of Harima-nada, whereas it appears before the arrival of the typhoon on the western Inland Sea.

3.4 Effect of typhoon speed

It is well known that the storm surge induced in a bay by a typhoon may grow abnormally high through the resonant mechanism when the typhoon traverses the bay with a speed nearly equal to that of the long wave in the bay, \( \sqrt{gh} \). But, as stated by WADACHI (1938), the growth of storm surge through the resonant mechanism will not be significant in bays which are small as compared with the scale of the typhoon. In order to examine the effect of typhoon speed on the growth of storm surge, we computed the storm surge caused by the model typhoon when it progresses with different
speeds of 40, 50, 60, 73 and 80 km/hr along the course E.

Fig. 13 shows the maximum surge height at selected stations for the respective speeds of the typhoon. The relation between the growth of storm surge and the typhoon speed is complex. The maximum surge height at Osaka, Kobe and Wakayama increases as the typhoon speed increases, and reaches its maximum at the speed of 73 km/hr and then decreases. A monotonous increase of surge height is seen at Sumoto as the typhoon moves fast. On the contrary, a monotonous decrease of surge height is seen at Komatsujima as the typhoon moves fast. From this, it cannot be concluded that the surge grows remarkably when a typhoon moves with the same speed as that of the long wave in the bay.

3.5 Comparison between the effects of atmospheric pressure and wind on storm surge

As is well known, remarkable storm surge is caused by very low atmospheric pressure and strong wind in a typhoon area, the latter effect prevailing especially in shallow bays. WADACHI (1938) found that the contributions to storm surge of atmospheric pressure fall and of wind set-up are nearly equal in seas where the water depth is about 120 meters, and either the pressure effect or the wind effect prevails according as the sea is deeper or shallower than 120 meters. He also deduced that the ratio of wind effect to atmospheric pressure effect at Osaka Harbor was about 3:1 or 4:1 in the storm surge caused by the Muroto Typhoon on Sept., 1934.
KUNISHI and YOSHIDA (1960) obtained from analyzing a number of observations that the ratio of the effects of wind, atmospheric pressure and the surge of the outer ocean was about 2:1:1 in the storm surge caused at Nagoya Harbor by Typhoon Vera.

In this section, we examine how much these effects contribute to the storm surge in the Inland Sea and Osaka Bay in case of the course E. Fig. 14 shows the time varia-

![Graphs showing time variation of sea levels](image)

**Fig. 14.** Time variation of $\zeta_{gw}$, $\zeta_w$ and $p$ when the model typhoon progresses along the course E.

At an early stage of the storm surge $\zeta_w$ is larger than $\zeta_w$. As the typhoon approaches the bay, $\zeta_w$ in creases rapidly and exceeds $\zeta_w$ in the mature stage of the storm surge at Osaka, because the wind effect is proportional to the square of wind speed. At Sumoto and Wakayama, $\zeta_w$ is somewhat larger than $\zeta_w$ even in the mature stage of the surge. $\zeta_w$ at Komatsujima is relatively small owing to the fact that the sea is deep enough and the station is near the outer ocean. In our computation, the ratio of the highest values of $\zeta_w$ and $\zeta_w$ at Osaka is 1.3. This is less than Wadachi's estimation, because $\zeta_w$ obtained here contains the effects of the surge invading from the outer ocean and of the propagation of the typhoon.

The ratio of the peak values of $\zeta_w$ and $p$ are 1.10, 1.39, 1.18 and 1.98 at Komatsu-
jima, Wakayama, Sumoto and Osaka respectively. This suggests that the effect of the atmospheric pressure fall on the storm surge increases gradually as the coast is nearer the bay head. The maximum value of \( \zeta_p \) appears later than that of \( p \), and the retardation is greater at the bay head.

Fig. 15 shows the time variation of \( \zeta_p, \zeta_w, \zeta_{p\cdot w} \) and \( p \) at selected stations on the coasts of the Inland Sea and the Bungo Straits. \( \zeta_p \) is very small at Uwajima and the storm surge is represented for the most part by \( \zeta_p \). The fall of the sea level which was remarkable at Kure and Shimonoseki is due to the wind effect. The maximum value of \( \zeta_p \) appears later than that of \( p \), and the retardation is greater toward the innermost part of the Inland Sea being 1.5 hours, 2 hours and 4 hours at Matsuyama, Kure and Takamatsu respectively. The ratio of the highest values of \( \zeta_p \) and \( p \) is 1.28, 1.41, 1.56, 1.30 and 1.41 at Uwajima, Shimonoseki, Kure, Matsuyama and Takamatsu respectively. This suggests that the effect of the atmospheric pressure fall on storm surge increases toward the inner part of the Inland Sea. The large value at Kure may be due to the topographical effect of the shallow Hiroshima Bay.

3.6 Flows through straits associated with storm surge
The Inland Sea is connected with the outer seas by many straits through which tidal currents run fast. These straits must be responsible for the fast currents associated with a storm surge. To get information about these currents will be important not only for the understanding of the mechanism of the storm surge but also for
practical purposes. Here will be shown the currents associated with the model typhoon which take six courses mentioned in Fig. 8.

Figs. 16 and 17 show the time variation of the computed mean flow through the

Fig. 16. Time variation of surge flow through the Tomogashima Straits when the typhoon progresses along the courses C, D, and E.

Fig. 17. Time variation of surge flow through the Akashi Straits when the typhoon progresses along the course C, D, and E.
Tomogashima Straits and Akashi Straits. The surge currents through these straits are fast in cases of the courses C, D, and E, while they are slow in the other cases. The fastest flow through the Tomogashima Straits is 184.4 cm/sec in the case of the course E. On the other hand, it is 70.9 cm/sec through the Akashi Straits in the case of the course D. As the velocity shown here is the mean over the vertical section of the straits, the surface flow may be faster locally than the values shown here.

In the case of the course E which causes the severest storm surge on the coast of Osaka Bay, the water mass transport through the Akashi Straits from Osaka Bay to the Inland Sea is only about half that which invades Osaka Bay through the Tomogashima Straits. Moreover, as the Inland Sea has a far larger area than Osaka Bay, the mass transport from Osaka Bay does not seem to make any significant contribution to the storm surge in the Inland Sea.

Fig. 18 shows the time variation of the computed mean flow through the Bungo Straits. The surge currents here are fast in cases of the courses A, B, C and D, while they are slow in the other cases. The fastest flow is calculated in the case of the course B; the maximum inflow, 141.5 cm/sec, occurs when the typhoon approaches nearest and the maximum outflow, 156.0 cm/sec, takes place about 5 hours after the typhoon passage. The water mass transport through the Bungo Straits from the outer ocean into the Inland Sea, in this case, is about 2.1 times that which invades Osaka Bay.

![Fig. 18. Time variation of surge flow through the Bungo Straits when the typhoon progresses along the courses A, B, C and D.](image-url)
through the Tomogashima Straits in the case of the course E.

Fig. 19 shows the time variation of the mean flow through the Kammon Straits. The surge currents here are fast in cases of the courses A, B and C, and slow in the other cases. The fastest flow is 317 cm/sec and 275 cm/sec from the Inland Sea to the outside in cases of the courses A and B respectively. But the water mass transport is small as the cross section of the straits is small, and cannot contribute effectively to the storm surge on the Inland Sea. For example, the mass transport through Kammon Straits to the outside is, in the case of the course B, only 1/7 of the invading water mass through the Bungo Straits.
3.7 Propagation of storm surge

The propagation of the storm surge in the Inland Sea and Osaka Bay is examined by the time isopleth analysis of the sea level along the longitudinal axis of the sea. Fig. 20 shows two time isopleths of storm surge: the upper one is the result computed
In the case of the course E and the lower one is that associated with Typhoon Nancy on 1961.

In this figure, the computation coincides fairly well with the observation. The surge which invaded Osaka Bay through the Tomogashima Straits encounters the surge invading the Inland Sea through the Bungo Straits near the Akashi Straits. Referring to Fig. 17, it will be concluded that the second peak of the storm surge which came several hours after the main surge at Takamatsu is not the surge invading from Osaka Bay through the Akashi Straits but the one propagating from the west. Indeed, in Fig. 17, the flow invading the Inland Sea through the Akashi Straits ceases at 13°, then again runs slowly between 13° and 15° and cannot have any influence on the formation of the second surge peak.

The situations mentioned above are also seen in other cases, so it is inferred at least from the apparent features that the storm surges in the Inland Sea and Osaka Bay are independent of each other and the interaction between them is not significant.

4. Conclusion

Remarkable storm surges on the coasts of the Inland Sea and Osaka Bay are caused by typhoons which take paths somewhat west of the station independent of its local topographical characteristics. Storm surges on the coast of Osaka Bay grow abnormally when the strong wind in the typhoon area quickens the inflow of water to the bay through the Kii Straits. Storm surges on the coast of the Inland Sea grow remarkably when the strong wind in the typhoon area drives on the flow of water into the sea through the Bungo Straits. The interaction between the surges originating from the Inland Sea and Osaka Bay, which takes place near the Akashi Straits, is not so significant.

These features have been examined by the numerical experiments. The results of the computation coincide fairly well with the observations. Moreover, the surge flow under severe meteorological conditions which have not yet been observed has been obtained. The grid size used here is not so fine as to represent the complexity of the coastal topography of the Inland Sea, which is dotted with small islands and has complicated coastal lines. For the analysis of the local characteristics of storm surge, numerical computation with a smaller mesh size is needed.

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References

気象擾乱によって起る日本沿岸の水位変動の研究 (VI)

瀧 崎 一 郎

1953～1962年の10年間の毎時潮汐記録を用いて瀧内海および大阪湾の高潮の生長と減衰に関する性質を明らかにする。これらの場合では、検潮所の局地的な地形に関係なく、台風が検潮所のやや西側を通る時に最も顕著な高潮が起る。瀧内海の高潮には風後の水位から流入する海水が大幅な役割を果たし、大阪湾の高潮は紀伊水道から流入する海水に支配される。瀧内海の高潮と大阪湾の高潮の相互干渉は明石海峡付近で起こっているが、その影響は小さいようである。
これらの性質はさらに数値実験によって調べられた。計算結果は観測事実とかなりよく合っている。