Sea-Level Changes Since the Early 1920’s from the Long Records of Two Tidal Gauges in Shanghai, China

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ABSTRACT


This paper reports on sea-level changes at the Changjiang river mouth since the early 1920’s, with a special emphasis on recent local tectonic movement, ground subsidence, and river discharge. Historical studies and mathematical correlations are used to examine the establishment and historical changes of tidal gauges and related bench markers as well as to establish the reliability of tidal records. In the past, some Chinese scientists proposed that sea-level has declined since 1950 while other foreign scientists attributed sea-level rise in the East China Sea to crustal and isostatic sinking. This study concludes that sea-level is rising at a rate about 1.0 mm a year, which is comparable to that of global sea-level rise. Meanwhile, it is found that the increase of the annual mean high tide level is remarkably greater, reflecting the estuarine morphological and hydro-dynamic effect on sea-level rise. The evidence suggests that the component of tectonic sinking accounts for only 1/2 or less of the relative sea level (RSL) rise. In contrast to the viewpoint of sea-level declining since 1950, this study shows a rising trend from 1951 to 1987, which is a continuation of sea-level rise since the beginning of this century.

ADDITIONAL INDEX WORDS: Geodetic levelling, tectonic movement, base marker, river discharge, Quaternary, sea-level rise, tidal-gauge.

INTRODUCTION

In recent years increased worldwide attention has been given to the issue of future global warming and sea-level rise. Because the coastal areas of China are highly vulnerable to sea-level rise, the Chinese academic circle has attached great importance to the study of sea-level change along the coast of China. Does the sea-level along the coast of China show any trend in this century? What is its future trend and possible impact on society? In order to answer these fundamental problems Chinese scientists lay emphasis on the history of sea-level changes in Shanghai because its unique geological environment and society are most vulnerable to sea-level changes and because Shanghai possesses two tidal gauges with 70-year long records. Until 1980, more than 200 tidal gauges were set up along China’s mainland and island coasts. However, most of them were established after 1950. Among the small number of tidal gauges with longer history, the two tidal gauges in the Wushong and Huangpu Park of Shanghai are the only ones with parallel data of geodetic levelling and a relatively stable tectonic base.

Several studies based on tidal gauge records have contributed to our understanding of recent sea-level changes along the coast of China. On the basis of a regression analysis on records from 7 tidal gauges along the mainland coast and in Hong-Kong, EMERY AND YU (1981) proposed that the rate of RSL rise is about 2.5 mm/year. WANG (1986) reached the conclusion also through regression analysis, that, among the twenty tidal gauges having records since the 1950’s, thirteen tidal gauges reflect a rising trend with a mean rate about 3.5 mm/year. YU (1986) suggests a mean rate of rise about 2.1 mm/year since 1960 through a regression analysis of data from 16 tidal gauges. Using Empirical Orthogonal Function (cf. BARNNET, 1983), the author determined an increasing rate about 3.0 mm/year from 11 tidal gauges uniformly located along the east coast of China (CHEN, 1987; YANG AND CHEN, 1988).
It should be noted that in the studies listed above, the time spans of tidal records are short and show great variety. The length of records are mostly shorter than 37 years which is equivalent to two 18.6-year astronomical cycles. Thus, the arbitrary beginning and end of data used in analyses will surely change the rate of sea-level changes. Meanwhile, there have been no studies concerned with local vertical tectonic movement, which is important to the interpretation of RSL changes. More importantly, these studies do not consider the reliability of published data or whether local bench markers underwent changes due to movement of the tidal gauge location or ground subsidence. The following report is an in-depth study from the long records of two tidal gauges in Shanghai with a special emphasis on these basic problems.

THE ESTABLISHMENT OF TIDAL GAUGES AND BENCH MARKERS

The earliest intrusion of foreign forces to Shanghai can be dated back to 1842. In order to guarantee the safe passage of their ships over the Inner Wushong Shoal, the Harbour Master installed the Woosung Signal Station (including a water gauge) at the Zhanghuabang, the bank of the Huangpujiang River, in 1860 (Figure 1). Geographically, Zhanghuabang is located several kilometers south of the present Wushong Tidal Gauge. From 1871 to 1900, a bench marker was established which is slightly lower than the Lowest Lower Water ever recorded during the period. This bench marker was originally called “Woosung Customs Zero” and later formally renamed as “Woosung Horizontal Zero (W.H.Z.)” (ZHU, 1985). The place name “Woosung” is now spelled as “Wushong.”

The two earliest automatic tidal gauges in Shanghai, the Wushong Tidal Gauge and the Huangpu Park Tidal Gauge, were established in January 1912 and December 1912, respectively. In December 1918 the location of Wushong Tidal Gauge was moved about one kilometer northward from the old one due to bank accretion of the Huangpujiang River. Since then its location as indicated in Figure 1 has remained constant.

The Sheshan Base Marker was established in June 1922 by the Whangpoo Conservancy Board (W.C.B.) and geodetic levelling placed it at 46.0647 m above W.H.Z. This base marker is located in Sheshan Hill (Figure 1) which is composed of volcanic rocks of Jurassic to Cretaceous age. Later, in 1965 a New Base Marker was laid at the north slope of the hill by precise levelling from the old one. When the old Sheshan Base Marker was destroyed during the Cultural Revolution (1967 to 1976), the historic data of geodetic levelling in the area continued consistently at the new base marker (ZHU, 1985). The repeated levelling data from Shanghai Geologic Bureau (1979) suggest that the relative altitude between the old and the new base marker always varies within the range of survey error (± 2 mm), reflecting no systematic differential movement.

LAND SUBSIDENCE AND TIDAL RECORD CALIBRATION

As the modern industry of Shanghai began to develop, more ground water was withdrawn, resulting in strong ground subsidence in the urban area. However, before the 1950’s there was little awareness about land subsidence due to ground water extraction. In July 1951, the second long-distance geodetic levelling was made and determined that the relative altitude between the Sheshan Base Marker and W.H.Z. had increased by 0.407 m compared with the measurement of June 1922. Years later it was perceived that the frequency of high-tide floods in the urban area along the Huangpujiang River bank became greater and greater and that navigation clearance under bridges became smaller and smaller during periods of high water. Meanwhile, stocks of steel pipes from deep wells often became exposed and had to be cut with saws. After a period of study and debate, the mechanism of land subsidence was clarified. It was decided to calibrate the tidal records of the Wushong Tidal Gauge from 1922 to 1951 according to the subsidence amount of 0.407 m. In the calibration scheme (ZHU, 1985) an annual increment about 12 to 16 mm is given to the total accumulated amount of land subsidence each year. The third precise geodetic levelling was made in September 1957 and the results show that the ground where the Tidal Gauge is located had subsided by 9.0 cm since 1951. Considering the sharp increase of ground water extraction and land subsidence during this period (Figure 2), the author adopted a
scheme for tidal record calibration in which there is a small increase in the annual increment contributed to the total accumulated subsiding amount of each successive year. Compared with the calibration scheme adopted by the Shanghai Channel Bureau (ZHU, 1985) in which the annual land subsidence amount is a constant, the annual mean sea-levels from the author's scheme are slightly greater during 1952–1956, with the difference generally following within the range of 1.0 cm. Since 1958, precise levelling and bench marker calibration have been conducted each year. The stochastic errors in levellings are very small and will not give rise to any contribution to the sea level trend. This prerequisite is important in the study of sea level changes.

SEA LEVEL CHANGES FROM 1922 TO 1987

Based on the precise long-distance geodetic levelling from the Sheshan Base Marker to the bench mark of the Wushong Tidal Gauge, ground subsidence components in the tidal records have been detected and eliminated, as mentioned above. The calibrated records from 1922 to 1987 are dotted in Figure 3a. A regression analysis shows that the rate of sea-level rise from 1952 to 1987 is 2.3 mm/year which is highly significant according to the F-test. Because the Wushong Tidal Gauge is located near the Changjiang River estuary, the effect of annual river discharge on sea-level should be detected. The statistics show that the correlation between the Wushong mean sea level and the Changjiang annual discharge measured at
Figure 2. Amount of ground water extraction and resultant rate of ground subsidence in Shanghai urban area (after Shanghai Geologic Bureau, 1979).

the Datong Hydrometric Station is highly significant at 0.5% level. Thus, the contribution of annual discharge to mean sea level can be eliminated according to this correlation and the results are shown in the right part of Figure 3b. The resultant rate of sea-level rise is 3.1 mm/year from 1952 to 1984, slightly greater than the rate 2.7 mm/year during the same period in which the contribution of annual discharge is not eliminated. This rate increase results from a slight decrease in Changjiang River discharge either from 1952 to 1984 or from 1922 to 1984, though the trend is far from the significant level.

When studying the earlier and longer sea level change history from 1922 to 1987, the author was puzzled at first by the behavior shown in Figure 3a, in which there is a distinct displacement between the periods before and after 1951. After eliminating the effect of river discharge on mean sea level, this displacement is more striking (Figure 3b). After careful consideration, it seems that this displacement cannot be attributed to other natural phenomena, viz hydrological, climatic, or local tectonic changes. In order to further determine the cause and amplitude of this displacement, it is necessary to follow a mathematical correlation.

The Huangpu Park Tidal Gauge and the Wushong Tidal Gauge were established in the same year, 1912. The former is located only several kilometers away from the latter. Both belong to the same system of geodetic levelling and management. In this study the Wushong tidal records are treated as the main data set and the Huangpu Park tidal records as subsidiary to test the reliability of the former data. This is because (1) the Huangpu Park Tidal Gauge is located in the Huangpujiang River, a final tributary of the Changjiang River (Figure 1). There is a strong effect of the Huangpujiang annual discharge on the Huangpu Park tidal records, however, there exists no parallel discharge records of the Huangpujiang River to detect this effect. Compared with the Changjiang River, the Huangpujiang River has a very small effect on the sea level recorded by the Wushong Tidal Gauge. (2) The river channel and banks of the Huangpujiang have historically undergone a strong modification, especially after the 1960's. (3) As a local base marker in East China and in the Changjiang
Figure 3. (a) The Wushong’s annual mean sea-level according to the published data, reflecting a remarkable drop after 1951. The black dots in the figure are the interpolated data mentioned in the paper; (b) when the contribution of the Changjiang River’s discharge to the sea-level is eliminated, this displacement becomes much more striking.

River basin, W.H.Z. has a closer relation with the Wushong Tidal Gauge. Nevertheless, the Wushong Tidal Gauge lacks records from 1937 to 1943 due to the Japanese invasion during World War II. In order to interpolate the 7-year records, the author first correlates the tidal records based on 14-year records (1930–36 and 1944–50) from the two gauges, then makes the interpolation by using the linear regression equation:

\[ y = 0.694 \times + 0.694 \]

\[ r^2 = 0.73 \]

The interpolated data from 1937 to 1943 are shown in black dots in Figure 3a.

When the annual mean sea level of the two tidal gauges from 1958 to 1987 are plotted (Figure 4), it is easy to recognize that the pattern of sea-level change is almost the same. The narrow data envelope in Figure 5 indicates that there is a good linear relation between the records of these two tidal gauges. Nevertheless, when the records from 1922 to 1987 are plotted (Figure 6), the dots from 1922 to 1951 are all located above a straight line indicated as “1922–51/1952–87 boundary line,” suggesting that the Wushong sea-levels are abnormally higher during 1922 to 1951 than during 1952 to 1987. This displacement is striking, with an amplitude of about 14 cm, coinciding with the one shown in Figure 3b.

Furthermore, the displacement is reflected in Figure 7. The vertical lines in the upper part of the figure indicate the differences of the annual mean high tide levels between the two gauges, while the vertical lines in the lower part indicate the differences of the annual mean low tide levels. The length changes reflected are both abrupt and remarkable between the two periods, showing that a displacement of water-surface slope occurred in the same year as that shown in Figure 3b. In contrast to Figure 6, when the tidal-range records of these two tidal gauges are also plotted in the same way, the dots corresponding to the two periods are all located in a narrow strip similar in pattern to Figure 5. Clearly, the time series of tidal-range records does not show any displacement because this parameter is independent of bench marker position.
Figure 4. Sea level changes from 1958 to 1987 recorded by the Wushong and the Huangpu Park Tidal Gauge.

Figure 5. Sea-level records of the Wushong plotted against that of the Huangpu Park from 1958 to 1987 show a strong linear relation.

\[ y = 0.283 + 0.829 \times \]
\[ r^2 = 0.714 \]
Now consider the displacement based on other evidence. As mentioned earlier, there is a significant linear relation between the Wushong's annual mean sea level and the Changjiang River's annual mean discharge. When they are plotted against each other the data from 1922 to 1951 are all located in the upper part of Figure 8, also indicating an abnormal high sea level during this period, as shown in Figure 3b.

From the above-mentioned mathematical correlation it is important to note that the displacement of the Wushong tidal record just appears in the year 1951 when for the first time the bench marker of the Wushong Tidal Gauge was adjusted and the tidal records calibrated due to the ground subsidence. If this adjustment and calibration were made in another year, 1948 or 1953 for example, the displacement would also occur in the corresponding year, which is easy to understand. This suggests that the true height of the Zero Marker of the Wushong Tidal Gauge in 1922 is lower than the value previously adopted, which results in the abnormal high sea-level from 1922 to 1951. The original cause may be attributed, at least in part, to the large error in geodetic levelling before 1922 and differential ground subsidence in different locations. "It seems impossible to evaluate the magnitude of error for lack of records. For example, it is unclear whether the Whangpoo Conservancy Board made an adjust-

Figure 6. Sea-level records of the Wushong plotted against that of the Huangpu Park, showing the dots corresponding to 1922–1951 all located above a boundary line due to the data displacement.
The amplitude of displacement in the Wushong tidal records between the two periods is determined according to the following aspects:

1. After eliminating the contribution of annual discharge of the Changjiang River, the data series itself shows a displacement about 14 cm (Figure 3b). When this displacement is corrected the transition from the former period to the latter shows a very natural behavior (Figure 9). Meanwhile, a regular 18-19 year cycle is obtained in the power spectrum estimate (Figure 10).

2. The mathematical correlations shown in Figures 6, 7 and 8 all confirm this amplitude of displacement.

Based on the above discussions, the RSL is found to show a rising trend of about 1.0 mm/year from 1922 to 1987. During the same period the rate of annual mean high-tide level rise is as great as 2.5 mm/year, reflecting the unique morphological and hydro-dynamical effect on the high-tide level as sea-level rises.

**ESTIMATE OF TECTONIC CONTRIBUTION TO RSL RISE**

Because the earth's crust under the Changjiang River delta has undergone a continuous downward tectonic movement since the late Cenozoic Period, the regional rate of crustal sinking can be estimated to find its contribution to RSL rise.
Tectonic structures in the Shanghai region are complicated because they are associated with a transitional zone of different geotectonic units. As a result of downward movement of the crust, the bedrock is covered by thick Quaternary deposits (150 to 400 m). The western and southwestern parts, however, contain a thin sedimentary veneer with exposures of small rocky hills such as the Sheshan Hill. A large number of deep-drillings reveal that the pre-Quaternary strata developed only in Sinian, Cambrian, late Ordovician, late Jurassic, Cretaceous and Tertiary Periods. These rocks may be divided into the following three types according to their dynamic origins and ages: (1) metamorphic rocks of middle to late Proterozoic Era; (2) sedimentary rocks of Palaeozoic Era, mainly consisting of clastic rocks and carbonates, and (3) Mesozoic to Tertiary volcanic rocks, fluvial-lacustrine rocks, and other red clastic rocks developed under a dry climate.

Faults developed in the bedrock trend northeast, northeast and near west-east directions. As far as the recent crustal movement is concerned, Shanghai as a whole is located on a relatively stable crust in China. From 1949 to 1981 earthquakes detected by precise instruments occurred 31 times. Of these quakes, all were less than 5.0 (Richter Scale) and most are less than 2.0 and located in the sea areas near the Changjiang River mouth. A large earthquake occurred in 1624; it was equivalent to 6.0 (Richter Scale) in intensity based on detailed historic records. Precise geodetic levelling between the Sheshan Hill and other hills adjacent to Shanghai suggests that vertical differential movement was only 2 to 3 mm from 1956 to 1973, with a rate about 0.12 to 0.18 mm/year (Table 1). Moreover, repeated levellings within the period indicate that the vertical movement is oscillating without any systematic trend.

In order to study the temporal and spatial behavior of land subsidence in Shanghai, 12 steel pipes were drilled to the buried rocky base from 1962 to 1974. These steel pipes vary from several tens of meters to three hundred meters in length. The repeated long-distance geodetic levelling from the Sheshan Base Marker to the rock-based steel pipes did not detect any systematic trend of vertical differential movement (SHANGHAI GEOLOGIC BUREAU, 1979).

Although controversy still exists worldwide about the process of sea-level change since the mid-Holocene, it is widely accepted in China that the position of the mid-Holocene sea-level is not significantly different from the present one. The difference is in the range of several meters or less. Provided that the rate of local crustal sinking is 1.0 mm/year, the cheniers developed 6300 yr BP in Shanghai (YANG AND CHEN, 1986) should now be buried 6.3 meters below the ground surface, not considering the contribution of sediment compaction above the rocky base. In fact the present position of chen-
Figure 9. Final results of the Wushong sea-level changes from 1922 to 1987 after correcting the displacement mentioned in the paper. (a) recorded annual mean sea level, (b) annual mean sea level after eliminating the Changjiang's contribution and (c) annual mean high tidal level.

CONCLUSION AND DISCUSSION

Sea-level changes since the early 1950's and 1920's both show a rising trend in the Changjiang River mouth after eliminating the component of ground subsidence in the tidal gauge records. The following three different rates since 1952 have been obtained: (1) 2.3 mm/year from 1952 to 1987, (2) 2.7 mm/year from 1952 to 1984 and, (3) 3.1 mm/year from 1952 to 1984 after eliminating the contribution of the annual river discharge to sea-level change. The rate of annual mean high-tide level rise since the early 1920's is 2.5 mm/year. This rate is remarkably greater than mean sea-level rise (1.0 mm/year) during the same period, reflecting the morphological and hydrodynamical effect of sea-level rise. The component of crustal sinking is significantly less than the rates of RSL rise mentioned above, possibly within the range of about 0.1 to 0.3 mm/year. After correcting the dis-
Sea-Level Changes at Shanghai, China

Figure 10. A power spectrum estimate in the Wushong's annual mean high tidal levels. The data before 1952 have been reduced by $-14\,\text{cm}$ in order to eliminate the displacement.

Table 1. Results of geodetic levelling between the Sheshan Base Marker and the ones in other hills adjacent to Shanghai. (After the Shanghai Geologic Bureau, 1979):

<table>
<thead>
<tr>
<th>Base marker</th>
<th>Altitude above W.H.Z. 1956 (m)</th>
<th>Altitude above W.H.Z. 1973 (m)</th>
<th>Difference (mm) between 1973 and 1956</th>
<th>Annual mean rate (mm/year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sheshan</td>
<td>46.0647</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rock 2</td>
<td>17.897</td>
<td>17.900</td>
<td>+3</td>
<td>0.18</td>
</tr>
<tr>
<td>Rock 4</td>
<td>20.170</td>
<td>20.172</td>
<td>+2</td>
<td>0.12</td>
</tr>
<tr>
<td>Rock 8</td>
<td>7.454</td>
<td>7.457</td>
<td>+3</td>
<td>0.18</td>
</tr>
</tbody>
</table>

Based on the tidal records from 1950 to 1970 (Figure 3a), Wang (1986) stated that “the Wushong mean sea-level has declined since 1950 and is now continually declining, which means that the earth crust below the Wushong, Shanghai has uplifted since 1950.” Furthermore, he suggests that “before 1950 the crust had sunk downwards.” Apparently, in his study many aspects associated with sea-level change and crustal movement were neglected.

The low-lying area of Shanghai is highly vulnerable to sea-level rise due to its unique geographical setting. The future rise of global sea level, on which the local ground subsidence is superimposed, will give rise to strong natural and societal impacts. Studies of sea-level changes since the last deglaciation indicate that sea-level rise in the Yellow Sea and the East China Sea was mainly completed by several major jumps (Yang, Chen and Xie, 1987) with a rate much greater than generally expected. This observation is important to determinations of human response to sea level change in the coming decades.
ACKNOWLEDGEMENTS

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LITERATURE CITED


RESUME

Les variations du niveau de la mer à l'embouchure du Changjiang depuis les années 1920 sont présentées en soulignant le rôle des mouvements tectoniques récents, de la subsidence et du débit solide du fleuve. Une corrélation mathématique avec les études historiques a été faite en vue de considérer l'implantation et les changements des échelles de marée avec comme marqueurs, les bancs qui leur sont associés. Elle devait permettre d'établir la fiabilité des enregistrements de marée. Dans le passé, certains scientifiques chinois ont pensé que le niveau de la mer avait baissé depuis 1950, alors que les scientifiques étrangers attribuaient la montée du niveau de la mer dans l'est de la Mer de Chine à un effondrement isostatique de la croute. Ici, on peut conclure que le niveau de la mer s'élève d'environ 1mm par an, ce qui est comparable à l'élévation globale du niveau de la mer. Dans le même temps, on a trouvé que l'élévation du niveau moyen des pluies mers est remarquablement plus importante, cela reflète l'effet de la morphologie de l'estuaire et de l'hydrodynamisme sur la montée du niveau marin. Ceci suggère donc que la composante effondrement tectonique n'entre que pour 1/2 ou même moins dans la montée relative du niveau de la mer. L'auteur ne pense pas qu'il y a eu baisse du niveau marin depuis 1950, mais qu'il y a une tendance à la montée de 1951 à 1987, laquelle est la continuation de l'élévation du niveau marin enregistrée depuis le début du siècle.—Catherine Bousquet-Bressolier, Géomorphologie EPHE, Montrouge, France.

RESUMEN

El artículo presenta un estudio profundo de las variaciones del nivel del mar en la desembocadura del río Changjiang desde el comienzo de los años veinte, con especial enfasis en los movimientos tectónicos locales, subsidencia del terreno y descarga del río. Se ha realizado estudios históricos y correlaciones matemáticas para examinar el establecimiento y los cambios históricos de los sensores de marea y los puntos de referencia con que están relacionados, así como verificar la bondad de los registros obtenidos.
En el pasado, algunos científicos chinos propusieron que el nivel del mar había descendido desde 1950, mientras otros científicos extranjeros atribuían este incremento de nivel de mar en el Este del Mar de La China al hundimiento isostático del terreno. En el presente estudio, el autor concluye que el nivel del mar está ascendiendo a un ritmo de 1.0 mm anual, lo que es comparable al ascenso del nivel del mar en el resto del planeta. Asimismo, se ha descubierto que el incremento del nivel medio anual de marea alta es remarcadamente mayor que el anterior, reflejando el efecto morfológico e hidrodinámico del estuario en el incremento del nivel del mar. Las evidencias sugieren que la componente de hundimiento tectónico solamente influye en una tercera parte o menos en el incremento relativo del nivel del mar. En contraste con la opinión de nivel de mar descendiendo desde 1950, el autor concluye que el nivel del mar ha mostrado una tendencia creciente desde 1951 hasta 1987, que es continuación del ascenso del nivel del mar desde comienzos de siglo.—Department of Water Sciences, University of Cantabria, Santander, Spain.

ZUSAMMENFASSUNG