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Sea level rise and its impact on storm surge and tide in Shanghai

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सार — शंघाई क्षेत्र में सात केन्द्रों के ऐतिहासिक ज्वार-भाटा गेज और भू-अवतलन के रिकॉडो के आधार पर माध्य वार्षिक यूस्टेटिक समुद्र तल (ई. एस. एल.) के परिवर्तन के साथ मेल खाता हुआ अरेखिक सांख्यिकी मॉडल का विकास किया गया है । मॉडल बहिर्वेशन द्वारा, शंघाई क्षेत्र में पिछली शताब्दी में ई. एस. एल. के लक्षणों को प्रदर्शित करने तथा आगामी पाँच शताब्दियों में माध्यवार्षिक सापेक्ष समुद्रतल (आर. एस. एल.) का आकलन किया गया । समुद्रतल की ऊँचाइयों के आकलित मान काफी हद तक तर्कसंगत पाए गए ।

शंघाई क्षेत्र में, आगामी शताब्दियों में, तूफान महोर्मि और ज्वारभाटों पर आकलित समुद्रतल उत्थान के प्रभाव का, द्वि-अक्षीय अरेखिक तूफान महोर्मि एवं ज्वार-भाटा गतिक मॉडलों द्वारा परिकलन किया गया ।

साथ ही, उसी गतिक मॉडल की मदद से संख्यात्मक समाकलन के आधार पर, आगामी शताब्दियों में आर. एस. एल. से प्राप्त होने वाले संभावित अधिकतम जलतलों का आकलन भी किया गया है । इसके लिए उष्णकटिबंधीय चक्रवात के पथ, तीव्रता, तट से टकराने का स्थान, अनुषंगिक कोण और वसंत ज्वार भाटे का प्रयोग किया गया ।

ABSTRACT. Based on both the historical tidal gauge and ground subsidence records for the seven stations in Shanghai region, a nonlinear statistical model fitting the variation of the mean annual eustatic sea level (ESL) is established to reveal the characteristics of the ESL in the past century and to estimate the mean annual relative sea level (RSL) in the next five decades by the model extrapolation for Shanghai region. The estimated values of the sea level rises are assessed to be fairly reasonable.

The impact of the estimated sea level rise in the coming decades on the storm surges and tides in Shanghai region is numerically computed by using the two-dimensional nonlinear storm surge and tide dynamic models.

In addition, on the basis of numerical integration of the same dynamic model, the probable maximum water levels resulting from the RSL in the coming decades are also estimated by the probable optimal combination of the track, intensity, landfall site, incident angle of tropical cyclone and spring tide.

Key words — Sea level rise, Step-wise regression, Long-term prediction, Impact, Tide, Storm surge, Probable maximum water level.

1. Introduction

The sea level, the shortened scientific term for the mean sea level in oceanography, can be divided into two categories, *i.e.*, the eustatic sea level (ESL) and relative sea level (RSL). Changes in ESL result from rising/subsidence of the sea level and therefore may be divided into the global one and the local one. Global changes in ESL originate from those in the global sea water content and the basin volume due to the thermal expansion of sea water and the melting

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of ice/snow. Local changes in ESL result from the factors, such as the differential thermal expansion of sea water and the varying direct run off etc. RSL at a site is the sum of ESL at the same site and the local ground subsidence.

Great attention has been paid on the study of the sea level rise and its impact. It has been verified by the analysis on the data extracted from the world-wide tidal stations that the rise in sea level in the last century may mainly be attributed to the global warming.

Considering many complex indeterminable factors in the mean ESL estimations, it was reported by IPCC in 1992 that the global ESL would rise by 8-29, 21-71 and 31-110 cm by the years 2030, 2050 and 2070 respectively. Again it was reported that the optimal estimation of the sea level rise would be 14 cm in 2030 and 22cm in 2050. However, IPCC's latest report (1995) gave a slight reduction of rise in the ESL estimates.

There are more than ten years of the systematic studies on the behaviour of the sea level in China. Most Chinese oceanographers dealt with RSL variation in China's coastal water.

The trend of mean RSL variation and its impact on storm surge and tide were generally estimated on a less than decade time scale by rather simple linear statistical models (Zuo *et al*. 1995, Huang 1991). Ren (1993) made a more or less subjective estimation of the RSL for Shanghai to be 30-40 cm by the year 2030. Also, rather simple methods based on the linear superimposition of storm surge and tide have been used in estimating the possible effects of the sea level rise on the storm surges in the Pearl River Delta and Tianjin area (Ho 1994, Peng and Yang 1994). Such estimations have lesser degree of accuracy in shallow waters as the nonlinear interaction between storm surge and tide is quite pronounced over there.

Shanghai, the biggest financial, economical and industrial city of China is situated at the middle section of the east coast of the east Asian Continent (31° 12′N, 121° 26′E) and to the east of the Yangtze Delta, facing the East China Sea. The nature of RSL changes in the past and its impact on storm surge and tide in the coming years in Shanghai is of vital importance.

In this paper, an analysis of the observed historical tide time series with ground subsidence calibration at Wusong (1912-93) and other six specified tidal gauge stations at urban and rural areas of Shanghai have been made in order to get an insight into the temporal change of the mean ESL in Shanghai region. A nonlinear statistical model fitting the variation of the mean annual ESL (MAESL) is set up to estimate the MAESL rises in the years 2010, 2030 and 2050 by extrapolation. The MARSL in 2010, 2030 and 2050 for Shanghai region is derived by algebraic summation of both the MAESL and total ground subsidence estimation.

Based on the MAESL rise and ground subsidence estimations in 2010, 2030 and 2050, an improvement is made, by using numerical integration of the nonlinear 2-D hydrodynamic model, in estimating the effects of the MARSL rises over the next fifty years on storm surges and tides in Shanghai region. To meet the needs of city planning and coastal ocean engineering design, the probable maximum water levels (PMWL) in the next fifty years for Shanghai region are also numerically computed.

2. Estimation of sea level rise at Wusong

2.1. *Data Processing*

The long-time series (1949-93) of the mean annual tidal level observations with ground subsidence calibration at Wusong, which is located close to the intersection of the Huangpu River and Yangtze River, are used to represent the MAESL series of the main tidal station in Shanghai. However, there are longer time series (1912-36, 1945-93) of the mean annual half tidal level observations at Wusong than those of the mean annual tidal observations. Therefore, the time series of the mean annual tidal observations has been extended to 74 years by extrapolation using the linear correlation formula $y = 29.1 + 0.849x$ between them with the correlation coefficient 0.96. The half tidal observations for the gap period 1937-44 at Wusong are filled up by interpolation using those at Huangpu Park. In addition, the systematic errors for Wusong due to certain subjective factors before 1951 have been calibrated (Ren 1993).

The tidal observations before 1951 are less accurate due to the changes in water gauge level base and the errors arising from the calibration of the ground subsidence. Therefore, a sample of the longer mean annual tide time series from 1912 to 1993 has been employed to study the characteristic change of the MAESL in the past decades and to estimate the MAESL in the next fifty years at Wusong. There are varying records of the local tidal data for other six stations of which four stations, *i.e.*, Huangpu Park, Gaoqiao, Mishedu and Zhagong are located on either side of the bank of the Huangpu River and two stations, *i.e.* Jinshan and Luchaogang are on the north bank of the Hangzhou Bay. Most of these have records of only last ten years or more. This creates difficulty in studying the long-term temporal variation of the MAESL at these stations with such short sample. However, the records may be extended by using good correlation between the MAESL at Wusong and any of these six stations.

2.2. *Time series model*

The variation of the MAESL at any tidal gauge station may be characterized by following time-dependent function:

$$Y(t) = T(t) + P(t) + N(t) \tag{1}$$

where $Y(t)$ denotes the observed MAESL with sufficient accuracy having more than 10 years of prognostic period of validity. $T(t)$ is the trend variation term, $P(t)$ the periodic variation component and $N(t)$ the random noise.

Eqn. (1) can be considered as a prognostic equation for the MAESL if the expressions for three components on the right hand side of Eqn. (1) can be found out with great accuracy. In general, owing to the error accumulation, the random noise term has little importance and can safely be ignored when the long-term extrapolation is carried out. Therefore, only two terms, $T(t)$ and $P(t)$ in Eqn. (1) are to be determined. Two computational schemes are used to determine $T(t)$ and $P(t)$ in terms of the tidal observations and the differences in the computational results from these two schemes are compared with each other.

(a) *Computational Scheme I*

The MAESL series can be considered as a quasi-stationary series with determinable trend variation.

To determine the trend variation term $T(t)$, a nonlinear regression model comprising ten sorts of functions is chosen to fit the MAESL observations at Wusong by the step-wise regression analysis, which is quite different from the linear temporal variation form prescribed in most of the work. The model is,

$$y_t = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + a_4 t^4 + a_5 t^{-1} + a_6 t^{-2} + a_7 t^{1/2} + a_8 t^{-1/2} + a_9 e^{-t} + a_{10} \ln t + \varepsilon, \tag{2}$$

where, a_i ($i = 1, 2, ..$) denotes the coefficients to be determined, ε is the residual.

It is worth noting that the MAESL series should be processed to filter out the relevant oscillations with 19 years' running mean.

The period analysis is performed to the MAESL residual time series by subtracting the trend variation component $T(t)$ from the raw MAESL time serieş $Y(t)$. The residual one can be considered as a set of stationary time series with certain periods which enable us to verify its periodicity by using the spectrum decomposition. Here, a combination of the power spectrum analysis with the maximum entropy spectrum analysis is used to seek its periods because the former can resolve the higher period components of the MAESL series while the latter can identity the lower period components of the MAESL series.

The low-pass filter should be manipulated to the raw MAESL series prior to the maximum entropy spectrum procedure so that the spectrum characteristics of the main periods are manifested on the lower frequency band. Subsequently, the harmonic analysis is employed to determine the coefficients preceding to the predominant periodic terms.

(b) *Computational Scheme II*

As pointed out by Zuo *et al.* (1995), the true trend variation of the MASEL series could be distorted by the eigen-periods involved in the series if the linear model $y = a + bt$ is used to determine the slope b of the MAESL. Therefore, to ensure that the computational results of the trend variation term are more reliable, it must eliminate the remarkable effects of the periods in the MAESL series in advance. Here, the initial model is set up incorporating both the components of the nonlinear trend variation and periodic variation at first and then the model coefficients can be determined by the least square procedure. It seems that the effects of the predominate periods have been eliminated in determining the trend variation in the MAESL series.

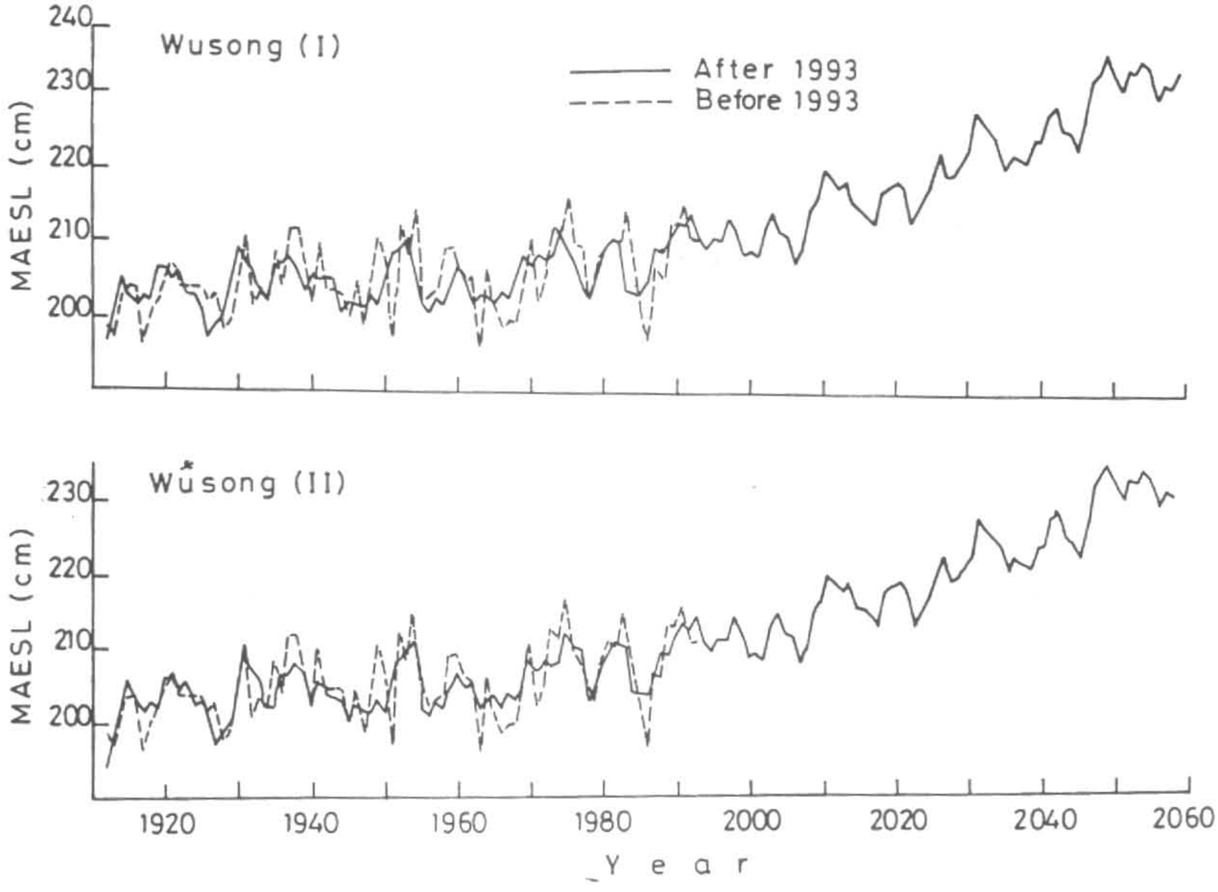

Fig. 1. Comparison of the fitting MAESL with the observed and predicted ones at Wusong during 1912-93. The sea level heights refer to those relative to Wusong's observed data (before 1993). The fitting MAESL is indicated by the dashed line. The observed (before 1993), fitting and predicted MAESL (after 1993) is indicated by continuous line

In fact, the accurate determination of the trend variation in the MAESL series requires the elimination of the actual periods from the series and the harmonic analysis requires a stationary MAESL series likewise. It also requires to eliminate the trend variation in the series. This complicated contradiction needs to be solved.

Fortunately, it seems that the initial time series is quasi- stationary with gently varying trends because the analyzed periods involved in the initial time series are roughly the same as those deduced from the scheme I. Therefore, both the periods and the first guess of the trend variation deduced from the scheme I can still be used in the determination of the prognostic model as follows :

$$\hat{y}_t = \sum_{i=1}^{m} Cf_i(t) + \sum_{k=1}^{n}\left(a_k \cos\frac{2\pi}{T_k}t + b_k \sin\frac{2\pi}{T_k}t\right) \quad (3)$$

where the coefficients a_i ($i = 1, 2, ... m$) and b_j ($j = 1, 2, ... n$) may be determined by using the linear least square procedure.

2.3. *Variation of the MAESL at Wusong in the past eighty years*

Fig. 1, indicating the true mean annual tide level observations with calibration of the ground subsidence in the last 82 years at Wusong, shows the diverse features of the MAESL rising in different periods. The MAESL at Wusong linearly rose at an average rate of 0.1 cm a year during 1912-1959 which is in accordance with the estimation of the global ESL in the last century. In addition, the linear average rate of rise in MAESL has rapidly increased to 0.2 cm per year since 1960's at Wusong, approximately twice in magnitude to that since 1910's. This implies that

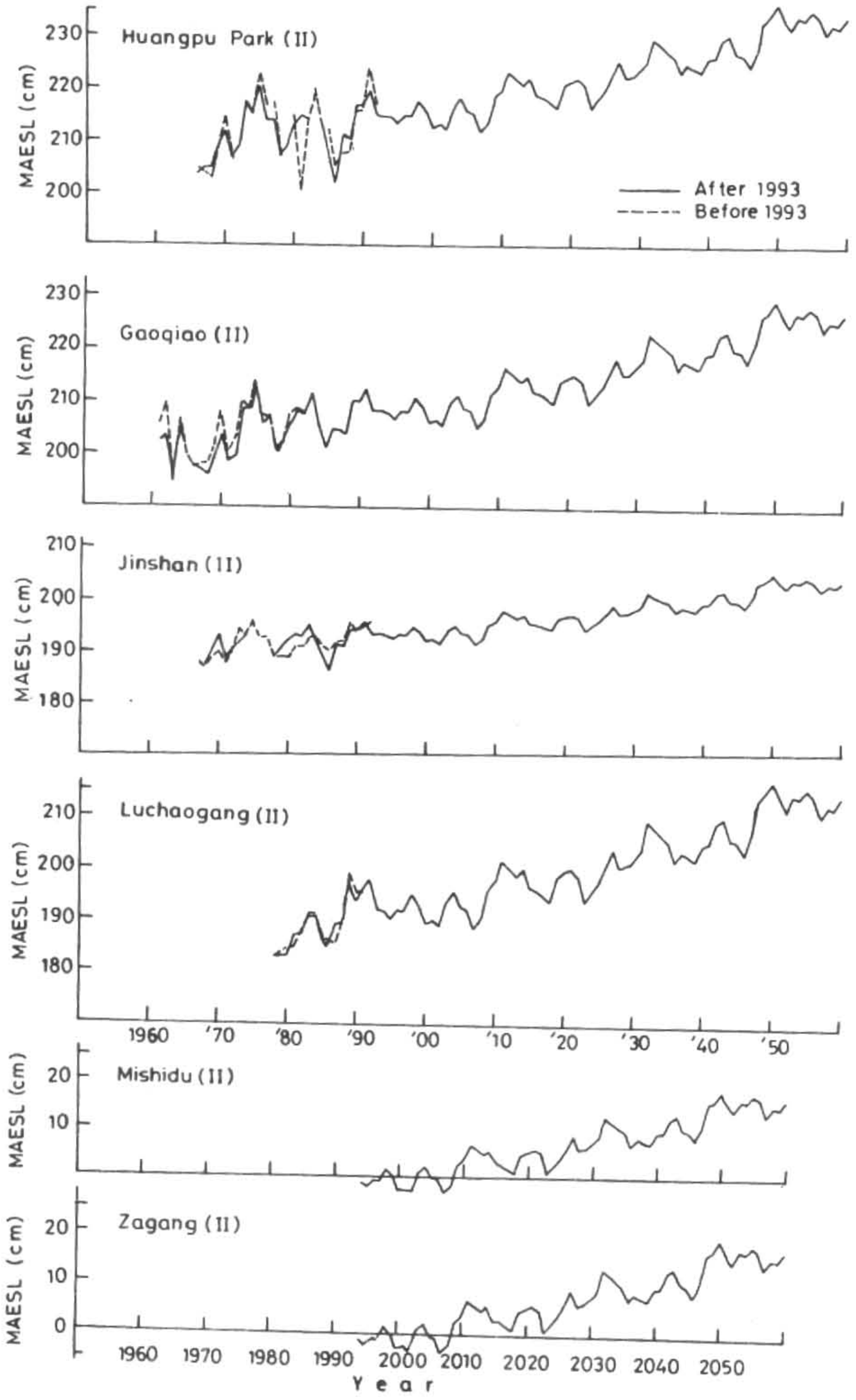

Fig. 2. Comparison of the fitting MAESL (from scheme II) with the observed ones (upto 1993) at six stations besides Wusong. Legend is the same as in Fig.1

the MAESL at Wusong tended to rise acceleratively. Consequently, the variation of the MAESL at Wusong depends on the tidal data sample period of validity. It relates to the prediction of the MAESL at Wusong in the coming years too by using Wusong's time-varying regularity of MAESL in the past.

It is shown by the maximum entropy spectrum analysis that there were five remarkable periods, *i.e.*, 19.0, 10.0, 7.4, 5.6 and 2.6 years, which qualify the F-test with confidence limit 0.05.

2.4. *Estimation of the sea level rise at Wusong in the next fifty years*

The prognostic model of the MAESL at Wusong calculated by both the schemes I and II may be expressed as follows :

$$\begin{aligned}\hat{y}_t = {} & 196.58 + 4.045 \ln t - 0.279\, t + 0.276 \times 10^{-2} t^2 \\ & + 2.15 \sin (2\pi t/19.0) - 0.64 \cos (2\pi t/19.0) \\ & - 0.22 \sin (2\pi t/10.0) + 1.77 \cos (2\pi t/10.0) \\ & - 0.12 \sin (2\pi t/7.4) - 1.95 \cos (2\pi t/7.4) \\ & + 0.55 \sin (2\pi t/5.6) - 1.62 \cos (2\pi t/5.6) \\ & + 1.20 \sin (2\pi t/2.6) + 0.34 \cos (2\pi t/2.6). \end{aligned} \tag{4a}$$

$$\begin{aligned}\hat{y}(t) = {} & 196.93 + 3.69 \ln t - 0.237 t + 0.24 \times 10^{-2} t^2 \\ & + 1.73 \sin (2\pi t/19.0) - 1.30 \cos (2\pi t/19.0) \\ & + 0.75 \sin (2\pi t/10.0) + 1.51 \cos (2\pi t/10.0) \\ & - 1.62 \sin (2\pi t/7.4) - 1.15 \cos (2\pi t/7.4) \\ & - 1.19 \sin (2\pi t/5.6) - 1.28 \cos (2\pi t/5.6) \\ & - 0.66 \sin (2\pi t/2.6) - 1.07 \cos (2\pi t/2.6). \end{aligned} \tag{4b}$$

The standard error fitting to the data series is calculated to be 4.6 and 3.7cm respectively.

In view of the efficiency in fitting the initial MAESL series, scheme II is superior to scheme I.

The MAESL prediction at Wusong may be achieved from the model Eqns. (4) and (5) by extrapolation if the prognostic period of validity is not too long.

The MAESL at Wusong tends to be wavy as shown in Fig. 1.

The computational results of the five point mean rise of MAESL in the years 2010, 2030 and 2050 from the two schemes are quite analogous. Only a slight difference in the rising MAESL in 2010, 2030 and 2050 can be obtained from both the schemes. This implies that the effect of the predominant periods of the MAESL time series upon the trend variation term is not strong because the sample of series used is considerably large.

In view of the research method, the scheme I is the usual one in which the periods can be sought from the "residual" time series by the spectrum analysis. This procedure could ensure the time series of the MAESL stationary. However, the trend variation term thus obtained preceding to the procedure must be distorted in a degree by the eigen-periods involved in the long initial time series. Such a kind of distortion can be eliminated from scheme II. However, the periods are designated by scheme I in advance and the prescribed function of the trend variation remains unaltered.

Based on the latest reports (Shanghai 1996 and 1997), the ground subsidence at Wusong due to the consolidation of the soft formation and sediments will be 12 cm in 2010, 20cm in 2030 and 25 cm in 2050 on average, whereas the regional crust vertically subsides 2cm in 2010, 4cm in 2030 and 6cm in 2050, respectively. Therefore, the sum of those two makes the total ground subsidence to be 14 cm in 2010, 24cm in 2030 and 31 cm in 2050, respectively which is larger in magnitude than the rises in MAESL.

2.5. *Estimation of the MARSL rise in Shanghai region in the next fifty years*

It is shown that on an average the MAESL at the seven tidal stations rose in the past (Figs. 1 & 2). Both the rises of MAESL and MARSL at the seven tidal stations in Shanghai region were different from one another because of the difference in their hydrological meteorological, geographical and geological conditions (Figs. 1 & 2). This implies that the regional comprehensive analysis of the sea level change at stations must be applied to get their approximate values for Shanghai region. For the purpose of simplification, the average of the sea level change has been taken at the seven stations.

TABLE 1

Estimation of the MAESL and MARSL (cm) in 2010, 2030 and 2050

Year	Predictional Item	Wusong	Gaoqiao	Huangpu Park	Jinshan	Luchaogang	Mishidu	Zagang	Average
2010	ESL Rise	5	5	4	2	3	4	4	4
	Crust Subsidence	2	2	2	2	2	2	2	2
	Ground Subsidence	12	17	7	8	8	8	8	10
	RSL Rise	19	24	13	12	13	14	14	16
2030	ESL Rise	11	10	10	6	10	9	10	9
	Crust Subsidence	4	4	4	4	4	4	4	4
	Ground Subsidence	20	27	10	12	12	12	12	15
	RSL Rise	35	41	24	22	26	25	26	28
2050	ESL Rise	21	20	19	11	20	17	18	18
	Crust Subsidence	6	6	6	6	6	6	6	6
	Ground Subsidence	25	30	12	15	15	15	13	18
	RSL Rise	52	56	37	32	41	38	37	42

As soon as the MARSL rise at Wusong is estimated in the next fifty years, the MARSL changes at other six stations may be obtained by using the computational method similar to that for Wusong. Adding the MAESL rise to the local subsidence at each station gives the corresponding MARSL rise and the average of the results gives estimation of the MARSL rise for Shanghai region. Consequently, the MAESL at the seven stations in Shanghai region will rise in the coming fifty years. The MAESL rise on average, with decadal rising rates of 2.0 mm /year of MAESL during 1991- 2010, 2.5 mm/year during 2011-2030 and 5.0mm/year during 2031-2050.

It is estimated that the MAESL for Shanghai will rise more than in 1990 by about 4, 9 and 18 cm in 2010, 2030 and 2050 respectively, whereas the MARSL will rise by 16, 28 and 42 cm in 2010, 2030 and 2050 respectively.

2.6. *Brief assessment of the predicted MAESL rise for Shanghai region*

To prove the feasibility of the MAESL prognostic method, several points should be mentioned in brief as follows :

(1) The data sample used is the longest one in the coastal area of China.

(2) A MAESL hindcast for the latter twenty years at Wusong has come into effect by the re-established prognostic model with leading 62-year time series. The fitting standard error (4.8 cm) is within the acceptable limit.

(3) Both computational schemes have their distinct priority and weakness. It seems reasonable that the averages of the MAESL deduced from two schemes are recommended as their prognostic values.

(4) The estimates of the MAESL rises in the coming decades for Shanghai region are consistent to some degree with those obtained by the international authorities concerned (IPCC 1992, 1995) and the Academician of the Department of Geoscience, Academic Sinica (1994). The estimated values are slightly smaller than the optimal estimate of global ESL rises issued by IPCC in 1992 and 1995.

The general rising trend of the global MAESL is most likely related to the greenhouse effect of the atmosphere because the concentration of gases inducing greenhouse effect has increased conspicuously since last century. The series of the mean annual air temperature (MAAT) exhibits a feature of wavy rise with an average increase of 0.5-0.6°C in the last century. It is readily shown that the decadal rising rate of the MAAT at Longhua station of Shanghai is 0.089°C in the past 121 years. Moreover, a relationship exists between the MAESL at Wusong and the MAAT at Longhua with the correlation coefficient of 0.44 which qualifies the F-test at a confidence limit of 0.05.

Using the method mentioned above, the trend variation of the MAAT at Longhua has been calculated. It follows that in 2030 and 2050 MAAT will rise by 0.7°C and 1.1°C respectively than in 1990. According to Dennes's (1987) conclusion that when the global mean annual air temperature goes up by 1.0°C, the global ESL would rise by 2.7 mm every year on average. The MAESL will rise upto 8 cm and 18 cm as compared to 1990 for Longhua.

3. Impact of sea level rise on storm surge and tide

3.1. *Models and methods*

Based on the above estimation of the future sea level rise in Shanghai, the nonlinear 2-D surge model along with the external atmospheric forcing expressed by the model typhoon air pressure and the associated model surface wind are used to estimate the impact of sea level rise on storm surge, whereas the nonlinear 2-D tide model, along with the travelling tidal waves comprising eight predominate constituents (M_2, S_2, N_2, K_2, Q_1, O_1, P_1 and K_1) from deep ocean, are applied to estimate the influence of the sea level rise on tide.

The dynamic models in differential form are descretized by using the semi-momentum finite difference with mesh size of 33 km and time step of 200s. The computational area covers main continental shelf of the East China Sea, Hangzhou Bay and the mouth of Yangtze River, *i.e.* 119° 48′ E-127°40′ E-27° 30′ N- 34°15′N.

The above models have been proved to be feasible in simulation and tentative prediction of storm surges and tides for Shanghai.

The rise in RSL results in an increase of the local water depth, which is characterized by large difference both in location and time. To simplify the problem and make the computation simple, the average of future rises in MAESL at five coastal and river mouth, *i.e.* Jinshan, Luchaogang, Wusong, Gaoqiao and Huangpu park stations are used which are 5, 11 and 20 cm in 2010, 2030 and 2050, respectively.

The total ground subsidence exhibits strong locality, so that its effect on the variation of water depth can only be considered locally and assumed to be restricted within twice the grid size.

The future total ground subsidence at the five stations estimated by the scientists in Shanghai are linearly interpolated to the neighbouring grids.

3.2. *Impact of future RSL rise on storm surge*

To test the effect of RSL rises on storm surges and tides, six tropical cyclones (TC) seriously threatening Shanghai region, TC5612, TC7413, TC9417, TC7910, TC8114 and TC8310, are selected for numerical experiments, in which the tracks of the former and latter three cases belong to the landing and offshore turning categories, respectively. Among them, three tropical cyclones (TC7910, TC8114, TC9417) met the spring tides by chance, while the other three TC5612, TC7413, TC8310 met with the ebbs. Therefore, the selected sample tropical cyclones are suitable for investigating the effect of rise in RSL on both storm surges and tides.

Using the estimated sea level rises in 2010 and 2030 relative to unaltered sea level in 1990, the storm surges induced by these six tropical cyclones are numerically tested and compared with one another. Several points need to be mentioned as follows :

(1) The rise in RSL would result in the decrease of local wind set-up (Fig. 3). The effect becomes strong (weak) when the wind-set intensifies (weakens), no matter what period is considered. The maxima for the effect and wind set-up occur simultaneously. The maximum effects of the sea level rises on the storm surges in 2010, 2030 and 2050 relative to 1990 would be –0.5, –2.5 and –5.0 cm respectively.

(2) The effect of the local sea level, rise is not the same in different storm surge processes. However, a little difference in the effects between them depends upon the track and intensify of the striking tropical cyclone. It is shown (Fig. 3) that the effect would be –0.5, –2.0 and –5.0 cm in 2010, 2030 and 2050 respectively. On the other hand, the effect of the local sea level rise on the storm surge is related to the intensity of the storm surge itself. For example, the maximum positive storm surge at the mouth of the Yangtze River was induced by the TC5612. The effect would be –0.5 cm in 2010, –3.0 cm in 2030 and –5.5cm in 2050 relative to 1990.

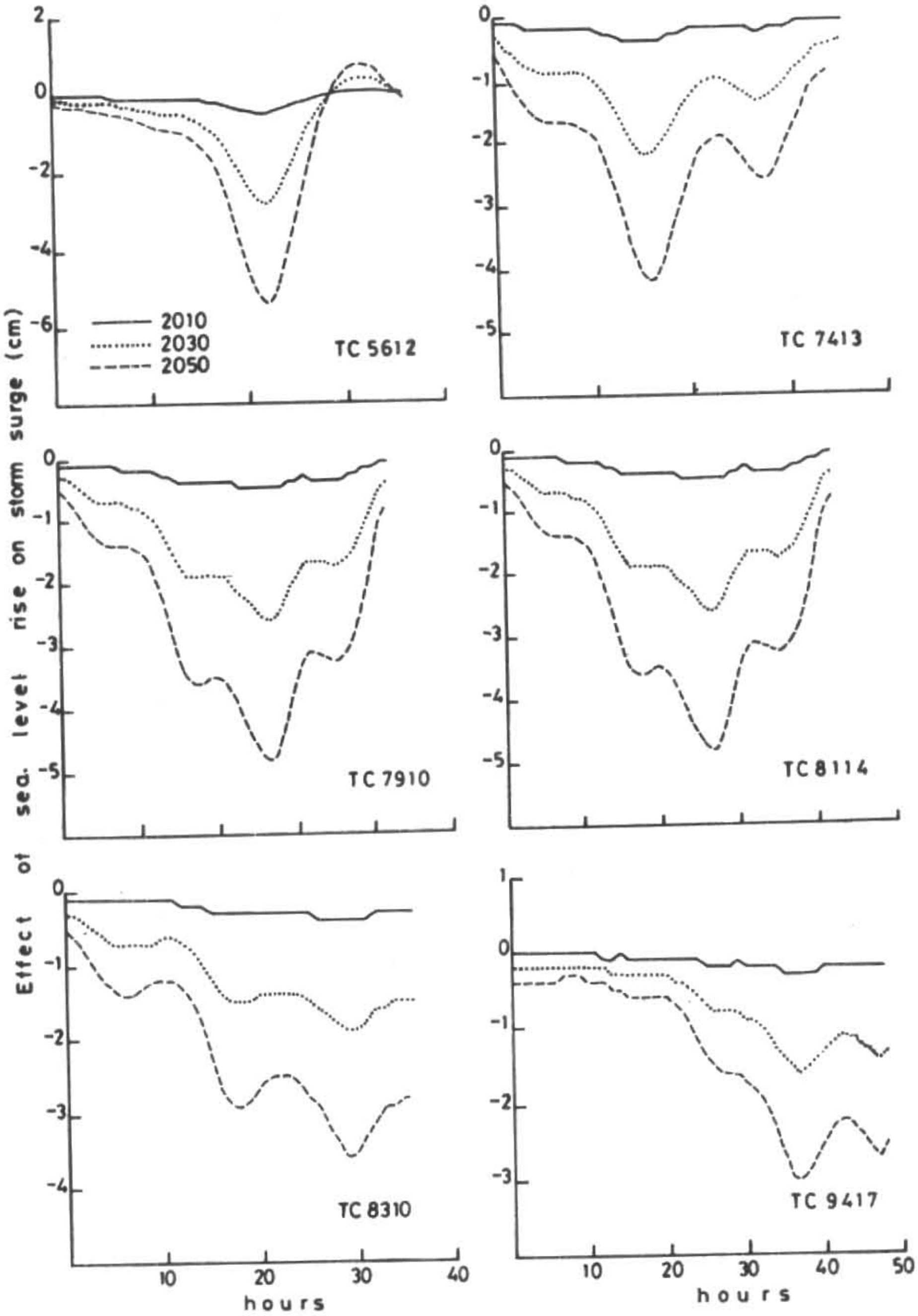

Fig. 3. The effect of sea level rise on the storm surge at Wusong

(3) Impacts on storm surges resulting from the local sea level rise are quite different from station to station. For instance, the maximum effect on storm surge induced by TC8114 at Wusong would be –4.8 cm and less than –2.0 cm both at Jinshan and Luchaogang in 2050 (Fig. 4).

In summary, the RSL rise makes the local water deeper than the initial one which leads to decrease of storm surge intensity. Undoubtedly it is physically reasonable. When a tropical cyclone and the associated forced longwave travel toward coast from the deep ocean, the wave height should increase because of decreasing water depth and corresponding concentration of energy. The reverse conclusion also holds true.

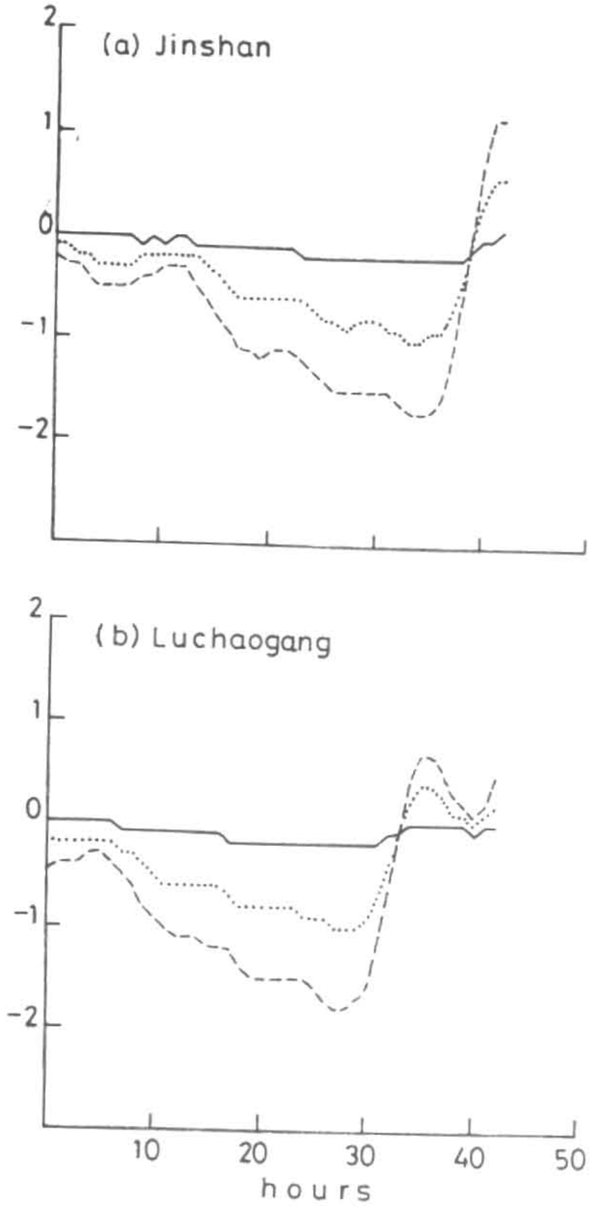

Fig.4. The effect of sea level rise on the storm surges at (a) Jinshan and (b) Luchaogang during the course of TC8114. Legend is same as in Fig. 3

As we are aware that the surface wind stress are often predominant external forcing over the air pressure force in the shallow water storm surges. Neglecting both the air pressure force and Coriolis force, one-dimensional quasi-steady, rectangular, semi-closed and uneven bottom model sea under the action of the uniform surface wind stress (τ_a) may be used to describe the contributions of the dynamical and geographical factors, such as the wind stress, water depth and scale of the sea to wind set-up. We get the slope of wind from the simple mathematical model,

$$\frac{d\zeta}{dx} = \frac{C\tau_a}{\rho\, g h(x)} \qquad (5)$$

Where the symbols have their usual meaning in physical oceanography except that $h(x)$ indicates water depth and C depends upon the turbulent viscosity structure of water and can roughly be considered as a constant for a prescribed storm.

It implies that the sea surface slope is directly proportional to surface wind stress exerted by the storm and therefore to the intensity of the storm and is inversely proportional to the water depth. In other words, the sea surface slope becomes steep (smooth) whenever either the storm intensifies (decays) or the water depth becomes shallow (deep).

Integration of Eqn. (5) gives the wind setup at the onshore coast if the linear slope of sea-bed is considered,

$$\zeta = \zeta_0 + \frac{C\tau_a L}{2\rho\, g h_0}\left(2 + \frac{\alpha L}{h_0}\right) \qquad (6)$$

Where ζ_0 indicates the deep water sea level height on the edge of continental shelf, L the length of model sea, h_0 the water depth on the bank. It is shown that both the scale and bottom slope of the sea have their positive contribution to the coast toward which the wind blows besides surface wind stress and the water depth. This is why the strong wind set on the onshore coast occurs in case of intensifying tropical cyclone, shallow water, small bottom slope and long fetch.

3.3. *Impact of future RSL rise on tide*

It is shown by six case numerical experiments that the effect of rises in RSL on tides exhibits periodic variation with the same period as that of the tide (Fig. 5). The effect increases with increasing rise in RSL and retains its period unaltered.

There is no effect of the RSL rise on tide at both high water and low water (Figures are not shown here). Its effect on tide is positive for the duration of rise of the tide below the mean sea level, whereas the negative effect occurs for the duration of fall of the tide. The reverse conclusions hold true in case it occurs above the mean sea level.

In addition, the impact of the RSL rise on tide depends on the tide itself and becomes intense when the spring tide happens and the amplitude of rising

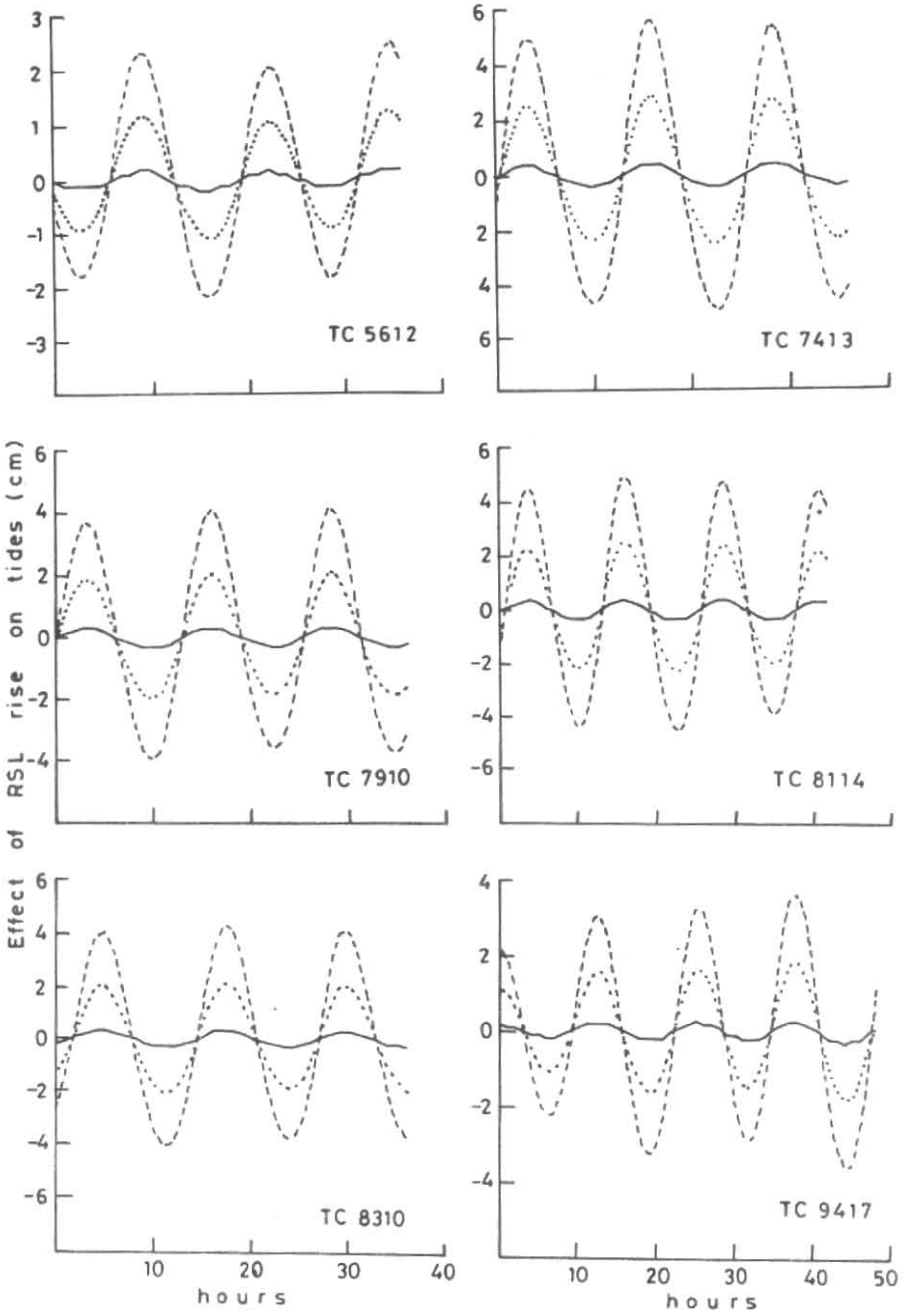

Fig. 5. The effect of sea level rise on tide at Wusong. Legend is same as in Figs. 3 & 4.

sea level increases. For examples, the effect on the amplitude of tide during course of TC5612 was less than that in TC8114, because the spring tide met with TC8114 by chance, whereas the ebb tide met with TC5612. During the course of TC8114, the effect of RSL rise on tide at Wusong would be around 0.5cm in 2010, 4cm in 2030 and 10 cm in 2050 relative to 1990.

3.4. *Estimation of probable maximum water level induced by RSL rise*

In estimating PMWL, the factors such as the tracks and intensities of tropical cyclones and the spring tides etc. must be taken into consideration.

In Shanghai, the TC8114 under the influence of spring tide moved offshore and resulted in the historical

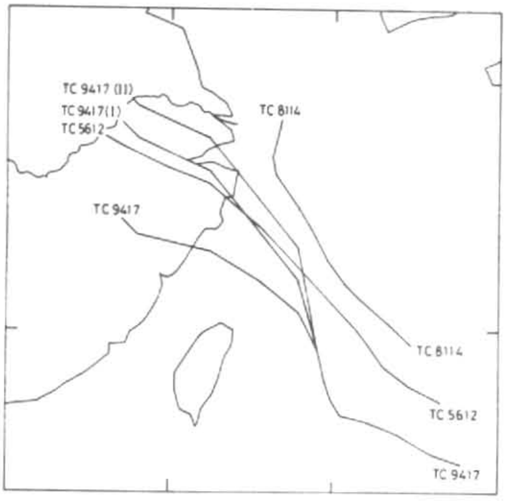

Fig.6. The hypothetical tracks of the three tropical cyclones designed for the computation of probable maximum water level

TABLE 2

Comparison of probable maximum water levels (cm) at Wusong resulting from the hypothetical tracks of three selected tropical cyclones

Year	1990	2010	2030	2050
Scheme 1	685	687	692	699
Scheme 2	709	712	717	724
Scheme 3	625	632	640	654
Scheme 4	668	674	683	696
Scheme 5	652	656	661	668
Scheme 6	609	612	617	624
Scheme 7	656	659	664	671
Scheme 8	669	672	677	684
Scheme 9	737	740	745	751

Scheme 1 - TC8114 moves one degree westward

Scheme 2 - TC8114 moves 1.5 degrees westward

Scheme 3 - Match TC 5612 with the spring tide during TC8114

Scheme 4 - TC 5612 moves 1.5 degrees northward and match it with the spring tide during TC8114

Scheme 5 - TC9417 moves three degrees northward

Scheme 6 - TC 9417 hits Shanghai with incident angle(I)

Scheme 7 - TC 9417 hits Shanghai with incident angle (II)

Scheme 8 - TC 9417 hits Shanghai with incident angle (II) and match it with the spring tide during TC 8114

Scheme 9 - TC 8114 moves 1.5 degrees and match it with the maximum intensity of the historic tropical cyclone

maximum water level (5.7 cm) at Wusong. It's track is favourable to the development of storm surge at the Yangtze River estuary.

TC5612, landfall on the coast of Zhejiang Province, to the north of Shanghai, resulted in the maximum storm surge at Wusong. Nevertheless, no higher water level occurred because the typhoon met with the ebb tide. It is assumed that matching TC5612 with the spring tide during TC8114 would possibly lead to a very high water level at Wusong.

TC9417 struck Wenzhou of the Zhejiang Province and caused maximum water level (7.35m) in its history. If TC9417 were artificially "forced" to move northward to Wusong, then maximum water level would have resulted.

The tracks of the above three typhoons may be hypothetically adjusted to the state which is more favourable to wind set-up. In case of matching the favourable track of typhoon with the spring tide, possible maximum intensity of the typhoon and RSL rise it would give the PMWL for Shanghai in the coming decades. According to experience there are three kinds of presumptions as follows :

(1) TC8114 is wholly adjusted to move longitudes 1.0 and 1.5 degrees westward respectively with its track unaltered (Fig. 6). Such tracks of typhoons will be the most dangerous ones to cause the storm surge at Shanghai region.

(2) TC5612 moves latitude 1 degree northward (Fig. 6) and land on Jinshan and then matches with the spring tide during TC8114.

(3) The track of TC9417 is adjusted to move latitude 3 degrees northward and strike Wusong at three different incident angles including facing Wusong (Fig. 6). The case in which the maximum water level at Wusong is numerically calculated is chosen to match the spring tide during TC8114.

It is shown by comparison of various hypothetical kinds of tracks for the three case tropical cyclones that the highest water level occurred at Wusong in the case of TC8114 with its track along longitude 1.5 degrees westward (Table 2). However, change in the intensity of TC8114 is not to be adjusted at all. In fact, the lowest pressure at the center of the tropical cyclone hitting Shanghai was recorded as 950 hPa, whereas the minimum central air pressure in TC8114 was 955 hPa. In order to get the PMWS at Wusong, an additional adjustment of the intensity of TC8114 seems to be necessary. Again, the above scheme with central pressure reducing by 5hPa every six hours for TC8114 is numerically computed. The PMWS at Wusong are obtained in 2010, 2030 and 2050 as 740, 745 and 751 cm respectively.

4. Concluding Remarks

The main results can be summarized as follows:

(*i*) The MAESL at Wusong tends to rise in a wavy manner. Its mean linear rising rate is 0.1 cm/year in the past 80 years with a conspicuous acceleration in recent 30 years. On the whole, the MAESL for Shanghai region rose acceleratingly in the background of the ESL rising in the East China Sea and Northwest Pacific Ocean(Qin *et al* 1997) since fifties of this century. It is estimated that the MAESL will still rise acceleratingly in the coming years by about 4, 9 and 18 cm compared to 1990 by the years 2010, 2030 and 2050 respectively. If the ground subsidence is taken into consideration, it can be easily obtained that the rise of RSL for Shanghai region is 16, 28 and 42 cm by the years 2010, 2030 and 2050 respectively.

(*ii*) In this paper, the prediction of the MAESL rise for Shanghai region is based on the regularity of sea level variation at Wusong in the past century. This implies that such a regularity will hold true for the future. However, we are aware that some factors, especially the man-made ones (*e.g.*, the great efforts made by the international community to control the gases inducing greenhouse effect) affecting the change in MAESL are hard to estimate. Therefore, the variation in MAESL in future may be different from the past one.

(*iii*) In view of a variety of indeterminable factors in the MARSL estimations, the reasonable values of the MARSL rising relative to 1990 for Shanghai region would roughly reach15-20 cm in 2010, 25-35 cm in 2030 and 40-50 cm in 2050.

(*iv*) It would be a better way to use stepwise regression with multi-variates in determining the MAESL trend variation form of function on the basis of tide observations than that to take a prescribed one, *e.g.* the linear function.

(*v*) There is no significant effect of the main periods on the determination of the sea level trend variation for the long data series. The impacts of MARSL rises in the coming decades on both the storm surges and tides for the main coastal tidal stations in Shanghai region are numerically computed in this paper by using 2-D nonlinear storm surge and tide models. Three intense tropical cyclones striking Shanghai and its neighbourhood are chosen for estimation of the probable maximum water levels in the background of the given MARSL rises in the coming decades. The MARSL rise tends to decrease the positive surge. Its effect on storm surges depends on the locations of the tidal stations and the tracks and intensities of the impinging tropical cyclones. The effect of MARSL rise on tide varies periodically with the same period as that of the tide. There is no effect of MARSL rise on tide at both high and low water. When the amplitude of rising sea level increases, the impact of the MARSL rise on tide becomes intense.

(*vi*) The impact of the future MAESL and ground subsidence on the tides and storm surges as well as the probable maximum water level are found on the prediction of the MAESL and ground subsidence.

(*vii*) The methods suggested for long-term prediction of MAESL and MARSL changes are reasonable and therefore the estimated MARSL rises in the coming decades are convincible except in 2050, since too long prediction period of validity by the model extrapolation is employed to ensure its reliability.

(*viii*) It is a quite complicated question to predict the sea level change. Generally speaking, longer the period of validity for the prediction, lesser the certainty of prediction. To reduce such uncertainty the perfect model needs to be developed by using a large and renewable sample of the related data.

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