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The Impacts of Wind and Air Pressure on Fluctuations of the Mean Bohai Sea Level

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ABSTRACT

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A numerical ocean model is employed to simulate mean sea level along coast of the Bohai sea for quantitative analysis on the contribution of wind and pressure to coastal mean sea level variations. It's shown that numerical results represent well the temporal and spatial character of mean sea level along coast of the Bohai Sea, and can be used to analyze mean sea level abnormity events. It's found that seasonal mean sea level variation caused by wind and air pressure accounts for about 70% of the variation of mean sea level. The three abnormal events of mean sea level occurred in Nov., 1988, Oct., 2006, and Feb., 2010 respectively indicate that sea surface air pressure and wind variation caused a wind-driven current. Consequently, water transportation is of great importance for the seasonal variations of mean sea level.

ADDITIONAL INDEX WORDS: *Bohai Sea, mean sea level fluctuations, numerical modelling, wind and air pressure.*

INTRODUCTION

Sea water expansion, melting of polar ice shelves and continental glacier caused by global warming are the main factors for global sea level rising. The distribution of global sea level rise indicates that there are obvious regional characteristics. The sea level rises in the western Pacific, eastern Indian Ocean and Atlantic, while it goes down in the eastern Pacific and western Indian Ocean (IPCC *et al.*, 2007). Fukumori *et al.* (1998) and Vivier *et al.* (1999) show that the large-scale and high-frequency sea level variability is mainly wind-driven and that the ocean adjusts via propagating barotropic Rossby waves. Other studies reported evidence of large-scale response of the ocean to wind forcing as barotropic Rossby waves (Brink, 1989; Luther *et al.*, 1990; Niiler *et al.*, 1993; Samelson, 1990).

China Sea locates in the region where the rate of sea level rise is higher. In addition of the variation of global sea level, the variation of regional sea level is also affected by the hydrological and meteorological factors such as air temperature, sea surface temperature (SST), currents, wind, atmospheric pressure and precipitation etc. (Yan *et al.*, 2008; Zhang *et al.*, 2009; Zheng *et al.*, 1999). Generally speaking, if air temperature and SST rise and atmospheric pressure reduces then the sea level would rise. The anomaly of a middle or shorter term of mean sea level is caused by non-astronomical factors such as atmospheric pressure, wind, precipitation, runoff and so on (Gu *et al.*, 2009; Wang *et al.*, 2012a, 2012b).

The Bohai Sea is a semi-closed shallow sea with a mean depth of around 18 m, composed of the Liaodong Bay, the Bohai Bay, the Laizhou Bay and the Bohai Basin, and connected to the North Yellow Sea through a latitudinal strait.

The consistent viewpoint is that the sea level variation of China Sea has a close relationship with atmospheric pressure and wind, whereas, the results of predecessors were focused on the qualitative analysis without quantitative model. In this paper sea level (driven by wind and atmospheric pressure) in the Bohai Sea was simulated using wind and atmospheric pressure data which was offered by ERA-Interim (Dee *et al.*, 2011) of European Centre for Medium-Range Weather Forecasts (ECMWF). Data of the ocean observing stations of China was also applied to do quantitative analysis about the effect of sea surface atmospheric pressure and wind on sea level variation in the coastal region of the Bohai Sea.

MODEL AND DATA

Estuarine Coastal Ocean Model (ECOM) (Blumberg *et al.*,

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1983) was adopted to build the sea level numerical model in the Bohai Sea. The model applied rectangular grid, and the model domain is 117°E –123°E, 36.5°N–41.5°N, the horizontal grid resolution of the model is 5 ′×5 ′. The water depths of the model were interpolated data from ETOPO5 (Figure 1). The model was forced by 1/8° horizontal resolution and 3–hourly interval atmospheric pressure and wind which are the product of ERA-Interim (*http://apps.ecmwf.int/datasets/data/interim-full-daily*). The boundary condition is derived from water level of the bigger zone model covers northwest Pacific Ocean which is also only forced by wind and air pressure of ERA-Interim. The Bohai Sea is shallow which makes the barotropic effect more important and a 2–D numerical simulation was applied to study the sea level variation. The model is purely two-dimensional adopted a zero initial condition and ran for the time period of 1st. Jan., 1979 to 31th Dec., 2012. Then hourly water level and vertical mean currents were produced and monthly mean sea level and current were calculated basing on the hourly result. The monthly mean sea level data of six observation stations along the coast of the Bohai sea were used to do the verification. Observation data covers from 1980 to 2012 with quality controlled and calibration. All the sea level value is based on the datum of mean sea level of 1980 to 1998.

The quality of wind and air pressure of ERA-Interim was checked by coastal station observation. Because of different time interval, which the ERA-Interim is of 3hr interval but the observed data is of 6hr interval, monthly mean result of ERA-Interim and observed data are compared to test the quality. Root-Mean-Square Error (RMSE) is calculated as shown in Table 1, which shows that the average RMSE of monthly mean air pressure is 0.46 hPa ranging from 0.30 hPa to 0.74 hPa, the RMSE of monthly mean of wind velocity is 0.67 ms^{-1} ranging from 0.60 ms^{-1} to 0.86 ms^{-1} with a fractional error ranging from 8% to 25%, the RMSE of monthly mean of wind U–component is 0.67 ms^{-1} ranging from 0.61 ms^{-1} to 1.02 ms^{-1} with a fractional error ranging from 9% to 28%, the RMSE of monthly mean of wind V-component is 0.68 ms^{-1} ranging from 0.49 ms^{-1} to 0.84 ms^{-1} with a fractional error ranging from 1% to 24%. The result illustrates high agreement between the reanalysis data and the observation, which means the ERA-Interim data is reliable for the sea level numerical simulation.

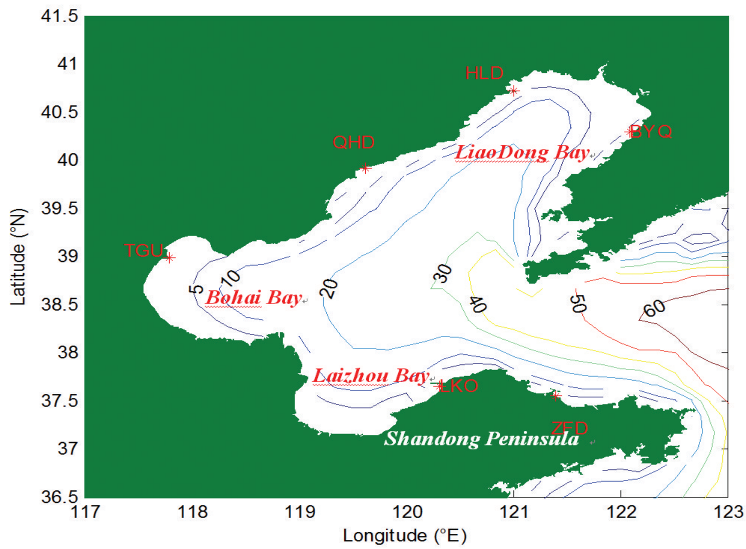


Figure 1. Study area and depth distribution

Table 1. *Comparison of ERA-Interim and observed data of station along coast of the Bohai Sea*

station	RMSE of monthly mean of air pressure /hPa	RMSE of monthly mean of 10m–wind					
		Velocity /ms^{-1}	Fractional Error	U /ms^{-1}	Fractional Error	V /ms^{-1}	Fractional Error
BYQ (BaYuQuan)	0.30	0.65	8%	0.63	11%	0.84	18%
HLD (HuLuDao)	0.36	0.62	18%	0.43	12%	0.65	21%
QHD (QinHuangDao)	0.53	0.66	25%	0.64	28%	0.72	24%
TGU (TangGu)	0.74	0.61	18%	0.61	9%	0.49	23%
LKO (LongKou)	0.35	0.86	23%	1.02	24%	0.81	20%
ZFD (ZhiFuDao)	0.46	0.60	10%	0.71	25%	0.58	1%
average	0.46	0.67	17%	0.67	18%	0.68	18%

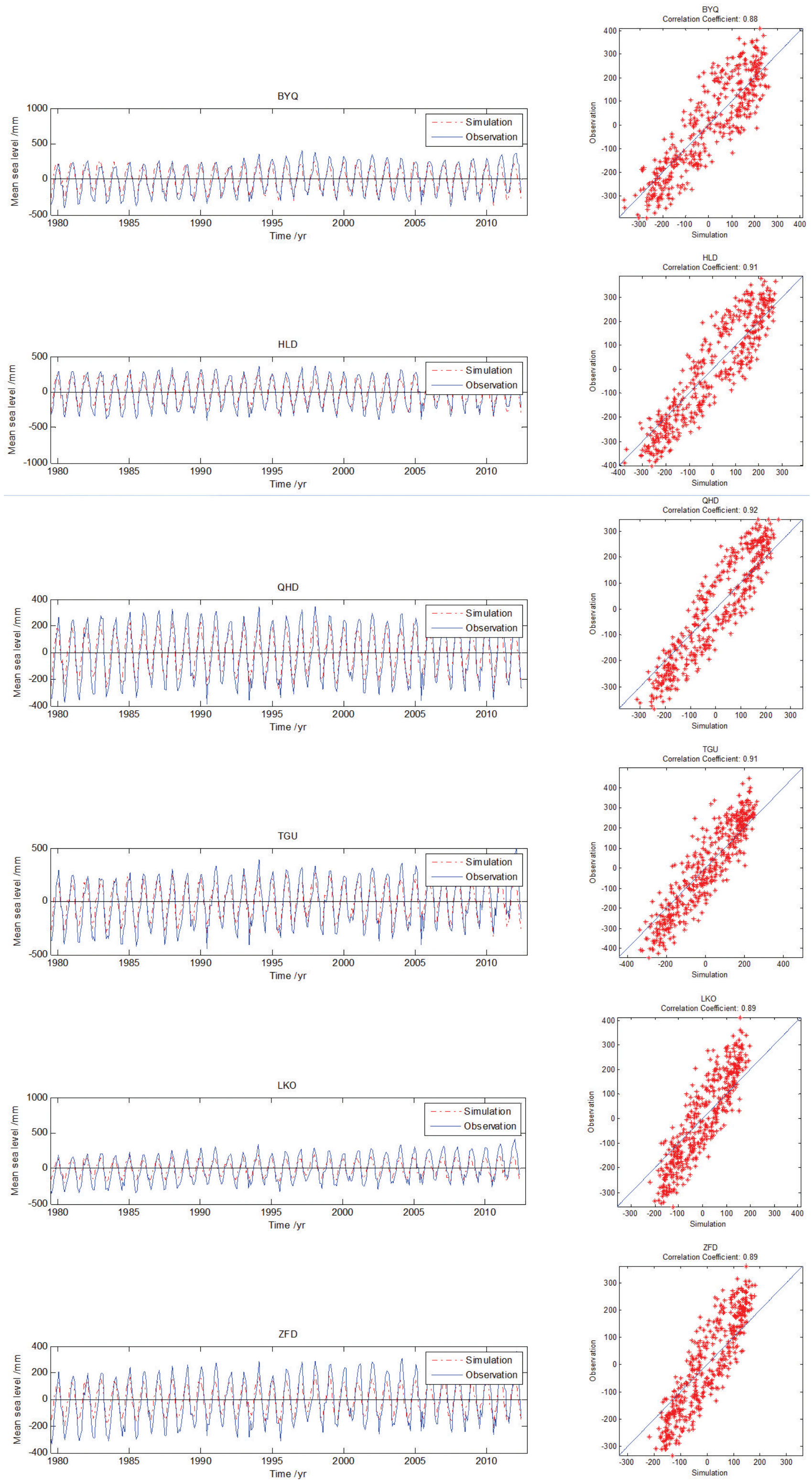


Figure 2. Comparison of monthly mean sea level between simulation and observation of station along coast of the Bohai Sea

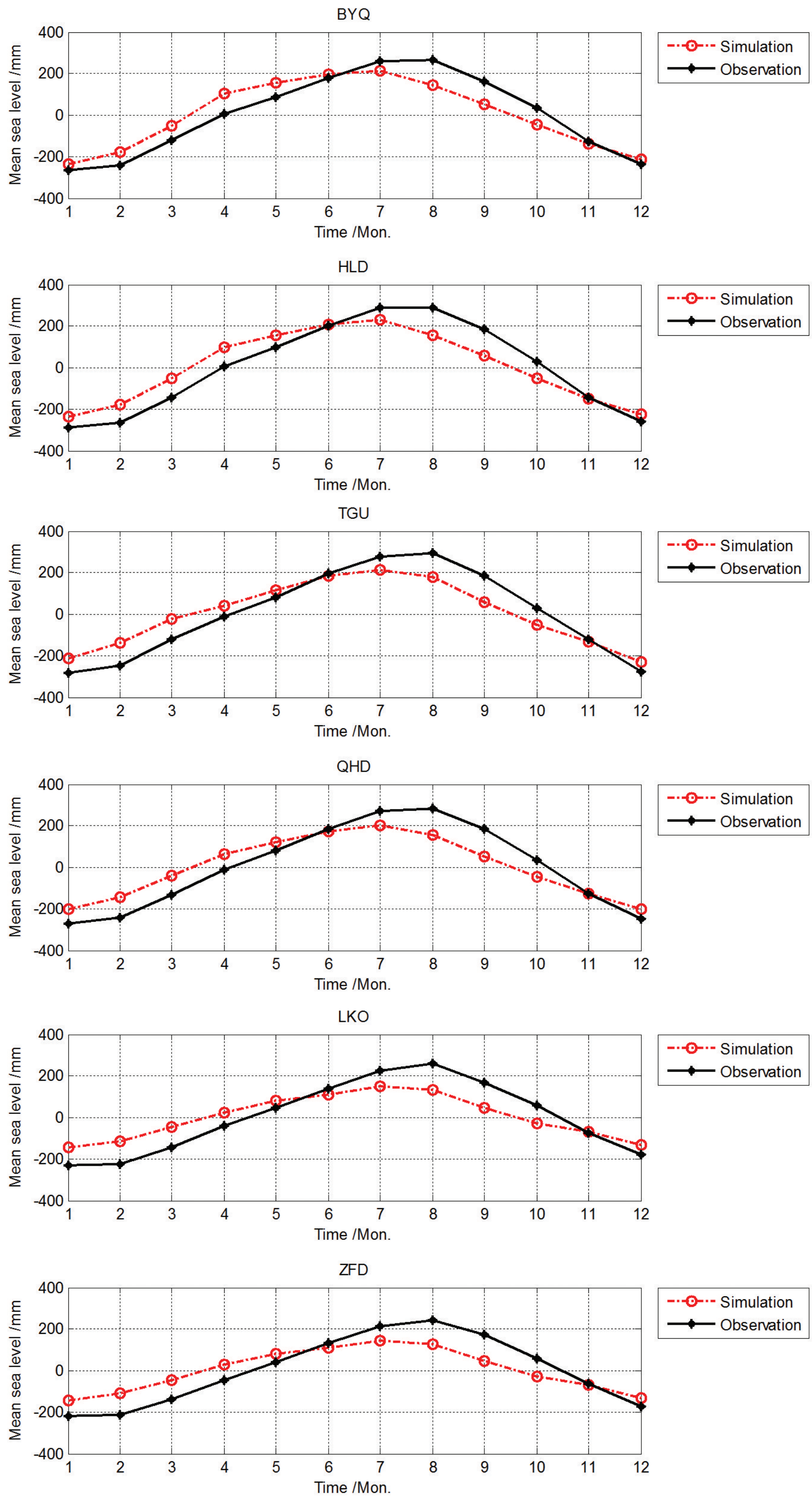


Figure 3. Comparison of seasonal mean sea level variation between simulation and observation of station along coast of the Bohai Sea

RESULT EXAMINATION OF THE MODEL

Arithmetic method was applied to get monthly mean sea level data which is from 1980 to 2012 at each node using hourly sea level calculated by the numerical model, and then climate monthly mean sea level could be calculated. The result of the verification between simulation and observed data is shown in Table 2. The contribution ratio referred in this essay is annual range ratio between simulation and observed data. It can reflect the contribution of seasonal sea level variation caused by atmospheric pressure and wind to the real variation if the precision of the simulation is good. The comparison of monthly mean sea level in each station can be seen in Figure 2, and seasonal variation in Figure 3.

Table 2. *Comparison of simulated result and observed data of station along coast of the Bohai Sea*

station	monthly mean sea level comparison		sea level annual range comparison		
	RMSE /mm	correlation coefficient	simulation /mm	observation /mm	ratio
BYQ (BaYuQuan)	102	0.88	450	528	85%
HLD (HuLuDao)	97	0.91	466	578	81%
QHD (QinHuangDao)	93	0.92	404	552	73%
TGU (TangGu)	104	0.91	447	578	77%
LKO (LongKou)	104	0.89	297	487	61%
ZFD (ZhiFuDao)	98	0.89	283	460	62%
average	100	0.90	391	531	73%

(1) Table 2 and Figure 2 show that the simulation results of monthly mean sea level are consistent with the observations. The error statistics show the average root-mean-square error (RMSE) is 100 mm ranging from 93mm to 104mm and all the correlation coefficients are about 0.90.

(2) Table 2 and Figure 3 show that the simulation could reflect the characteristics of seasonal sea level variation. The amplitudes and phases have a good agreement with the observations. The annual range of simulated sea level is 391 mm and that of observed is 531 mm, which means the atmospheric pressure and wind are the main factors of sea level variation along coast of the Bohai Sea with a contribution ratio of 73%. BYQ and HLD are two stations with the largest contribution rate of more than 80%, followed by the TGU Station of 77%. As the three stations are located in the top of bay where water depth is relatively small, it seems comprehensible that wind and air pressure play an important role. Although the correlation coefficients are very high, the amplitude of simulated result is less than that of observed meanwhile it seems that the simulated result has a month ahead of observed data (Figure 3). Maybe that's because of the assumption of the numerical model, the atmospheric condition is taken into consideration only, which means some other factors affecting sea level such as sea temperature or salinity are not considered in the model. Thus the modeled amplitude is less than observed is comprehensible.

All these above suggests that the simulation results could basically reflect the characteristics of monthly mean sea level variation along coast of the Bohai Sea taking the model assumption of only air condition forcing into consideration. The amplitudes and phases have a good agreement with the observations and the correlation coefficients of six stations are all over 0.85. The air pressure and wind are the main factors for the seasonal sea level variation of coastal area, and the contribution ratios of six stations are more than 60% viewed from annual range.

ANALYSIS OF SEA LEVEL ANOMALY

Extreme weather and climate events happened frequently along with the global warming, and also result in big variation of regional sea level. The big variation happens to China coastal area every year. *Chinese Sea Level Bulletin* 2012 pointed that the sea level along China coastal area in 2012 reached a maximum since 1980. And the sea level was higher than ordinary year in May, June, August and October. Sea temperature, air temperature, atmospheric pressure and wind were the main factors which caused the anomaly of the sea level.

The mean sea level abnormal events (short as MSLAE) defined in this essay are that when the monthly mean sea level is 100 mm higher than ordinary year. Three typical MSLAE occurred in the Bohai Sea are discussed using the simulation results and observed data as following.

The sea level anomaly low along coast of the Bohai Sea in Nov., 1988

The sea level was abnormally lower along coast of the Bohai Sea in Nov., 1988. Monthly mean sea level observed from stations are of 100 mm lower than that of ordinary year while the lowest station is TGU which is more than 200 mm lower. The comparison between simulation and observation is in Figure 4. It shows that the simulation can reflect the abnormal variation of sea level in each station. Although the absolute value of simulated is less than that of observed, the spatial distribution trend is basically consistent. Both simulated and observed result indicates that the Bohai Bay has the lowest sea level variation.

The analysis of sea level along coast of the Bohai sea, the simulation of wind-driven flow and anomaly of wind and atmospheric pressure (Figure 5a) show that the direction of wind field anomaly is northward, and value is about 2 m/s. North-westward to northward wind was the prevail wind which means the north-westward wind was strengthen in this month. From the results of the simulation of wind-driven current (Figure 5c), we can see that there is a strong coastal current along the coast of eastern Liaodong Bay and northern Shandong Peninsula, the direction is from the Bohai sea to the Yellow Sea which means water transport out of Bohai leading to the mean sea level significantly lower; where in the Bohai Bay there are two circulation with opposite direction, the south wing of counterclockwise, the north wing of clockwise, the combined effect of the two circulation leads to outward transport of the top area of Bohai Bay, resulting in mean sea level anomaly low at the station of TGU.

From the pressure field anomaly distribution (Figure 5a), air pressure of the Bohai Sea is of 0.5 hPa ~ 1.5 hPa lower in Nov., 1988 than that of the same period of prevail year. Considering from the static effect positive pressure anomaly would lead to lower sea level while negative pressure anomaly would lead to higher sea level. In this case, air pressure over Bohai sea is negative anomaly, would cause the sea level rise, while the actual sea level is significantly negative anomaly, thus we could draw a conclusion that water transport effect caused by wind-driven current plays a dominant role for this MSLAE.

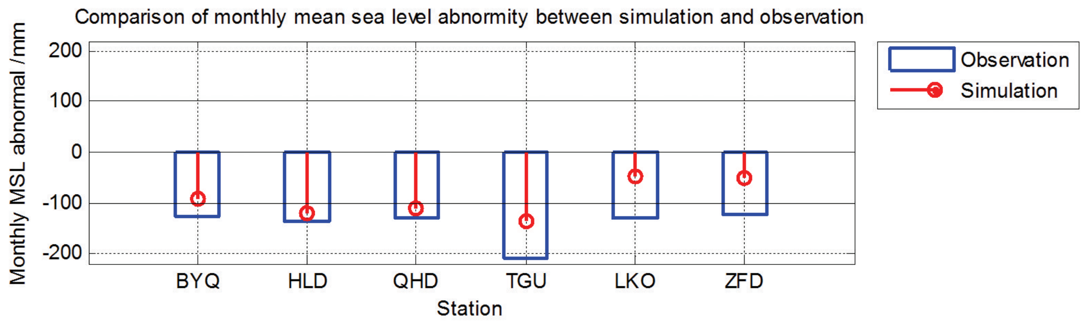
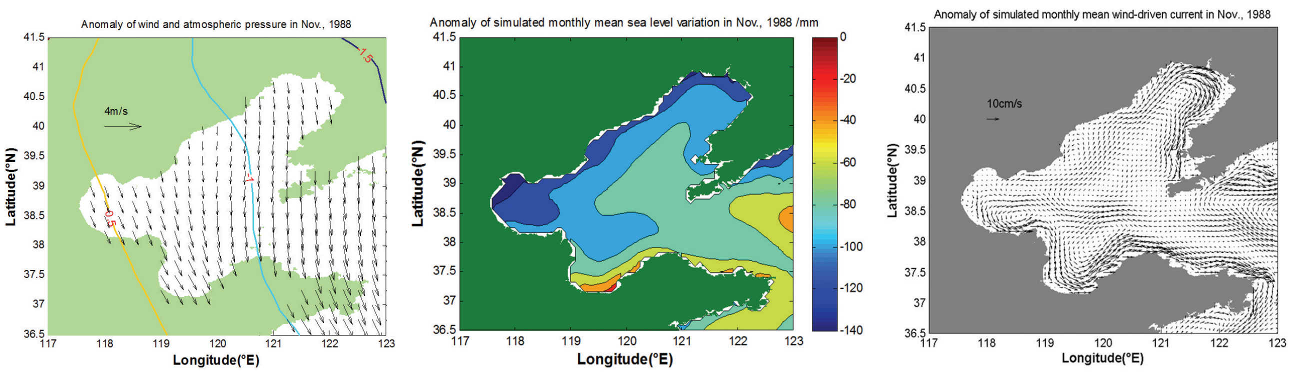


Figure 4. Comparison of monthly mean sea level abnormity between simulation and observation of Nov., 1988



(a) (b) (c)

Figure 5. Anomaly of simulated monthly mean sea level variation and wind-driven current, anomaly of wind and pressure in the study area in Nov., 1988

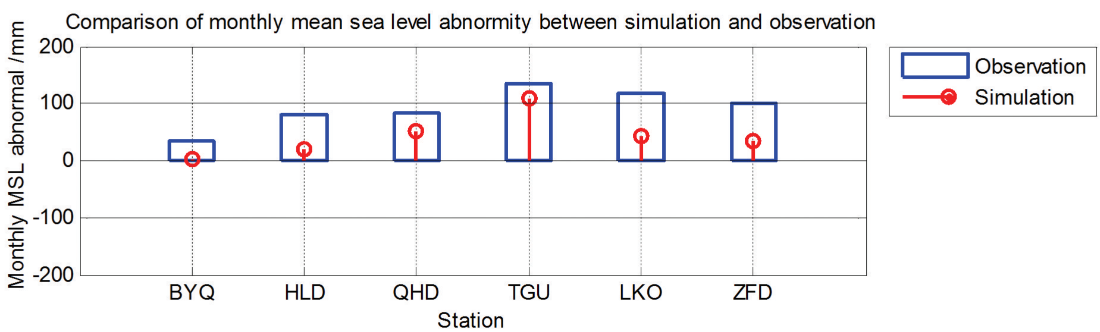
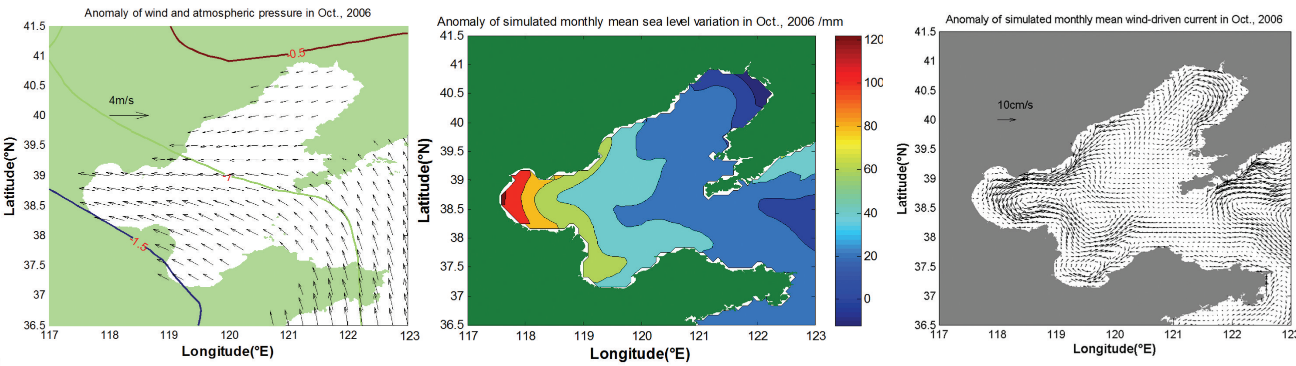


Figure 6. Comparison of monthly mean sea level abnormity between simulation and observation in Oct., 2006

The sea level anomaly high along coast of the Bohai Sea in Oct., 2006

The sea level was abnormally higher along coast of the Bohai Sea in Oct., 2006. Monthly mean sea level of TGU and LKO stations are of 100 mm higher than that of ordinary year. The comparison between simulation and observation is in Figure 6. It shows that the simulation can reflect the abnormal variation of sea level in each station. Although the absolute value of simulated is less than that of observed, the spatial distribution trend is basically consistent. Both simulated and observed result indicates that the Bohai Bay has the highest sea level variation and the Liaodong Bay has the lowest sea level variation.

The analysis of sea level along coast of the Bohai sea, the simulation of wind-driven current and anomaly of wind and atmospheric pressure (Figure 7a) shows that direction of wind anomaly is east - northeast with quantity value of about 2 m/s, and the west-northwest wind was the prevail wind in October of ordinary year, which indicates that compared to the same period of average year the west-northwest wind was significantly weaker resulting in water transported from the Bohai sea to the Yellow Sea transport decreasing, further leading to mean sea level higher than the same period of average year. There is a strong counter clockwise wind-driven circulation in the Bohai Bay, resulting in monthly sea level of TGU station significantly higher than average state; meanwhile, atmosphere pressure over the whole Bohai Sea is of 0.5 hP ~ 1.5 hPa lower than that of average year, which would result in a positive anomaly effect to the mean sea level. The above analysis shows that the combined action of wind and pressure is an important cause of this MSLAE.



(a) (b) (c)

Figure 7. Anomaly of simulated monthly mean sea level variation and wind-driven current, anomaly of wind and pressure in the study area in Oct., 2006

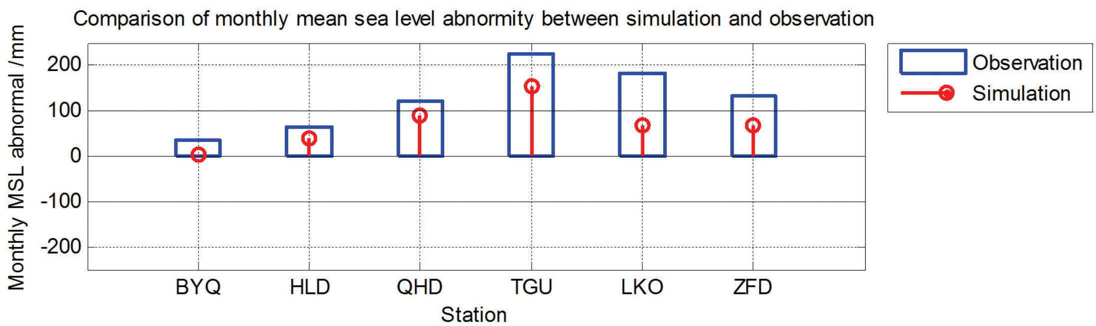
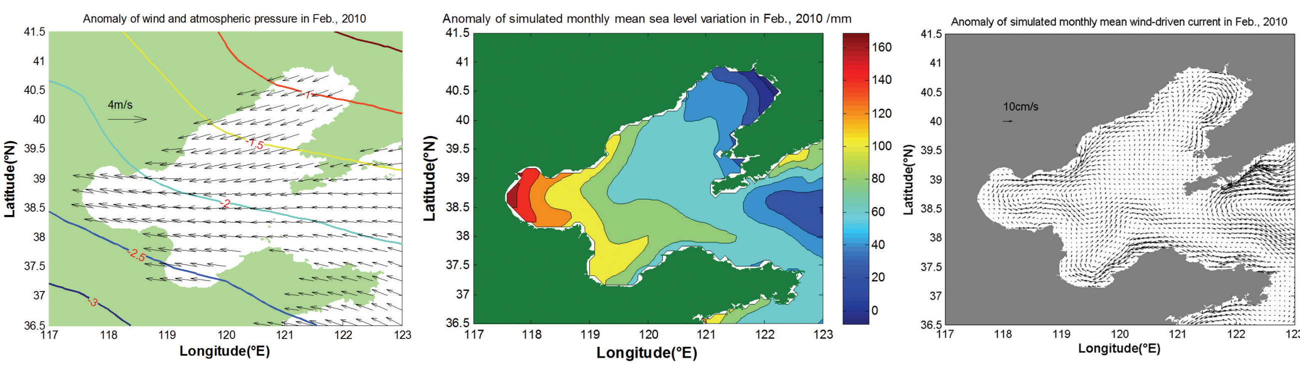


Figure 8. Comparison of monthly mean sea level abnormity between simulation and observation in Feb., 2010



(a) (b) (c)

Figure 9. Anomaly of simulated monthly mean sea level variation and wind-driven current, anomaly of wind and pressure in the study area in Feb., 2010

The sea level anomaly high along coast of the Bohai Sea in Feb., 2010

The sea level was abnormally higher along coast of the Bohai Sea in Feb., 2010. Monthly mean sea level of TGU stations are of more than 200 mm higher than that of ordinary year. The comparison between simulation and observation is in Figure 8. It shows that the simulation could reflect the spatial character of sea level abnormal along coast of the Bohai Sea. Although the absolute value of simulated is less than that of observed, the spatial distribution trend is basically consistent. Both simulated and observed result indicates the Bohai Bay has the highest sea level variation and the Liaodong Bay has the lowest sea level variation.

The analysis of sea level along coast of the Bohai sea (Figure 9b), the simulation of wind-driven current (Figure 9c) and anomaly of wind and atmospheric pressure (Figure 9a) shows that direction of wind anomaly is east with value of about 4 m/s, and the northwest wind was the prevail wind in Feb., of average year. which indicates that the west wind was significantly weaker than that of average state, causing offshore water transport reducing in Bohai Bay. From the result of simulated wind-driven current (Figure 9c), there exists strong coastal current along the coast of northern Shandong Peninsula, the direction is from the Yellow Sea to the Bohai Sea, that means water transport to the Bohai is positive, resulting in mean sea level overall higher; wherein the Bohai Bay there are two circulation with opposite direction, one is at the north wing, with strong anti-clockwise circulation, the other is at the south wing with weak clockwise circulation, the combined effect of the two circulation leading to the water shoreward accumulation, resulting in monthly mean sea level significantly higher in the Bohai Bay. Meanwhile, atmosphere pressure over the whole Bohai Sea is of 1.0 hP ~ 2.5 hPa lower than that of average year, which would result in a positive anomaly effect to the mean sea level. The above results show that this MSLAE was mainly caused by an abnormality of air pressure and wind.

In summary, model result could basically characterize the spatial features in coastal Bohai area during the three MSLAEs, although the absolute value of simulated is less than that of observed. Absolute bias between model and observation might due to the neglect of other factors such as sea temperature and salinity.

CONCLUSIONS

Numerical simulation was applied to quantitatively analyze the impact of meteorological factors (atmospheric pressure and wind) on the mean sea level variation in the coastal area of the Bohai Sea. The main conclusions are as follows.

(1) The comparison between simulation and observation suggests that the numerical model driven by air pressure and wind could characterize the spatial and temporal features of monthly mean sea level variation along coast of the Bohai Sea. The average RMSE of monthly mean sea level is 100 mm, and the average correlation coefficient is 0.90.

(2) The trend of seasonal sea level variation is basically consistent between the simulation and observation. The contribution ratio of air pressure and wind to the sea level variation in the coastal area of the Bohai Sea is about 73%, and they are the main factors for the seasonal variation.

(3) According tothe analysis of three typical MSLAE occurred in Nov., 1988, Oct., 2006 and Feb., 2010, the simulation results can reflect the spatial characteristics of the sea level anomaly. It suggests that air pressure and wind variation leading wind-driven current and consequently water transportation are of great importance to the abnormal variations of mean sea level along coast of the Bohai Sea.

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