Influence of Tide Models on the Use of Altimetry Data to Research Sea Level Anomaly

XU Jun  BAO Jingyang  LIU Yanchun  YU Caixia

Abstract  A tide model (named DN1.0), which contains 12 principal constituents over China seas and the Northwest Pacific is estimated by along-track harmonic analysis with TOPEX/Poseidon altimetry data taken from 1993 to 2002. CSR3.0, FES95.2 and DN1.0 are used respectively to detide the data for the time series of sea level anomaly (SLA) in the Yellow Sea, East China Sea, South China Sea and Northwest Pacific. The SLA curves and the power spectral density show that the major components that exist in SLA in China seas arise from the error of the tide models.

Keywords  satellite altimetry; sea level anomaly; tide model; tidal aliasing

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Introduction

Variations in mean sea level are important indicators for a variety of phenomena affecting the earth system, including climate change. They also have a number of social and economic consequences. Compared with the tide gauge stations, altimetry satellites have a major advantage in that satellites can observe the “global” ocean in order to obtain tide constituents or to research the variations in mean sea level. The TOPEX/Poseidon (T/P) satellite is an excellent example which repeats every 9.915 6 d and has a 300 km spacing at the equator.

Many researches on the mean sea level variations have been reported[1-7]. Dong Xiaojun[2] monitored the process of the 1997 El Niño by T/P altimeter data. Wang Haiying[3] calculated the rise rate of mean sea level in the regions of the China seas and the influences of El Niño. Li Jiancheng[4] studied the mean sea level variations using multi-satellite altimeter data. Dong Xiaojun[1] analyzed the influences of weighting, depth and the tide model in calculating the mean sea level variations. An approximate 60 d component was discovered by Dong Xiaojun[1] and Wang Haiying[3], and their viewpoint is that its mechanism may be the aliased tides. However, Minster[6] concluded that it is caused by the error of the inverse barometer correction. Cheinway Hwang[7] concluded that the effects of the errors of the tide models on SLA in the South Sea was small.

1  Sea level anomaly from T/P

The research area covers the China seas and the Northwest Pacific (0º-38ºN, 109º-150ºE), excluding...
the Philippine Sea and the Japan Sea. We use the MGDR-B from A VISO to generate corrected SLA from Cycle 11 (January 1, 1993) to Cycle 348 (February 27, 2002). The oscillator drift and the bias between TOPEX and Poseidon have been corrected.

In this paper, the altimeter ranges are the radar pulse passes between the altimeter and the reflecting sea surface. To generate SLA, the range should add all range corrections including troposphere correction, ionosphere correction and tide effects, but with the exception that no correction is applied for the inverse barometer effect. There is about 1 km transverse drift between different cycles for the same pass, which means that vertical bias may be mistakenly associated with sea level variability. So we choose the OSU mean sea surface model 1995 (OSUMSS95) as reference surface to reduce the vertical bias.

The polynomial approach, instead of the collinear method, is chosen to generate normal points along track at 0.1° latitude intervals. The SLA of each normal point is obtained by a polynomial which is set up by the points in 10′ around. The polynomial approach has two advantages: first, it can reduce the effect of the random error; and second, it can interpolate the rejected data arising from the abnormal observation. But when there is no observation data in 5 s around the normal point, the SLA cannot be interpolated in order to ensure precision.

After the polynomial interpolation, all normal points distribute symmetrically along track. But the interval between the adjacent tracks becomes smaller when the latitude becomes higher. It means that equal weight will magnify the effect of the high latitude area. So the weight should be \( \cos \phi \) (where \( \phi \) is the latitude of the geographic footprint).

When there are \( N_j \) normal points in Cycle \( j \) in one region, the SLA of this cycle is

\[
\bar{h}^j = \frac{\sum_{k=1}^{N_j} h_k^j w_k^j}{\sum_{k=1}^{N_j} w_k^j}
\]

where \( h_k^j \), \( w_k^j \) is the SLA and weight of a normal point in the cycle, respectively. In this paper, we choose the following three tide models used to detide the data: CSR3.0, FES95.2 and the tide model we obtain from T/P by along-track harmonic tidal analysis (named DN1.0).

2 Along-track harmonic tidal analysis and comparison among tide models

When \( p = 9.915 \text{ d} \) is the T/P repeat period, the constituent whose period is shorter than \( 2p \) will be aliased into a long period signal. Table 1 lists the tidal alias periods of 9 constituents.

| Wave | \( M_l \) | \( Q_1 \) | \( O_1 \) | \( P_1 \) | \( K_1 \) | \( N_2 \) | \( M_2 \) | \( S_2 \) | \( K_2 \) |
|------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| Alias periods/d | 36.2 | 69.4 | 45.7 | 88.9 | 173.2 | 49.5 | 62.1 | 58.7 | 86.6 |

Aliasing induces tidal correlations. Therefore, a time span that is much longer than that of tide gauges is needed to separate different constituents. According to Rayleigh’s rule, 9 years of T/P data is enough for reliable harmonic analysis or response estimation of tides\(^{[10]}\). The DN1.0 tide model established by along-track harmonic analysis contains 12 principle constituents\(^{[10-12]}\). The accuracy and reliability of the results are assessed by intercomparison between the results of both ascending and descending ground tracks at crossovers. Table 2 is the result of the comparison.

| Wave | \( S_a \) | \( S_m \) | \( M_m \) | \( M_l \) | \( Q_1 \) | \( O_1 \) | \( P_1 \) | \( K_1 \) | \( N_2 \) | \( M_2 \) | \( S_2 \) | \( K_2 \) |
|------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|---------|
| RMS/cm | 0.9 | 0.7 | 0.6 | 1.3 | 1.7 | 1.3 | 1.9 | 2.7 | 1.4 | 1.3 | 1.1 | 1.8 |

Table 2 shows that the T/P-derived tide constituents are quite reliable in China shallow seas and that
the accuracy in shallow seas is consistent with that in deep ocean. CSR3.0 and FES95.2 are recommended tide models, in which a large error still remains in shallow seas, especially in the China seas.

CSR3.0 and FES95.2 are selected for inclusion in the MGDR-B, and they both use the FES94.1 as their reference model. Then about 2 years of T/P altimetry is used to solve for corrections. However, 2 years’ data is too short to separate different constituents. Thus, the corrections are obtained in 3°×3° spatial bins, and smoothed by Gaussian filter. The corrections can improve the performance of the tide models in deep ocean, but do not work well in shallow seas. Table 3 lists the deviation of CSR3.0 and FES95.2 compared with DN1.0.

| RMS/cm | $Q_1$ | $O_1$ | $P_1$ | $K_1$ | $N_2$ | $M_2$ | $S_2$ | $K_2$ |
|--------|-------|-------|-------|-------|-------|-------|-------|-------|
| Yellow Sea | CSR3.0 | 1.5 | 4.6 | 2.4 | 7.9 | 5.4 | 28.6 | 8.5 | 2.4 |
| | FES95.2 | 1.2 | 11.2 | — | 14.0 | 4.5 | 28.1 | 38.0 | 2.4 |
| East Sea | CSR3.0 | 1.2 | 2.5 | 1.9 | 5.2 | 5.4 | 31.4 | 10.8 | 3.4 |
| | FES95.2 | 1.2 | 7.1 | — | 11.8 | 14.3 | 73.0 | 28.9 | 3.0 |
| South Sea | CSR3.0 | 0.9 | 2.2 | 1.0 | 2.4 | 1.3 | 4.5 | 2.6 | 1.5 |
| | FES95.2 | 0.8 | 1.8 | — | 2.7 | 2.4 | 7.5 | 2.0 | 1.2 |
| Northwest | CSR3.0 | 1.0 | 1.2 | 1.1 | 2.0 | 0.9 | 2.0 | 1.2 | 1.5 |
| Pacific | FES95.2 | 1.0 | 1.0 | — | 1.6 | 0.9 | 1.5 | 1.0 | 1.5 |

compared with DN1.0.

From Table 3, we know that the differences among models are relatively small in deep oceans, but quite large differences occur, even the RMS difference reaches 73 cm in shallow seas.

3 Analysis of sea level anomaly

Fig. 1 is the time series of SLA in the Yellow Sea, the East Sea, the South Sea and the northwest Pacific. The SLA detided by CSR3.0 and FES95.2 shows a distinct annual component.

To see the characteristics of the SLA in the frequency domain, we perform spectral analyses to obtain periodograms of the four time series (Fig.2). In Fig.1 and Fig.2, the dashed line represents FES95.2, the thin line represents CSR3.0, and the thick line represents DN1.0. In Fig.1 the results are smoothed with a 30 d boxcar filter. Below is a summary of Fig.1 and Fig.2.

1) CSR3.0 and FES95.2 do not contain the long-period tides, so the annual component, the largest one in the long-period tides, has been taken into SLA. But DN1.0 contains 4 long-period tides so that the corresponding time series does not have the annual component. Attention should be paid to the fact that the annual component arises from the wind, barometer, and other forcing. When we research the relation between SLA and wind, barometer, and other forcing, the annual component should not be used to detide the data.

2) An approximate 60 d component exists in the time series detided by CSR3.0 and FES95.2 in the Yellow Sea, the East Sea and the South Sea. The alias period of $M_2$ and $S_2$ is 62 d and 59 d respectively, so Wang Haiying [3] concluded that the approximate 60 d component arose from the error of the tide models. That the SLA detided by DN1.0 does not have the component proves it is right. The magnitude of the approximate 60 d is largest in the East Sea, less in the Yellow Sea, and least in the South Sea. And the magnitude of the approximate 60 d detided by FES95.2 is larger than that detided by CSR3.0 in the Yellow Sea and the East Sea.

3) From Table 1 and Fig.2, the periods of the major components are coherent with the alias periods of the principle constituents, such as $M_2$: 62 d; $S_2$: 59 d; $P_1$, $K_2$: approximate 90 d; $O_1$: 45 d; $N_2$: 49 d and $K_1$: 173 d.

From Table 3 and Fig.2, the deviation of the principal constituents of CSR3.0 and FES95.2 is proportional with the power spectral density of the corresponding components. Therefore, we conclude that the major components in SLA in the China seas arise from the errors of the tide models.
However, owing to the complexity of tides in the Yellow Sea and the East Sea, the tide models do not work well in these shallow seas. Many components still exist in the SLA detided by DN1.0, which may be the effects of the aliased minor constituents or the variability of the mean sea level. So the tide model in the shallow waters, such as the Yellow Sea and the East Sea, should be improved.

4) CSR3.0, FES95.2 and DN1.0 all work well in the South Sea and the Northwest Pacific. But the SLA of northwest Pacific in Fig.1 indicates a fall of mean sea level in 1994 and in 1997 which coincides with the El Niño events, and a rise in 1998 which coincides with the La Niña. It may be the reason why the rise rate calculated by different experts is different.

5) In the viewpoint of Minster[6], the error of the inverse barometer (IB) correction creates the major components in SLA. We analyzed the effects of IB correction on tidal parameters derived from altimetry data in another paper[13]. Research shows that the IB correction mainly affects the annual constituent $S_a$. And the contribution of IB in other major constituents is less than 0.5 cm. Cheinway Hwang[7] concluded that the approximate 60 d component is not affected by the aliased $M_2$ and $S_2$ tides because the component has different amplitudes at different times. But it cannot be the exclusive foundation, because we found that the harmonic constants varied when we dealt with the tide gauge data. The harmonic constants are not constant.

4 Conclusions

Errors of the ocean tide correction create alias period components which will interfere with the real variation of the mean sea level. Therefore, enough attention should be paid to the precision of the tide model especially in the shallow seas, such as in the Yellow Sea and in the East Sea. The high-precision and high-resolution region tide models are essential to research the variation of the mean sea level from satellite altimetry data.
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