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Validation of Sea Level Data in the East Asian Marginal Seas: Comparison between TOPEX/POSEIDON Altimeter and In-Situ Tide Gauges

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ABSTRACT

In an effort to assess the reliability of satellite altimeter systems, the authors conduct a comparative analysis of sea level data that were collected from the TOPEX/POSEIDON (T/P) altimeter and 10 tide gauges (TG) near the satellite passing ground tracks. The analysis is made using datasets collected from marginal sea regions surrounding the Korean Peninsula at T/P cycles of 2 to 230, which correspond to October 1992 to December 1998. Proper treatment of tidal errors is a very critical step in data processing because the study area has very strong tide. When the T/P data are processed, the procedures of Park and Gamberoni (1995) are adapted to reduce errors associated with the tide. When the T/P data are processed in this way, the alias periods of M2, S2, and K1 constituents are found to be 62.1, 58.7, and 173 days repectively. The compatibility of the T/P and TG datasets are examined at various filtering periods. The results indicate that the low-frequency signals of the T/P data can be interpreted more safely with longer filtering periods (such as up to the maximum selected value of 200 days). When RMS errors for the 200-day low-pass filter period are compared with all 10 tidal stations, the values span the range of 2.8 to 6.7 cm. The results of a correlation analysis for this filtering period also show a strong agreement between the T/P and TG datasets across all stations investigated (e.g., p-values consistently less than 0.001). Hence according to the analysis, the conclusion is made that the analysis of surface sea level using satellite altimeter data can be made safely with reasonably extended filtering periods such as 200 days.

Key words: sea level, TOPEX/POSEIDON, altimeter, tide gauge

1. Introduction

Continuous monitoring of sea level changes can be considered as one of the most fundamental steps for a better understanding of the ocean dynamics. This is because numerous oceanographical and geophysical processes leave a broad spectrum of signatures on the sea surface topography . The level of accuracy in the global scale observations of sea surface height (SSH) has been improved dramatically with the development of satellite altimeter systems such as the one deployed with the TOPEX/POSEIDON (T/P) satellite. The T/P satellite altimeter system has been measuring the global SSH using two altimeter radars since August 1992.

As the satellite follows the same ground track at 10-day intervals, the T/P altimeter data can be used to provide valuable information including: large-scale ocean circulation, seasonal changes of surface sea level, global scale climate change, etc. Because of their wide applicability, a number of studies have attempted the calibration and/or validation of the T/P altimeter data with in-situ sea level data (Mitchum, 1994; Christensen et al., 1994; Tapley et al., 1994; Katz et al., 1995; Park and Gamberoni, 1995; Picaut et al., 1995; Verstraete and Park, 1995). It turns out from the results of these enormous efforts that the sea level

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values from the T/P altimetry data can be as accurate as 2–3 cm of level in the open-ocean areas (e.g., Marshall et al., 1995).

Despite notable progresses made in the field of satellite altimetry, its application can still be confined geographically from some areas. For example, coastal sea areas are well known for complicated tidal periodicity and strong variations of seawater density with changes of temperature or salinity (Nishida, 1980; Yanagi and Takahashi, 1993). In those areas, propagation of error is significant in the tide model computation. Hence, corrections are essential for some factors such as the inverse barometric effect (as a climate factor) and tidal aliasing (as an oceanographic factor). Irrespective of the recognition of such problems, such corrections have rarely been made.

In an effort to assess the level of accuracy in the satellite altimeter data from a geographically complicated coastal area, we conducted a comparative study using the data acquired by in-situ tide gauges (referred as TG hereafter) from comparable geographical locations. Comparison of the two different datasets was made for one of the most dynamic oceanic regions of the world, the coastal sea of the Korean Peninsula and the eastern Asian marginal seas for the periods covering 1982–1998. Upon the completion of the assessment of those SSH datasets, we present a procedure through which we attempted to reduce errors inherent in the satellite altimeter data.

2. Background

2.1 *Factors affecting sea level change*

It is acknowledged that there are various factors contributing to the sea level changes of the world oceans. Despite the complexities involved in such factors, a quantitative description of the major components can be made as follows (AVISO, 1998).

$$h_{\rm sl} = h_{\rm t} + h_{\rm ib} + h_{\rm w} + h_{\rm c} + h_{\rm s} + h_{\rm e} + h_{\rm g} + r\ , \quad (1)$$

where each subscript denotes: sea level, tide, inverse barometric, wind, current, steric, eustatic, and geological, respectively. The last term, r denotes the effect of man-made activities in the ocean.

Here, $h_{\rm w}$ represents the effect of pressure change on sea level; $h_{\rm s}$ is regulated mainly by the combined effects of seawater temperature and density (salinity); $h_{\rm e}$ reflects changes of the reservoir capacity of the ocean; and $h_{\rm g}$ is the effect proceeding on a geological time scale. The effects of $h_{\rm g}$ and r are rather insignificant, as they are reflected slowly and steadily on a long-term scale. Hence, it is reasonable to conclude that the remaining five terms are the most dominant components affecting the sea level change.

The pattern of sea level change can be diversified in temporal scale, especially across seasons. For example in the coastal areas of the Korean Peninsula, the changes appear to be more significant during summer than winter. According to Kang and Lee (1985), the factors regulating the seasonal sea level changes in the area can be classified into two major categories: (1) meteorological and environmental parameters including pressure, temperature, salinity, shear stress of wind, current, and so forth; and (2) hydrological parameters including evaporation, precipitation, and river run-off. It is noteworthy that the relative role of those factors governing the periodic changes of SSH is strongly variable on a spatial scale. A good example of these spatial effects can be seen very clearly from the coastal sea areas of East Asia among the neighboring three countries, Korea, Japan, and China. Oh and Park (1994) reported that in sea level fluctuations of northeastern Asia, the dominant period of the first mode is seasonal, and the interannual average for each month shows a typical seasonal variation in which February is the minimum and August is the maximum. Oh et al. (1993) also showed that seasonal oscillations are most dominant in the sea level variations of the East Sea, and semiannual oscillations are also observed. Pang and Oh (1995) found that the sea level variations by oceanic causes are the largest in the coasts along the Tsushima Current, and become small in the distant areas. The variations of MSL along the coast of Korea is produced mainly by the steric departure and barometric effect (Yi, 1967; Patullo et al., 1955). The variations of MSL associated with the barometric change is relatively simple. The MSL values can be estimated with the assumption that sea level adjusts hydrostatically to the atmospheric pressure. (For example, a barometric increase of 1 hPa can reduce the MSL by 1 cm.) In the Japan sea, temperature change is the utmost factor affecting sea level change followed by the barometric effect (Nomitsu and Okamoto, 1927). By contrast in southern China, the barometric effect is of minor significance relative to such a factor as the monsoon wind (Tvi, 1970). As such, accurate assessment of sea level change requires simultaneous consideration of both temporal and spatial variables involved.

2.2 *Estimation of dynamic heights*

In principle, dynamic height refers to the distance of the sea surface above the geoid (Park and Gamberoni, 1995). It can be expressed in a quantitative manner using the following equation:

$$\text{Dynamic height} = \text{altimeter orbit} - (\text{altimeter range} + \text{corrections}) - \text{geoid} - \text{errors}\ , \quad (2)$$

where “errors” comprise all the uncertainties that could possibly arise due to such terms as: the computed altimeter orbit, altimeter range, geophysical corrections, model geoid, and so forth.

The inaccuracy associated with the contemporary tide model is relatively large for a number of reasons. Since only eight constitutions (major diurnal plus semidiurnal) have been taken into consideration for their evaluation, errors arising from the application of the tide model should be considered as the upper-bound limit. These errors are also quite variable depending on locality, as the model itself is based on geographically variable statistical datasets. In addition, the geoid uncertainty, especially in the region of short wavelengths, turns out to be crucial in accurate computation of the dynamic height (Park and Gamberoni, 1995). Although there has been great improvement in developing the geioid theory in recent years (e.g., Nerem et al., 1994), a geoid with a 10 cm accuracy can hardly be achieved for actual scales less than 1000 km (Centre National d'Etudes Satiales, 1994). With the present knowledge of the geoid, only large-scale circulation signals of wavelengths greater than ~2000 km can be separated reliably (Naeije et al., 1993; Nerem et al., 1994). However, the geoid error does not directly affect the temporally variable constituents in the computation of dynamic heights, as T/P data are collected along the identical ground tracks at a fixed periodic interval.

In the study area surrounding the Korean peninsula, the strength of tidal activity is significantly large. For instance, the Yellow Sea is known to consume about 7% of the total tidal energy worldwide (Choi, 1980). To reduce aliasing errors under this condition, one needs to develop tide models that can account for tidal activities typical enough to represent shallow and dynamic oceanic regions.

2.3 *Time-series analysis of SSH data*

In order to interpolate our data into a smooth time series (at regular time intervals), we used a successive correction scheme adapted from Park and Gamberoni (1995) as

$$H(t,p+1)=H(t,p)+\left\{\sum_{i=1}^{n}\omega_i(t)[\eta_i-H_i(p)]\right\}/\sum_{i=1}^{n}\omega_i(t)\,,$$

where $H(t,p)$ is the interpolated value at time t from the pth iteration, η_i is the observed value at time t_i, and $H_i(p)=H(t_i,p)$ is the estimate of η_i from the pth iteration. The weights $\omega_i(t)$ are derived from a Gaussian filter calculated according to

$$\omega_i(t)=\exp[-(t-t_i)^2/1.44T^2]\,,$$

where T is in timescale.

3. Materials and methods

One of the main purposes of our study is to derive a meaningful interpretation of sea level data acquired using the T/P satellite altimeter. Hence, the collection and proper treatment of T/P data are the basic prerequisites among others. We used the merged T/P geophysical data records (GDR-M) collected by the Archiving, Validation, and Interpretation of Satellite Data in Oceanography (AVISO) Center. The datasets were selected to cover the entire eastern Asian marginal seas (20°–50°N, 115°–160°E) with the T/P cycles of 2 to 230 (corresponding to the period of October 1992 to December 1998). As a reference to check the validity of T/P datasets, we collected TG datasets that were measured from 10 tide gauge stations during the the same period (Fig. 1). These TG stations were selected for their proximity to either the ascending or descending passing track of the T/P satellite within +0.5° latitudinal range (~55 km). Along the passing track of T/P, the altimeter data are produced at intervals of 5.8 km per second.

The T/P data were processed by the standard procedures of Park and Gamberoni (1995) as follows. To begin with, dynamic heights were quantified for each tracking point at each cycle of the T/P satellite. For this computation, we applied geophysical corrections according to the AVISO manual (AVISO, 1998) and assessed SSH by the procedures recommended by CNES (1994). A time-series analysis was then conducted to derive the mean sea level and sea level anomaly (SLA) for each tracking point of the T/P data acquisition.

The TG data from 10 monitoring stations were obtained using two different types of tide gauges. Except for the one station using the acoustic type (JMJ station in Table 4), all the rest were using the float type TG to obtain sea level data. The float type TG has a hole that limits the rate at which seawater penetrates the wall; hence the gauge is suitable to mechanically filter sea level variability caused by high-frequency surface gravity waves. Because the float type gauge records the change of sea level by the movement of float, the effects of the atmospheric pressure change (inverse barometric effect) and the steric departure can be well-reflected. In the case of the acoustic type gauge, the water surface height is measured by the travelling time of a reflected acoustic pulse. For acoustic type TG data, no corrections for barometric effect are necessary, as is the case of the floating type TG.

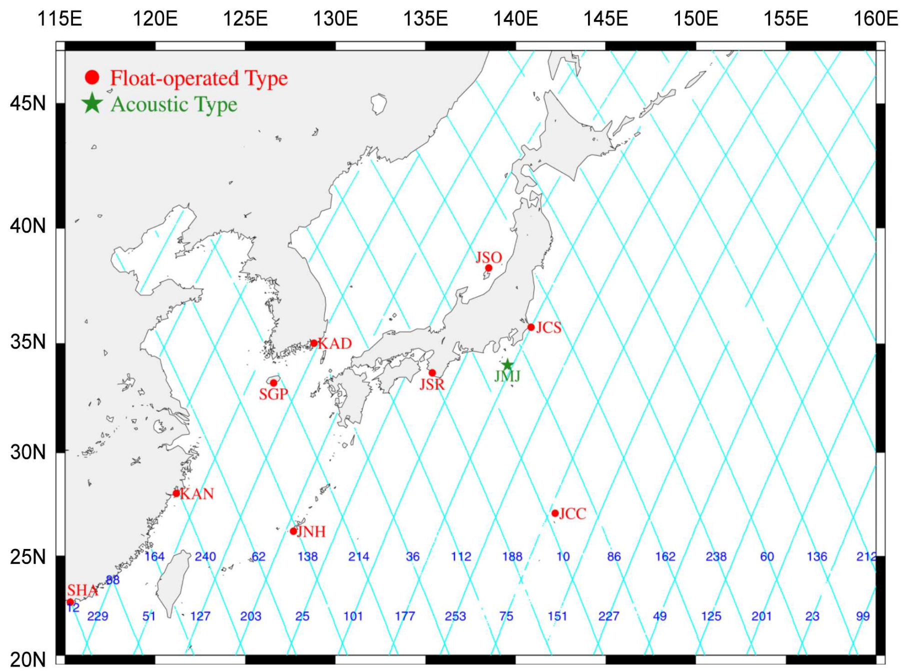

Fig. 1. Location of the tide gauge stations from which sea level data were collected for this study. Ground tracks passing the nearest tide gauge station are indicated.

The most energetic constituents of the ocean tide can be denoted as the following eight components: O1, N2, S2, M2, Q1, K2, P1, and K1 tides. The discrepancy between tidal period and measurement interval of the satellite altimeter can cause spatial aliasing of the tidal signals (Cartwright and Ray, 1990; Jacobs et al., 1992). Since the study area is well-known for strong tidal activity, it is important to properly eliminate aliasing errors. Table 1 shows the basic structure of T/P tidal aliasing suggested by Park and Gamberoni (1995). It is found that 75% of aliasing error consists of an alias period between 45–62 days, with M2 tides (62 days) being the most dominant followed by K1 tides. In addition, alias periods of S2 tides (59 days) appear to be comparable with those of M2 tides. Hence with the exception of the K1 constituent, all tidal aliases for T/P have periods shorter than 90 days. It may thus be likely that they are not confounded with long-period sea surface height signals from real oceanic processes (Schlax and Chelton, 1994).

Table 1. Tidal alias periods of TOPEX/POSEIDON (T/P) altimeter data for eight major diurnal and semidiurnal constituents

Tide	Tidal Period (hours)	Alias Period (days)	Model Tide Error (cm)	variance contribution (%)	
				Aliasing Error	Cumulative
O1	25.819342	45.7	1.16	7	7
N2	12.658348	49.5	1.63	13	20
S2	12.000000	58.7	1.57	12	32
M2	12.420601	62.1	2.97	43	75
Q1	26.868357	69.4	0.52	1	76
K2	11.967235	86.6	1.15	7	83
P1	24.065890	88.9	0.78	3	86
K1	23.934470	173.2	1.71	14	100

*The results of RMS errors in Texas tides and their variance contribution to the tidal aliasing error (Park and Gamberoni, 1995) are also provided

Table 2. Comparison of RMS errors of Sogwipo (Korea) and Chichijma (Japan) as a function of low-pass filtering period

Filter Period		Station	
		Sogwipo (SGP)	Chichijima (JCC)
30 days	RMS error (㎝)	25.43	9.16
	Correlation	0.35	0.80
	p-value	0.0001	0.0001
	Number of data	2087	2269
60 days	RMS error (㎝)	22.22	6.48
	Correlation	0.39	0.80
	p-value	0.0001	0.0001
	Number of data	2087	2269
100 days	RMS error (㎝)	3.90	4.02
	Correlation	0.93	0.94
	p-value	0.0001	0.0001
	Number of data	2087	2269
200 days	RMS error (㎝)	2.81	3.02
	Correlation	0.96	0.96
	p-value	0.0001	0.0001
	Number of data	2087	2269

Table 3. Amplitudes of major harmonic constituents (units: cm). From Park and Gamberoni (1995)

Constituents	Station	
	Sogwipo (SGP)	Chichijima (JCC)
O1	17.71 (7.9%)	12.06 (12.3%)
N2	16.32 (7.3%)	5.19 (5.3%)
S2	33.79 (15.1%)	12.60 (12.8%)
M2	76.56 (34.1%)	28.15 (28.6%)
Q1	3.60 (1.6%)	2.46 (2.5%)
K2	8.94 (4.0%)	3.50 (3.6%)
P1	7.92 (3.5%)	5.32 (5.4%)
K1	24.32 (10.8%)	16.39 (16.7%)

As a means to examine the level of tidal aliasing errors between different locations, we selected and compared T/P datasets of Sogwipo (SGP) in Korea (on shore) and Chichijima (JCC) in Japan (offshore). The results of a harmonic analysis indicate strong contrasting patterns (Table 2). In Table 3, amplitudes of major harmonic constituents are also compared between the two stations. In the case of SGP, the portions of M2 and S2 tides were almost 50% followed by the K1 of about 10%. The results of JCC were also comparable with the portions of M2, K1, and S2 comprising 28.6, 16.7, and 12.8%, respectively. It is noteworthy that the proportion of K1 is large for an offshore (JCC) relative to an onshore area (SGP). Considering the significance of these constituents, the errors associated with them should be properly treated.

To eliminate tidal aliasing errors associated with tide constituents, we applied a Gaussian low frequency filtering to the datasets. The response function of this Gaussian filter has a cut-off period near T and a half-amplitude pass period near $2T$. This Gaussian filter removes high-frequency fluctuations for a short half-amplitude pass window less than 200 days. However, it can preserve signals of longer periods relatively well without any deformation of phase. Through an application of this filtering procedure, components of short-period tides (diural or semidiural constituents) were subtracted from the data.

4. Results and discussion

4.1 *Comparison of T/P and TG datasets from an onshore area*

There have been numerous studies to validate the T/P altimeter against field-based sea level data such as those measured by tide gauges (Mitchum, 1994;

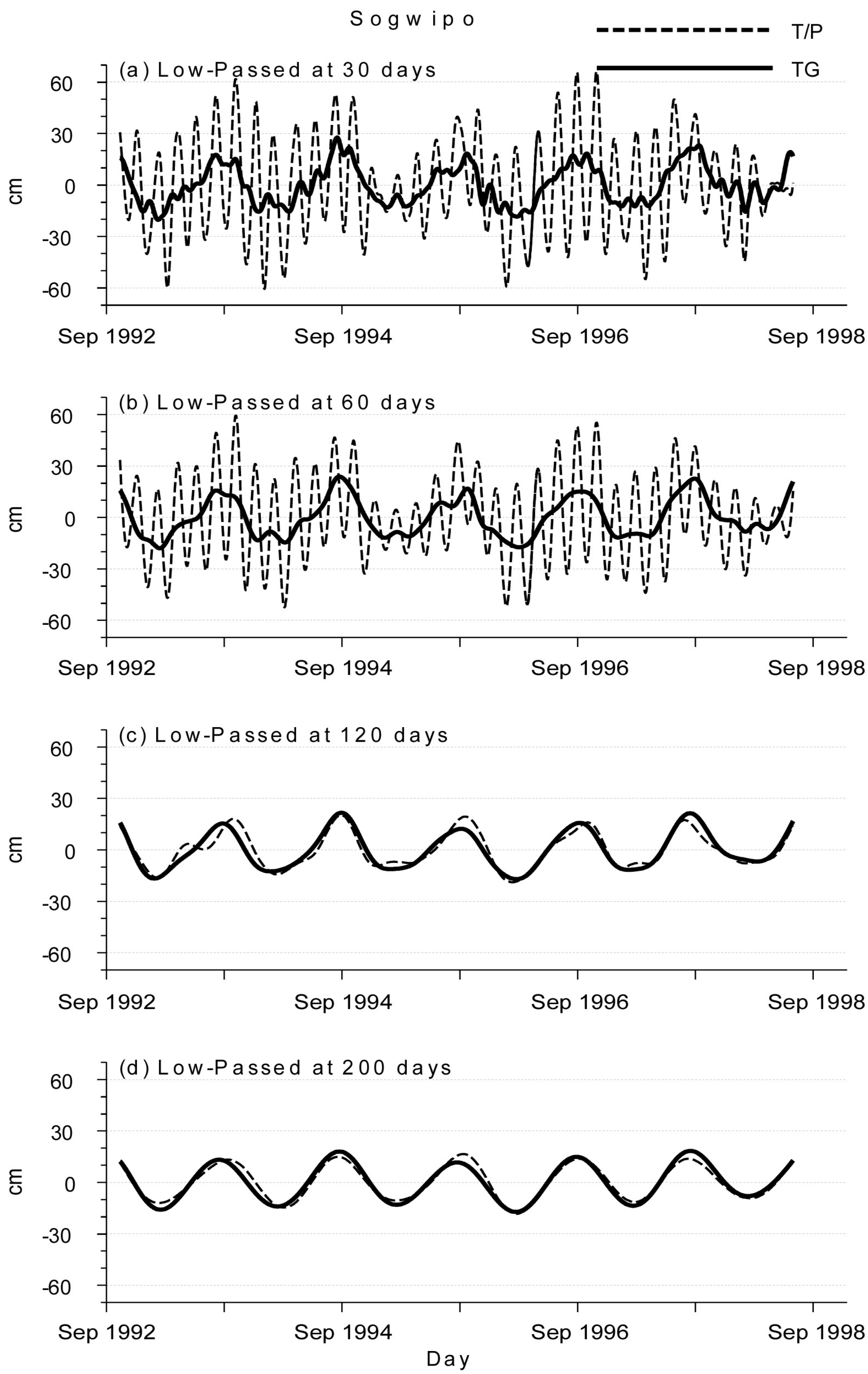

Fig. 2. Comparison of sea level time series derived from the TOPEX/POSEIDON altimetry (dashed line) without inverse barometric correction and the tide gauge measurements (solid line) at Sogwipo in Korea. Data have been low-pass filtered using a (a) 30-day, (b) 60-day, (c) 120-day, and (d) 200-day Gaussian filter.

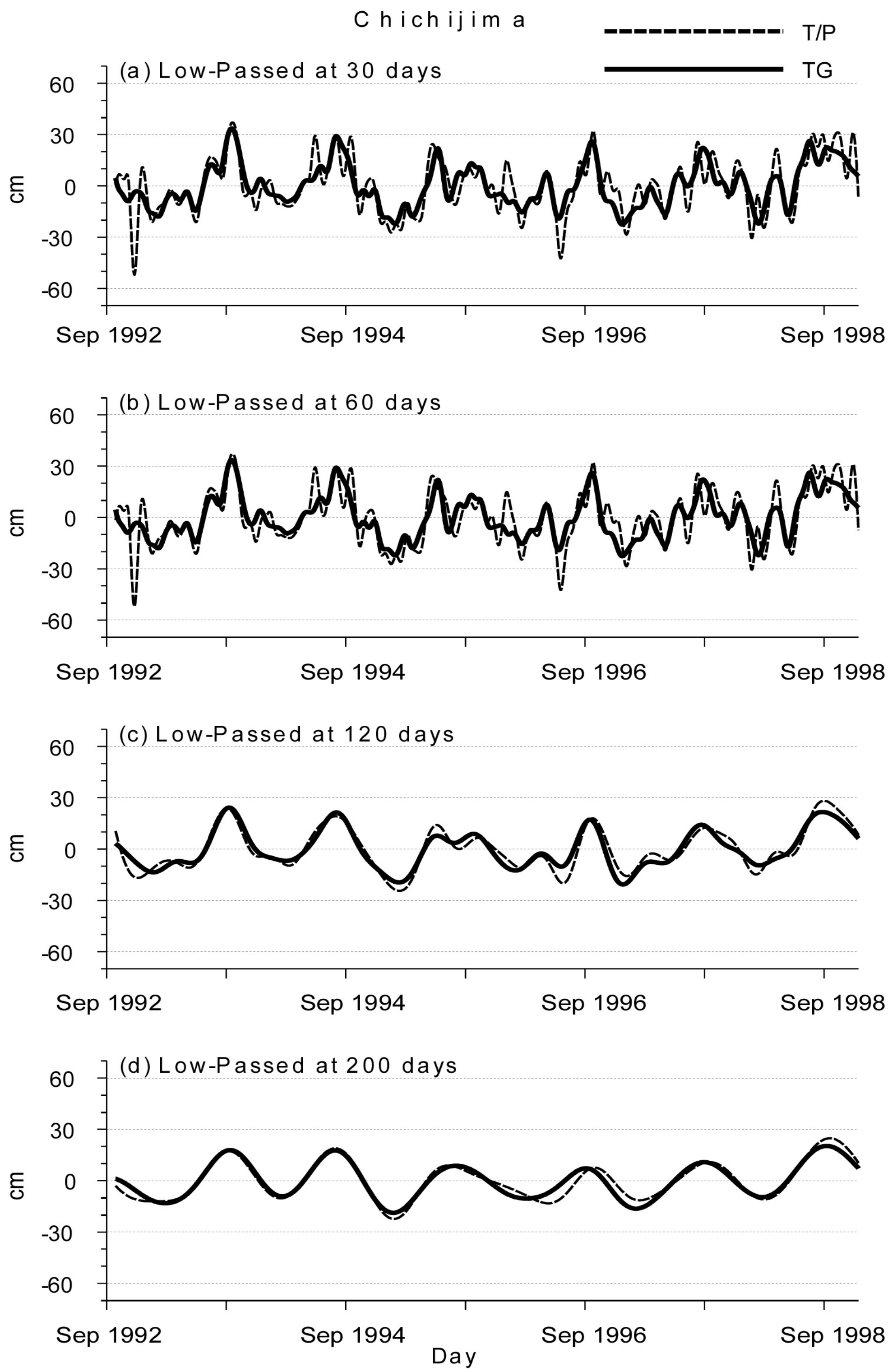

Fig. 3. Comparison of sea level time series derived from the TOPEX/POSEIDON altimetry (dashed line) without inverse barometric correction, and the tide gauge measurements (solid line) at Chichijima in Japan. Data have been low-pass filtered using a (a) 30-day, (b) 60-day, (c) 120-day, and (d) 200-day Gaussian filter.

Table 4. A comparison of T/P and TG datasets from 10 tidal stations. All data have been low-pass filtered using a 200-day Gaussian filter. For each station investigated, the parameters compared include: root mean square (RMS) error, correlation coefficient, *p*-value, number of data, and type of tide gauge

Station	RMS Error (cm)	Correlation coefficient	p-value	Number of data	Type of tide gauge
Kadukto (KAD)	3.23(6.05)*	0.94(0.64)	0.0001(0.0001)	1288	Float
Sogwipo (SGP)	2.81(7.43)	0.96(0.69)	0.0001(0.0001)	2087	Float
Kanmen-a (KAN)	6.70(5.59)	0.88(0.89)	0.0001(0.0001)	809	Float
Shanwei (SHA)	4.08(4.64)	0.86(0.86)	0.0001(0.0001)	818	Float
Naha (JNH)	5.24(6.42)	0.92(0.82)	0.0001(0.0001)	2260	Float
Chichijima (JCC)	3.02(4.12)	0.96(0.91)	0.0001(0.0001)	2269	Float
Shirahama (JSR)	4.91(6.43)	0.87(0.75)	0.0001(0.0001)	2250	Float
Miyakejima (JMJ)	5.16(6.25)	0.80(0.65)	0.0001(0.0001)	642	Acoustic
Choshigyoko (JCS)	4.30(5.15)	0.81(0.72)	0.0001(0.0001)	2260	Float
Sado (JSO)	3.78(6.88)	0.95(0.85)	0.0001(0.0001)	712	Float

*The values in parentheses are the RMS values corrected for inverse barometric effect.

Christensen et al., 1994; Tapley et al., 1994; Katz et al., 1995; Park and Gamberoni, 1995; Picaut et al., 1995; Verstraete and Park, 1995). Tapley et al. (1994) attempted to compare T/P altimeter data with those measured by tide gauges from the Pacific (13 monitoring stations) and the Indian Ocean (6 stations) and reported that RMS values fell in the range of 4 to 6 cm. By contrast, based on measurements from two monitoring stations in the western Pacific, Picaut et al. (1995) argued that they could attain an accuracy with RMS values as low as 3 to 4 cm by the selection of a correction scheme. Verstraete and Park (1995) also made a comparison between T/P and TG methods using the data collected from Sao Tom Island. They indicated that seasonal and annual changes were well reflected at low frequency filtering of 60 days, yielding RMS values as low as 2.2 cm.

In order to check the differences in surface sea level between the two methods, we made a comparison of T/P and TG datasets from one of the most inshore regions of 10 stations. Figure 2 shows a comparison of the T/P and TG sea level time series at the SGP station; for this comparison, different window sizes (30, 60, 120, and 200 days) were applied to the data obtained during the period of October 1992 to December 1998. The TG sea level data measured at one hour intervals were initially treated in terms of a harmonic function, and the Gaussian filter was applied after eliminating the tidal constituents of short periods (e.g., diurnal, semidiurnal components). The SGP station is under the influence of strong tidal activity. Hence, when the Gaussian filter was applied to the altimetric time series obtained from SGP at the filtering intervals of 30 ($T = 15$) and 60 ($T = 30$) days, the results were quite contrasting between the T/P and TG datasets. The T/P data exhibited strong signals with certain periodicity, while there were no such signals from the TG datasets. These unusual signals from the T/P datasets, while being suspected to be false ones not related to real oceanographical phenomena, are due to tidal aliasing associated with M2, S2, and K1 tides (e.g., Schrama and Ray, 1994; Park and Gamberoni, 1995). If this comparative analysis is examined for 120 days ($T = 60$), the existence of the false signals can still be found. However when the Gaussian filter was applied to 200 days ($T = 100$ days), the results showed a good agreement between the T/P and TG datasets.

4.2 *Comparison of T/P and TG datasets from an offshore area*

For offshore regions, strong compatibility is expected for the filtered datasets between the T/P and TG sea level measurements. To check for this possibility, we made a comparison between the two datasets collected from the JCC station; the selected station is most favorable for this purpose, since it is located on the most offshore region among all 10 stations investigated (Fig. 1). According to this analysis, the similarities and differences between the two datasets were quite apparent. For example, since tidal activity is weak in the JCC region, the false signal of T/P data is much weaker in JCC than in SGP. However when treated by the 200-day low-pass filter (T=100 days), both the T/P and TG datasets exhibited quite a compatibility in sea level (Fig. 3). In Table 2, the results of the comparative statistical analysis between the T/P and TG sea level time series are given for the different window sizes (30, 60, 120, and 200 days); the results of this analysis were expressed mainly in terms of such parameters as RMS, correlation coefficient, and *p*-value. For the results of the 200-day Gaussian filter,

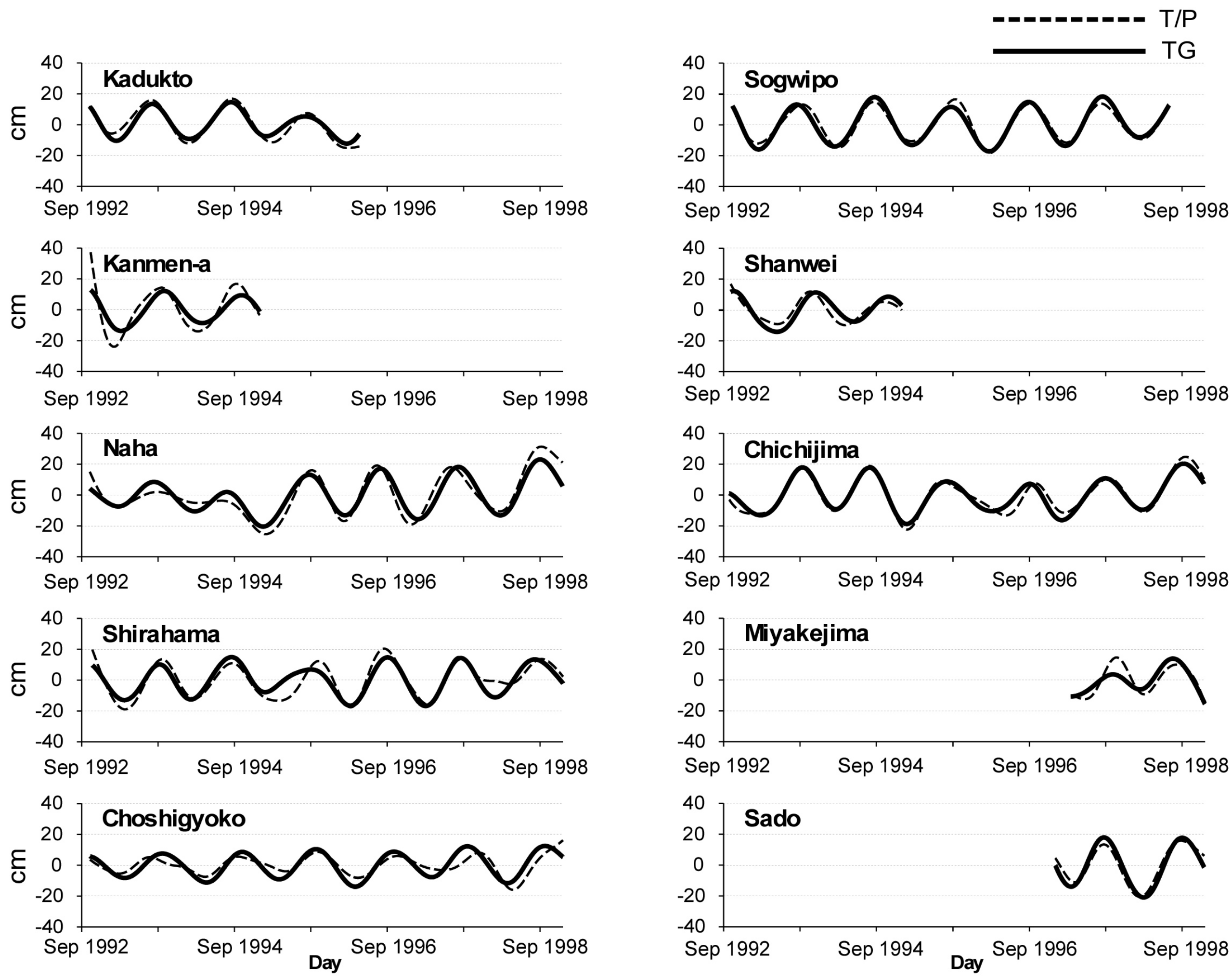

Fig. 4. Comparison of sea level time series derived from the TOPEX/POSEIDON altimetry (dashed line) without inverse barometric correction and the tide gauge measurements (solid line) at ten tide stations in the East Asian Marginal Seas. Data have been low-pass filtered using a 200-day Gaussian filter.

the correlation coefficient was as high as 0.96 with the RMS values of 2.81 cm (T/P) and 3.02 cm (TG). This observation indicates that the compatibility of the two datasets can become significant with the increase of filtering period, such as up to 200 days. Hence, it appears that both T/P and TG data seem to preserve signals with long periods.

As a means to check for the consistency of the two datasets, we extended this comparison to all the remaining stations (Fig. 4).

When compared with the 200-day Gaussian filtering period, most stations consistently show strong agreement between the two datasets. If the level of this agreement is compared among different stations in terms of correlation analysis, their relationships appear to be statistically significant for all stations investigated (Table 4). In addition, since the barometric and steric effects are reflected in our TG data, they can be compared to the T/P altimeter data without corrections for such effects. Hence, in accordance with our expectation, the results shown in Table 1 indicate that RMS values become much larger if TG data are corrected for such effects.

5. Conclusion

As a means to check the accuracy of satellite altimeter data, we undertake a comparative analysis of surface sea level heights derived using data from the T/P altimeter and 10 tide gauge monitoring stations in the marginal sea regions of the Korean Peninsula. Unlike the open ocean areas investigated in many previous studies, the areas selected for the present study are well known for strong tidal activity. Hence to properly evaluate the T/P data sets, errors associated with the tidal aliasing need to be significantly reduced. The T/P altimeter data, initially processed for the computation of dynamic heights, are compared with the TG data through an application of Gaussian filtering with various periods. Using those datasets, a detailed comparison of the two different sea level measurements is made between the inshore and offshore area. The results for the inshore area generally show a lack of compatibility between the two methods, relative to those of the offshore area. However, it is confirmed that the level of disagreement in explaining the sea level change between the two methods can be reduced substantially with reasonably long filtering periods of ∼200 days. The results of this study hence support the idea that sea level changes from strongly dynamic oceanic zones can be interpreted using satellite altimeter data.

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REFERENCES

Archiving, Validation, and Interpretation of Satellite Data in Oceanography (AVISO), 1992: AVISO User Handbook: Merged TOPEX/ POSEIDON Products, Publ. AVI-NT-02-101-CN, 2.1, Cent, Natl. d'Etudes Spatiales, Toulouse, France.

AVISO, 1998: AVISO User Handbook: Corrected Sea Surface Heights (CORSSHs), AVI-NT-011-311-CN.

Cartwright, D. E., and R. D. Ray, 1990: Oceanic tides from Geosat altimetry. *Journal of Geophysical Research*, **95**, 3 069–3 090.

Centre National d'Etudes Spatiales (CNES), 1994: SWT/JASO Meeting, Publ. TP-CR-03-8554-CN, Toulouse, France.

Choi, B. H., 1980: A tidal model of the Yellow Sea and the East China Sea. Korea Ocean Research and Development Institute (KORDI) Report, 80-02, 1–72.

Christensen, E. J., and Coauthors, 1994: Calibration of TOPEX/POSEIDON at Platform Harest. *Journal of Geophysical Research*, **99**, 24 465–24 485.

Jacobs, G. A., G. H. Born, M. E. Parke, and P. C. Allen, 1992: The global structure of the annual and semiannual sea surface height variability from Geosat altimeter data. *Journal of Geophysical Research*, **97**, 17 813–17 828.

Kang, Y. Q., and B. D. Lee, Byung, 1985: On the annual variation of mean sea level along the coast of Korea. *Journal of the Korean Society of Oceanography*, **20**, 22–30.

Katz, E. J., A. Busalacchi, M. Bushnell, F. Gonzalez, L. Gourdeau, M. McPhaden, and J. Picaut, 1995: A comparison of coincidental time series of the ocean surface height by satellite alitimeter, mooring, and inverted echo sounder. *Journal of Geophysical Research*, **100**, 25 101–25 108.

Marshall, J. A., N. P. Zelensky, S.M. Klosko, D. S. Chinn, S. B. Luthcke, and K. E. Rachlin, 1995: The temporal and spatial characteristics of TOPEX/POSEIDON radial orbit error. *Journal of Geophysical Research*, **100**, 25 331–25 352.

Mitchum, G. T., 1994: Comparison of TOPEX sea surface heights and tide gauge sea level. Journal of Geophysical Research, **99**, 24 541–24 553.

Naeije, M. C., E. Wisse, R. Scharro, and K. F. Wakker, 1993: Ocean Dynamics from the ERS-1 35-day repeat mission. *Proceedings of the Second ERS-1 Symposium*, Humburg, 11–14 October 1993, Eur. Space Agency Space. Publ., ESA SP-361, 1–6.

Nerem, R. S., and Coauthors, 1994: Gravity model development for TOPEX/POSEIDON: Joint gravity models 1 and 2. *Journal of Geophysical Research*, **99**, 24 421–24 447.

Nishida, H., 1980: Improved tidal charts for the western part of the North Pacific Ocean. *Report of Hydraulic Researches 15*, 55–70.

Nomitsu, T., and M. Okamoto, 1927: The causes of the annual variation of the mean sea level along the Japanese coast. *Journal of Marine Research*, **14**, 88–155.

Oh, I., S., B. R. Alexander, M. S. Park, and R. N. Mansurov, 1993: Seasonal sea level oscillations in the East Sea (Sea of Japan). *Journal of the Korean Society of Oceanography*, **28**, 1–16.

Oh, I. S., and M. S. Park, 1994: A study on the variation of monthly mean sea level of northwestern Asia by empirical orthogonal functions. *Journal of the Korean Earth Science Society*, **15**, 207–218.

Pang, I. C., and I. S. Oh, 1995: Warm water circulation and its origin by sea level fluctuation and bottom topography. *Journal of the Korean Fisheries Society*, **28**, 677–697.

Park, Y. H., and G. Gamberoni, 1995: Large-scale circulation and its variability in the south Indian Ocean from TOPEX/POSEIDON altimetry. *Journal of Geophysical Research*, **100**, 24 911–24 929.

Patullo, J. W., Munk, R. Revelle, and E. Strong, 1995: The seasonal oscillation in sea level. *Journal of Marine Research*, **14**, 88–156.

Picaut, J., A. J. Busalacchi, M.J. McPhaden, L. Gourdeau, F. I. Gonzalez, and E. C. Hackert, 1995: Open-ocean validation of TOPEX/POSEIDON sea level in the western equatorial Pacific. *Journal of Geophysical Research*, **100**, 25 109–25 127.

Schlax, M. G., and D. B. Chelton, 1994: Aliased tidal errors in TOPEX/POSEIDON sea surface height data. *Journal of Geophysical Research*, **99**, 24 761–24 775.

Schrama, E. J. O., and R. D. Ray, 1994: A preliminary tidal analysis of TOPEX/POSEIDON altimetry. *Journal of Geophysical Research*, **99**, 24 799–24 808.

Tapley, B. D., D. P. Chambers, C. K. Shum, R. J. Eanes, J. C. Ries, and R. H. Stewart, 1994: Accuracy assessment of the large-scale dynamic ocean topography from TOPEX/POSEIDON altimetry. *Journal of Geophysical Research*, **99**, 24 605–24 617.

Tvi, N. N., 1970: Seasonal sea-level variations of the South China Sea and their causes. *Journal of Oceanography*, **10**, 465–471.

Verstraete J. M., and Y. H. Park, 1995: Comparison of TOPEX/POSEIDON altimetry and in situ sea level data at Sao Tome Island, Gulf of Guinea. *Journal of Geophysical Research*, **100**, 25 129–25 134.

Yanagi, T., and S. Takahashi, 1993: Seasonal variation of circulations in the East China Sea and Yellow Sea. *Journal of Oceanography*, **49**, 503–520.

Yi, S. U., 1967: On the variations of monthly mean sea level along the coast of Korea. *Journal of the Korean Society of Oceanography*, **2**, 24–33.