Non-linear Sea Level Variations in the South China Sea from Satellite Altimetry and Tide Gauges

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Abstract: Non-linear sea level trend in the South China Sea (SCS) was investigated by means of satellite altimetry and tide gauge data over 24 years period from 1993 to 2016. GIA corrections and inverted barometer corrections were applied to the satellite and tide gauge data, and the monthly sea level anomalies (MSLAs) were compared between each other in details. Thirty tide gauges located in the SCS are in good agreement with satellite-derived results, with RMSDs ranging between 0.85 and 9.92 cm and correlation coefficients were more than 0.70 for 85.71% of stations. Non-linear sea level trend of observations during period of 1993-2016 was analysed by empirical mode decomposition, the sea level rise rate derived from satellite altimetry and tide gauge data are 4.29 ± 0.29 and 3.93 ± 0.12 mm/year, respectively.

1 INTRODUCTION

Sea level rise due to climate change can generate significant impact on the social economy, natural environment and ecosystem, especially in coastal areas. Many contributing factors make the sea level trend an integral measure of climate change (Church et al., 2010; Milne et al., 2009)

Satellite altimetry is an essential tool to describe the sea-level changes of the open ocean and marginal seas, as it provides precise and continuous datasets with global coverage and moderate spatiotemporal resolution (Cazenave and Llovel, 2010). Nowadays more than 20 years of satellite altimetry data are available, while most of the regional sea level changes observed from both satellite altimetry and tide gauge data were found to be different (Ishii and Kimotom 2009; Levitus et al., 2009; Lombard et al., 2005a; Lombard et al., 2005b; Stammer et al., 2013). However, temporal and spatial variability of sea level complicates estimation of sea level rise rates at regional and global scales. Regional sea level changes may differ substantially from a global average, showing complex spatial patterns, which result from ocean dynamical processes, lateral mass transport fluxes (Pinardi et al., 2014), and changes in gravity (Stocker et al., 2013).

South China Sea (SCS) is the largest marginal sea in Southeast Asia. Due to the unique bottom topography characteristics and the potential impacts of sea-level rise in SCS, understanding sea-level changes and monitoring of sea-level variability in this area becomes urgent. In the literature, many works study the sea-level trend in SCS using merged satellite data (Cheng and Qi, 2007; Feng et al., 2012). However, the short record of altimetry-based studies mostly reflects the interannual-decadal variability and cannot obtain the non-linear sea level variations. Gridded altimetry data were also validated at sea-level trend by comparison with tide gauge data (Luu et al., 2015; Marcos et al., 2015; Tay et al., 2016). Despite gridded satellite data is an interpolation of along-track data, it has a better temporal and spatial resolution due to multi-mission satellite-based. Therefore, the multi-mission satellite altimetry gridded data-set were used to analysis the sea level trend that are not possible with along-track data.

In this work we analysis the sea-level variations and trends using the gridded satellite data and all the tide gauge data available in the SCS over 24 years period from 1993 to 2016. The objectives of this paper are, to compare the sea-level anomalies between satellite data and tide gauge data, in terms of the error difference and correlation coefficient, and then to determine the non-linear sea-level

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variations and residual trend by performing empirical mode decomposition.

2 DATASETS

2.1 Satellite Altimetry Data

The delayed-time and reference gridded Sea Level Anomaly (SLA) weekly data product is used because it is more precise than near-real time data and has the best possible spatial and temporal sampling. The SLA observations produced by SSALTO/DUACS and distributed by AVISO for 24-year period from January 1993 to December 2016.

The satellite altimetry dataset used consist of merged data from multi-mission altimeter. Along track sea-level data are corrected for instrumental noise, orbit error, tidal effects and the dynamic atmospheric correction. The correction of atmospheric pressure and wind forcing was applied combines the high frequency sea-level variability of the barotropic ocean model MOG2D with the low frequency of the inverted barometer (IB) correction (Carrère and Lyard, 2003; Pascual et al., 2009). The corrected sea level data were then interpolated with objective analyses (Ducet et al., 2000), producing a regular grid with a horizontal resolution of 1/4°, every seven days. Data were averaged monthly at each grid point in order to use the same temporal resolution as the in-situ data.

2.2 Tide Gauge Data

Monthly mean sea level data were downloaded and extracted from the Permanent Service for Mean Sea Level (PSMSL). PSMSL provided the Revised Local Reference (RLR) tide gauge records with datum control (Woodworth and Player, 2003), in general, only RLR data should be used for time series analysis (www.psmsl.org). In the SCS area we selected 30 stations that have at least 20 years of data time series from 1993 (the beginning time of satellite window), a distance up to around 30 km between station and the nearest grid point, and at least 90% of the complete valid observations.

Vertical Land Motion (VLM) can affect the local sea level measurements, in order to obtain the reliable sea-level rates purely associated with the ocean dynamics, the VLM corrections have to be eliminated. System d' Observation du Niveau des Eaux Littorales (SONEL) aims at providing high-quality continuous measurements of sea and land levels at the coast from tide gauges (relative sea levels) and from modern geodetic techniques (vertical land motion and absolute sea levels) for studies on long-term sea level trends. However, not all the tide gauge stations co-equipped with the GPS measurements around the world. In the SCS, though there are 8 stations listed to measure the land displacements, their GPS data either have short (ranging from 4-7 years) records (6 out of 8 stations) or too much (20.53% and 30.04%, respectively) missing data (2 out of 8 stations). Since the Glacial Isostatic Adjustment (GIA) is the major component of the VLM in addition to the tectonics, subsidence, sedimentation and self-attraction and loading (Santamaría-Gómez et al., 2017), the GIA model result is applied as the VLM correction to the tide gauge stations.

3 METHODOLOGY

3.1 IB Corrections

In order to compare satellite and tide gauge monthly sea level data, the IB correction was applied to the tide gauge data, as explained for the satellite data. The IB correction was computed using Mean Sea Level Pressure (MSLP) from the monthly NECP/NCAR reanalysis data (Kalnay et al., 1996) provided by National Oceanic and Atmospheric Administration (NOAA) with a spatial resolution of 2.5°×2.5°. The IB correction mentioned above can be represented as (Dorandeu and Traon, 1999):

$$\eta^{IB}(x,y,t) = -\frac{1}{\rho g}[P(x,y,t) - P_{ref}(t)] \quad (1)$$

Where ρ is the sea water density, P is the MSLP, and $P_{ref}(t)$ is the MSLP spatial mean over the global ocean computed from 1993 to 2016.

3.2 EMD Method

EMD is widely used in dealing with non-linear and non-stationary time series. EMD decomposes an oscillatory signal, the time series y(t), with a sifting algorithm consisting of the following steps:

1. Identify all extrema of y(t).
2. Determine the two envelopes $e_{max}(t)$ and $e_{min}(t)$ by spline interpolating the minima and maxima of the signal.
3. Compute the average of the two envelopes, $R(t)=(e_{max}(t)+e_{min}(t))/2$.
4. Extract the residual signal, $d_n(t)=y(t)-R(t)$.

5. If $d_n(t)$ is an IMF, stop. Otherwise, iterate on $d_n(t)$ through steps 1 to 4.

Through the EMD process, the time series y(t) can be decomposed into n IMFs which embody the local characteristic information of the original signal. The objective of EMD is to extract IMFs that are physically and mathematically representative of the original time series. The decomposition can be expressed as follows:

$$y(t) = \sum_{i=1}^{n} x_i(t) + r(t) \tag{2}$$

where the final r(t) is the residual component, also can be considered as the n+1 IMF, and $x_i(t)$ is the finite number of IMFs.

4 RESULTS AND DISCUSS

4.1 Comparison of Satellite Altimetry and Tide Gauge Data

In this section we compare the sea-level signals of satellite and tide gauge at tide gauge stations using the nearest satellite altimetry grid point.

To obtain high precision of SLAs series, quality analysis was performed at each tide gauge station. Smoothed and interpolated data were obtained mainly for the missing data and appreciable errors using non-linear interpolation method. Figure 1 shows the comparison results between satellite and tide gauge, the difference errors between them were ranging from -45.46 to 59.14 cm, the errors have a normal distribution and 87.35% of them are within the range of ±10 cm.

The SLAs obtained from both two datasets show that they present similar performance in most of the cases considered, with mean root-mean-square difference (RMSD) was 2.72 cm, and 85.71% of them were under 5 cm. There are just 3 stations with higher RMSD than 6 cm. The stations with high RMSD are mainly due to the SLAs extracted from satellite and tide gauge have much larger mean square error difference errors, for example, the mean square error of satellite and tide gauge in HONNGU station is 2.88 and 8.74 cm, respectively. These results clearly indicate that the SLAs obtained from tide gauge data can be well represented by the majority of the nearest satellite point data, this is in agreement with findings by (Ruiz et al., 2015) for the annual component of sea level variations compared with the 478 worldwide distributed tide gauges. Through the correlation analysis of the two datasets, correlation coefficient of them for 85.71% of stations was above 0.70, and only two stations were below 0.50.

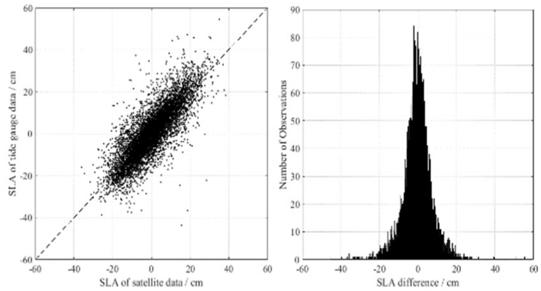

Figure 1: Comparison between sea-level signals of satellite and tide gauge data (left panel). Histogram of residuals between satellite and tide gauge data (right panel).

4.2 Sea Level Variations Analysis

Empirical Mode Decomposition (EMD) method is suitable for the analysis of non-linear and non-stationary signal sequences with high signal-to-noise ratio (Barnhart, 2011; Huang et al., 1998). Empirical mode decomposition is a key to this method, it can make the complex signal decomposed into a finite number of Intrinsic Mode Function (IMF), the decomposition of each IMF component contains the original signals of the local characteristics of different time scales.

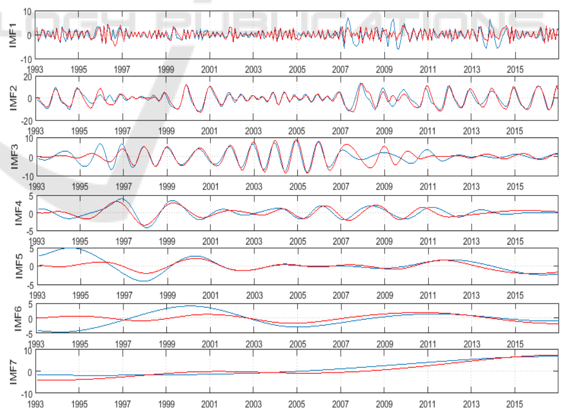

Figure 2: EMD analysis performed using satellite altimetry data (blue lines) and tide gauge data (red lines). The sea-level data time series are decomposed into 7 IMFs.

To examine the non-linear sea-level variations of satellite and tide gauges, we calculate the average of all tide-gauge stations and satellite altimetry sea-level signals. Considering 24 years of monthly data in 30 stations, EMD gives 7 IMFs in both data-sets.

Significant correlations were found for all the modes, which increase up to 0.98 in the residual component (IMF 7). Figure 2 shows the IMFs series, and the residual component (bottom panel). According to (Ezer and Corlett, 2012), which explaining that the residual component can reveal the sea level trend when EMD was applied to sea-level data, the residual component in this study shows the sea-level signals have a positive trend of 4.29 ± 0.29 and 3.93 ± 0.12 mm/year in terms of satellite and tide gauge data.

5 SUMMARY AND CONCLUSIONS

The aim of this work was to analysis the non-linear sea-level trends of the SCS retrieved from tide gauge and gridded altimetry data over 24-year (from 1993 to 2016). The comparison results between 30 tide gauge stations and the nearest grid satellite point show error difference are within the range of ±10 cm for 87.35% of the cases, correlation coefficient was above 0.70 in 85.71% of stations, and the mean RMSD was 2.72 cm. By averaging tide gauge and nearest grid point satellite data in the tide-gauge stations, two different non-linear sea-level trends were observed by applying a least squares method to the residual signals given by EMD from 1993 to 2016, which were 4.29 ± 0.29 and 3.93 ± 0.12 mm/year, respectively.

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