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ORIGINAL PAPER

ITERATION EMPIRICAL MODE DECOMPOSITION TO REDUCE THE NORTH-SOUTH STRIPING NOISE IN GRACE POST-PROCESSING

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ABSTRACT

Considering that the traditional EMD method cannot be used to sufficiently extract true geophysical signals during GRACE time-varying gravity field postprocessing, a novel iterative empirical mode decomposition (EMD) processing strategy was proposed. The proposed iterative EMD method fully considers the inadequacy of the traditional EMD method in extracting geophysical signals and filtering noise. In this research, a 14-yr spherical harmonic (SH) time series of GRACE CSR RL06 data truncated to degree and order 60 was analysed by the iterative EMD method, and the results were compared with those of the traditional EMD method. To gain insight into the extracted signals, we analysed them from two perspectives: the spectral domain and the spatial domain. The results showed that the correlation coefficients between the filtered SH coefficients obtained by the iterative EMD method and the original SH coefficients are lower than those obtained by the traditional EMD method; for example, the correlation coefficients of $C_{12,12}$ and $C_{60,60}$ were 0.95 and 0.88 and 0.72 and 0.58, respectively. The spatial domain results indicated that compared with the traditional EMD method, the iterative EMD method could effectively retain the signal intensity while filtering north−south stripe noise. Moreover, to evaluate the noise filtering efficiency, the ratios of the latitude-weighted RMS over land and ocean were adopted, and the mean RMS ratios for all available months obtained via the iterative and traditional EMD methods were 3.54 and 3.34, respectively, representing a relative improvement of 6.17 %. Finally, to verify the accuracy of the iterative EMD method in extracting geophysical signals, two river basins were analysed via comprehensive comparison with GRACE mascon data, and the results showed that the estimated regional mean mass change series obtained via the iterative EMD method is closer to that obtained from the GRACE mascon data. Thus, it can be concluded that the iterative EMD method can be employed to effectively suppress noise and more accurately extract real geophysical signals relative to the traditional EMD method.

1. INTRODUCTION

With the development of geodesy, satellite geodesy has become an extremely important means to monitor Earth changes. In particular, in the Gravity Recovery and Climate Experiment (GRACE), which is a joint research and development project of the United States and Germany and was launched in March 2002 (notably, the distance between the two satellites and the change in distance are continuously monitored) (Tapley et al., 2004), the change in the Earth's gravity field is obtained, which can be used to monitor terrestrial water storage change (TWSC) (Duvvuri and Beighley, 2023; Huan et al., 2023a; Pardo-Igúzquiza et al., 2023) and glacier melt (Wang et al., 2023; Xu et al., 2023), drought and flood conditions in a specific area (Cui et al., 2023; Huan et al., 2023a; Vishwakarma, 2020).

Considering that postprocessing of the adopted datasets is vital for follow-up work, the purpose is to effectively extract useful information from these datasets. Satellite orbit errors, sensor errors and model errors can produce a large amount of north–south stripe noise (Chen et al., 2005), which is unfavourable for subsequent inversion tasks. To precisely recognize changes in geophysical signals and surface mass, GRACE level-2 data must be filtered to achieve an improved spatial resolution. Many efficient filtering methods have been developed to suppress north–south stripe noise and effectively extract true geophysical signals, such as the original spatial Gaussian filtering method (Wahr et al., 1998), the anisotropic Gaussian filtering method, which is an improvement of the classical Gaussian filtering method (Han et al., 2005), and the Fan filtering method (Zhang et al., 2009), as well as certain decorrelation filters (Swenson and Wahr, 2006), several variations of the PnMm method, such as the P3M6 and P4M6 methods (Chambers, 2006; Chambers and Bonin, 2012; Chen et al., 2007), and sliding variable window polynomial fitting to remove correlation filtering (Duan et al., 2009). Other

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types of filtering methods, such as multichannel singular spectrum analysis (MSSA) (Zotov and Shum, 2010) and weighted MSSA (Shen et al., 2021) and improved MSSA methods (Wang et al., 2020), have been developed. Spectral class analysis methods, such as empirical mode decomposition (Huan et al., 2022), ensemble empirical mode decomposition (Huan et al., 2023c), and local mode decomposition (Huan et al., 2023b), have also been introduced for GRACE temporal gravity model postprocessing. Among these methods, spectral class analysis methods can be employed to efficiently extract the annual term, semiannual term, and long-period term of dataset time series, and the effect of filtering is greater than that of the other methods.

Motivated by the studies of Huan et al. (2022), Xia et al. (2019) and Qiu et al. (2022), we proposed an iterative EMD method for GRACE time-varying gravity field model processing. The novelty of the proposed method is its development based on certain criteria. For the first time, noise can be extracted from geophysical signals, which can greatly increase the accuracy of TWS inversion.

The remainder of this paper is organized as follows: in Section 2, the iterative EMD method is developed after a brief introduction to the traditional EMD method. The real GRACE temporal gravity model from April 2002 to August 2016 in the spectral domain is analysed in Section 3. The analysis of real GRACE data filtering results in the spatial domain is described in Section 4. To evaluate the iterative EMD method, concluding remarks are provided in Section 5.

2. DATA AND METHOD

2.1. *GRACE DATASETS*

The GRACE RL06 GSM which is released by the CSR (Center for Space Research) is adopted and which is truncated to degree and order 60 (Chen et al., 2021; Göttl et al., 2018). Monthly GRACE time-varying gravity field model contains measurements of April 2002 to August 2016, which can be obtained in http://icgem.gfz-potsdam.de/series. In addition to this, the RL06 GRACE GSM need to be added the degree- 1 term (Sun et al., 2016), and the C_{20} term is also needed to be replaced which is provided by Satellite Laser Ranging (Loomis et al., 2019).

2.2. *TRADITIONAL EMPIRICAL MODE DECOMPOSITION METHOD*

Empirical Mode Decomposition (EMD) is spectrum class analysis method which is useful for the analysis and processing of nonlinear non-stationary signals (Huang et al., 1998). The method has been extended to many fields, such as the processing of the GNSS signals and mechanical signal fault diagnosis (Qiu et al., 2021; Yu et al., 2005). The traditional EMD method processes the time series that can form a certain amount of IMFs (Intrinsic Mode Function) (He et al., 2020), each IMF can reflect various time- scale information. Each IMF need satisfy two criterions: (1) The number of local extreme points and zero crosses must be equal, or at most one different, throughout the data segment. (2) At any moment, the average value of the upper envelope formed by the local maximum point and the lower envelope formed by the local minimum point is zero, that is, the upper and lower envelope are locally symmetric with respect to the time axis. And the traditional EMD specific processing procedure is as follow:

Step 1: To find the extremum point of the original time series.

Step 2: To use the cubic spline interpolation method to fit the upper and lower envelope.

Step 3: Calculate the mean value of the Envelope *m(t)*.

Step 4: To get the *r(t)* which is by the original time series $x(t)$ minus the mean value *m(t)*.

Step 5: To judge whether the intermediate signal *r(t)* meets the two constraints of IMF. If yes, it is an IMF component and take $h_1(t)$ as the first IMF; if no, go back to Step 1 to iterate process time series. In actual processing procedure, it is hard to satisfy the condition of the average of upper envelope and lower envelope equals 0 for the IMF. The threshold formula of IMF to stop filtering is described below:

$$SD = \sum_{t=1}^{N}\left[\frac{|d_{k+1}(t)-d_k(t)|^2}{d_{k-1}^2(t)}\right] \tag{1}$$

where $d_k(t)$ and $d_{k-1}(t)$ are two adjacent data series in the IMF selection processing and *N* represents the length of data series, *SD* is the threshold at which each IMF stops filtering, which is generally taken as a number between 0.2 and 0.3 (Huang et al., 1998).

Step 6: $r_1(t)$ is the generated time series which is given by subtracting original time series $x(t)$ from $h_1(t)$.

$$r_1(t) = x(t) - h_1(t) \tag{2}$$

Step 7: To take the $r_1(t)$ as the new time series to perform above steps, decomposition stops until the residual component is a monotone function or constant and obtain n IMF components. The residual component is usually denoted as res. The original data series can be represented as follows:

$$x(t) = \sum_{i=1}^{n} IMF_i + res \tag{3}$$

where i and n respectively is the number of IMF and the index of IMF, $res$is the residual term.

2.3. *ITERATION EMPIRICAL MODE DECOMPOSITION FOR FILTERING GRACE FIELD SOLUTIONS*

Considering the traditional EMD method which has some disadvantages, the extracted noise portion processed by traditional EMD method may still have

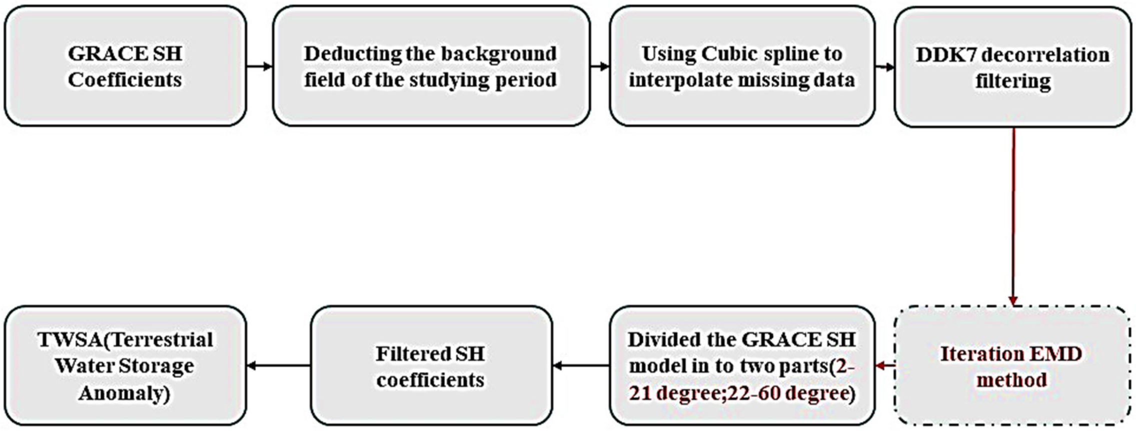


Fig. 1 The postprocessing flowchart of iteration EMD.

part of the real geophysical signal not fully extracted and motived by Huan et al. (2022) and Xia et al. (2019). The iteration EMD method is adopted to filter the GRACE time-varying gravity model. The process of postprocessing GRACE time-varying gravity field model by iteration EMD is shown in Figure 1. To better enhance the filtering effect, the filtering processing of iteration EMD is as follows:

1. Deducting the background of the studying period and using the cubic spline interpolation to fill the missing monthly data.
2. To adopt the decorrelation strategy which is similar to Huan et al. (2022), the DDK7 filtering is used to post processing.
3. To divide the GRACE Spherical harmonic (SH) coefficient model into two parts, degree 2 to 21 as one part, degree 22 to 60 as other part. The separated two parts are filtered separately, firstly, to extract the anniversary term as well as the part greater than the anniversary term by traditional EMD. And then, generating signal and noise two parts. Secondly, given that the extracted noise also contains some real geophysical signals, the noise part was iterated to generate the signal and noise part. In the iteration EMD processing, we adopted the power spectrum analysis method when selecting the IMF component, firstly, extracted the signal whose period ranged from 0.9 to 1.1, and then for the rest, extracting the signal whose period ranged from 0.4 to 0.6. The signals extracted from these two parts are synthesized into new signals, the noise part continues to perform the above signal extraction process, and the extracted signal is then added back to the first generated signal, iterating for a certain number of times. The number of iterations is an empirical value, which is finally determined to be 10.
4. To obtain the filtered GRACE SH model and convert SH into the Equivalent Water Height (EWH) in grid form.

3. RESULTS AND ANALYSIS

3.1. RESULTS AND ANALYSIS IN SPECTRUM DOMAIN

Considering the principle of the traditional EMD method and its processing strategy, the results were analysed in the spectral domain, which can facilitate the observation of the variation in the SH coefficient (Yi and Sneeuw, 2022). Although the traditional EMD method aims to preserve more information related to the original SH coefficient, the remaining part still contains noise, which adversely affects inversion processing. We account for this disadvantage by adopting a novel processing strategy. Considering the advantages of the traditional EMD method in terms of its high order and degree, contingencies cannot occur. Thus, two distinct degrees of SH coefficients, namely, $C_{12,12}$ and $C_{60,60}$, are employed for comparison to verify the proposed method, as shown in Figure 2. The first-row subgraph of Figure 2 shows that the curve of the SH coefficient obtained via the iterative EMD method is smoother than that of the SH coefficient obtained via the traditional EMD method, and because the high-degree part contains more noise, the processing result is reasonable. The second-row subgraph of Figure 2 shows that the curve of the SH coefficient processed by the iterative EMD method is also smoother than that of the SH coefficient processed by the traditional EMD method, which indicates that the iterative EMD method can achieve better noise filtering performance. Table 1 provides the correlation between the filtering coefficients obtained with the two methods and the original data. The correlation coefficients of the SH coefficient processed by the iterative EMD method are lower than those processed by the traditional EMD method.

The correlations with the original data after processing with the traditional and iterative EMD methods are shown in Figure 3. Various degrees of correlation are found in the low- and high-degree parts, and the SH coefficients in the low-degree part after traditional EMD filtering exhibit a higher

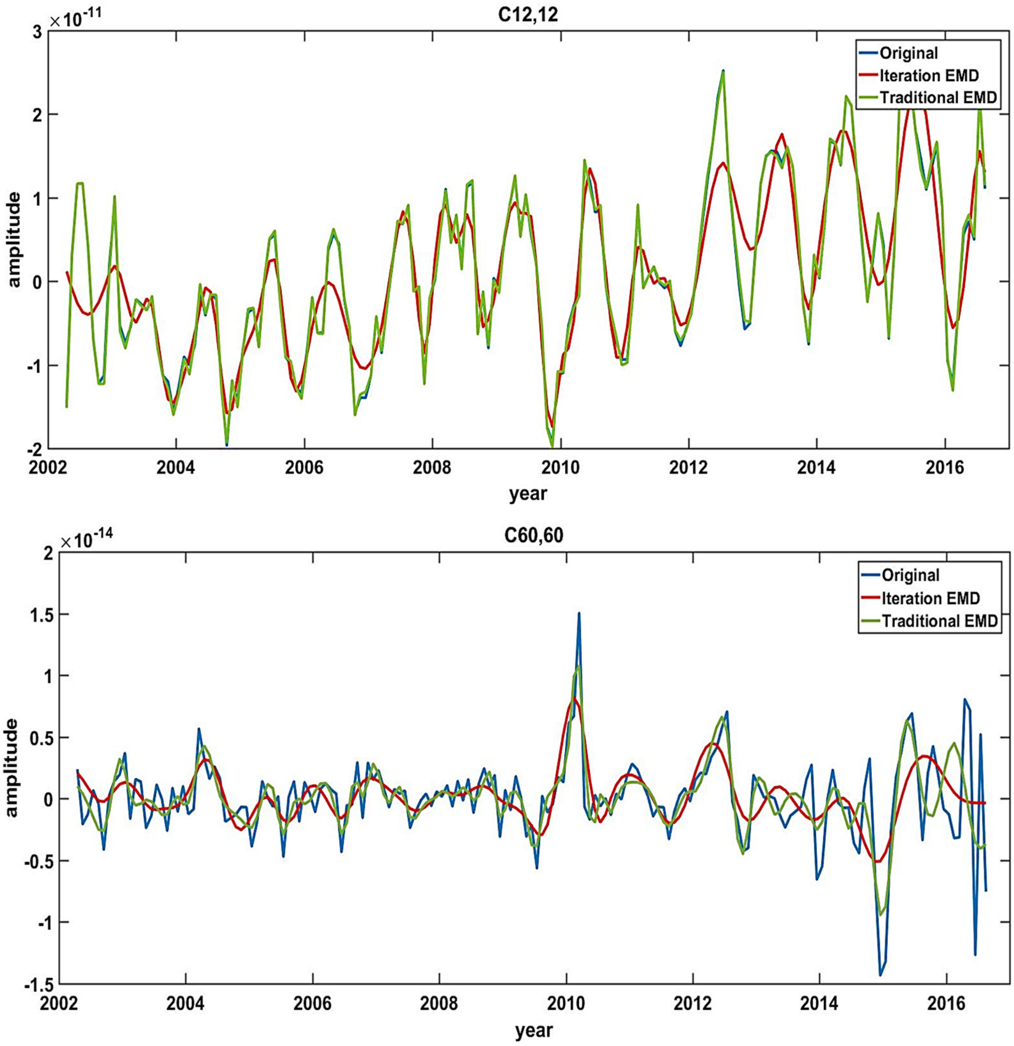


Fig. 2 $C_{12,12}$ and $C_{60,60}$ SH coefficients comparison of filtering and unfiltering.

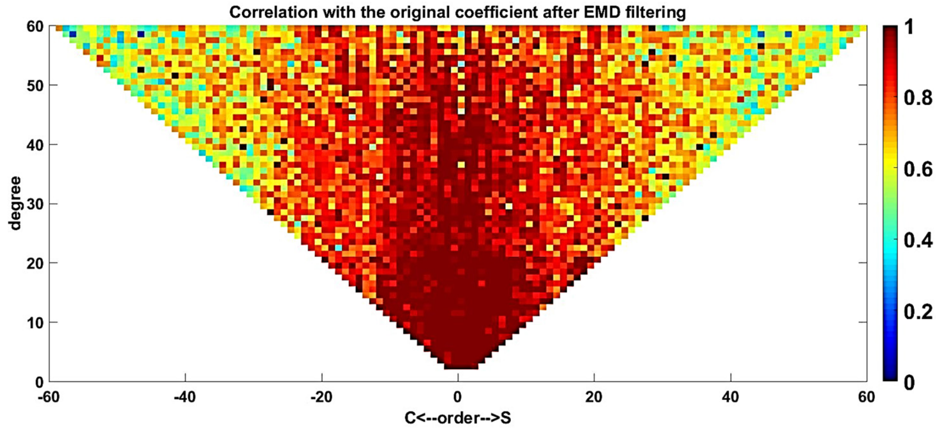
Table 1 The correlation coefficients of $C_{12,12}$ and $C_{60,60}$ SH coefficients between the filtered by traditional and iteration EMD and the original SH coefficients.

Index	Traditional EMD	Iteration EMD
$C_{12,12}$	0.95	0.88
$C_{60,60}$	0.72	0.58

correlation with the original coefficients than do those obtained after iterative EMD filtering, which demonstrates that the traditional EMD method removes less information related to the original SH coefficients. The extracted information may contain more noise, which requires further verification. Compared to those obtained with the iterative EMD method, the SH coefficients in the relatively high- degree part after traditional EMD filtering exhibit a higher correlation with the original SH coefficients. This also reflects that the traditional EMD method can be used to extract more information related to the original data. Here, correlation analysis revealed that the traditional EMD method can preserve more of the original SH coefficient information than does the iterative EMD method. However, this method may yield information with more noise, which must be further validated.

3.2. RESULTS AND ANALYSIS IN SPATIAL DOMAIN

The SH coefficients model from April 2002 to August 2016 is used in the research, which includes 156 months, based on the whole fact, using linear interpolation to fill the missing monthly data. To comprehensively analyze the filtering efficiency of stripe noise removal, the spatial inversion graphs of two randomly selected months (January 2003 and March 2016) are displayed in Figure 4. Considering the denoised ability of the EMD method, the combined filtering is adopted to process the GRACE temporal gravity field model (Huan et al., 2022; Huan et al., 2023).



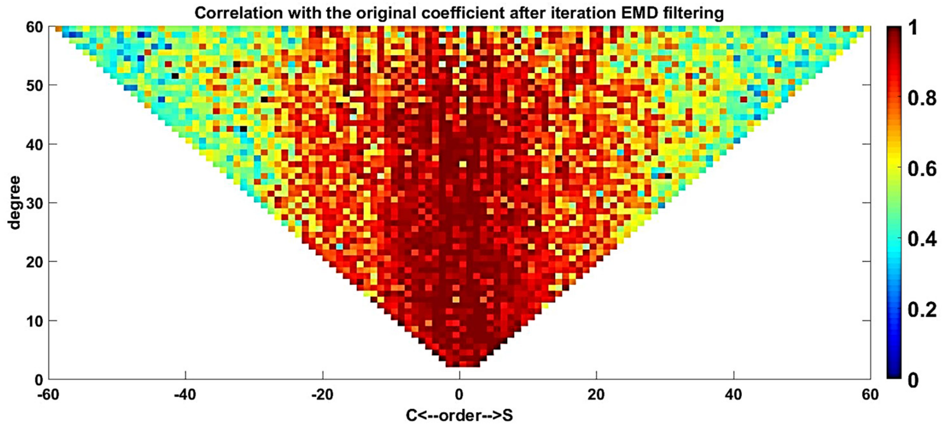


Fig. 3 The correlation coefficients between the filtered SH coefficients by traditional EMD, iteration EMD and the original SH coefficients for all degrees and orders.

There is notable stripe noise in the spatial inversion graph during the unfiltered period, both in January 2003 and March 2016, and stripe noise removal after iterative EMD filtering was better than that after traditional EMD filtering, thereby retaining stronger signals in some areas. To evaluate the filtering efficiency, the ratio of latitude weighted RMS of land and oceans is adopted to evaluate the denoised efficiency of the two methods which is based on the fact that the surface mass of the land as a whole is more variable than that of the oceans., in addition to the C_{20} term, the variability ratio is the ratio of latitudinal weighted RMS values on land and ocean signals (Chen et al., 2006).To reduce the leakage of signals from land, we adopt a 300km buffer zone.

$$RMS\_ratio = \frac{RMS(MASS_{land}+Err)}{RMS(MASS_{ocean}+Err)} \tag{4}$$

$MASS_{land}$ and $MASS_{ocean}$ are the signals on land and ocean, respectively, and Err is the noise. The IMP of RMS_ratio of iteration EMD with respect to traditional EMD method is calculated by,

$$IMP = \frac{RMS\_ratio_{Iteration\_EMD} - RMS\_ratio_{EMD}}{RMS\_ratio_{EMD}} \times 100\ \% \tag{5}$$

Figure 5 shows the RMS ratios of all degrees for all available months obtained via the traditional and iterative EMD approaches from April 2002 to August 2016. Almost all the RMS ratios obtained by the iterative EMD approach are greater than those obtained by the traditional EMD approach, while it can also be concluded that the iterative EMD method can be used to more effectively extract geophysical signals and filter noise for all degrees of the SH coefficient model than can be achieved by the traditional EMD approach. To further verify the denoising efficiency and signal extraction ability of the iterative EMD method, we choose the 20th degree as the range and process the data only before 20 and 40 degrees to comprehensively validate the filtering performance of the iterative EMD method and avoid chance occurrences. The RMS ratios of the two methods for the partial degrees of the SH coefficient model in all

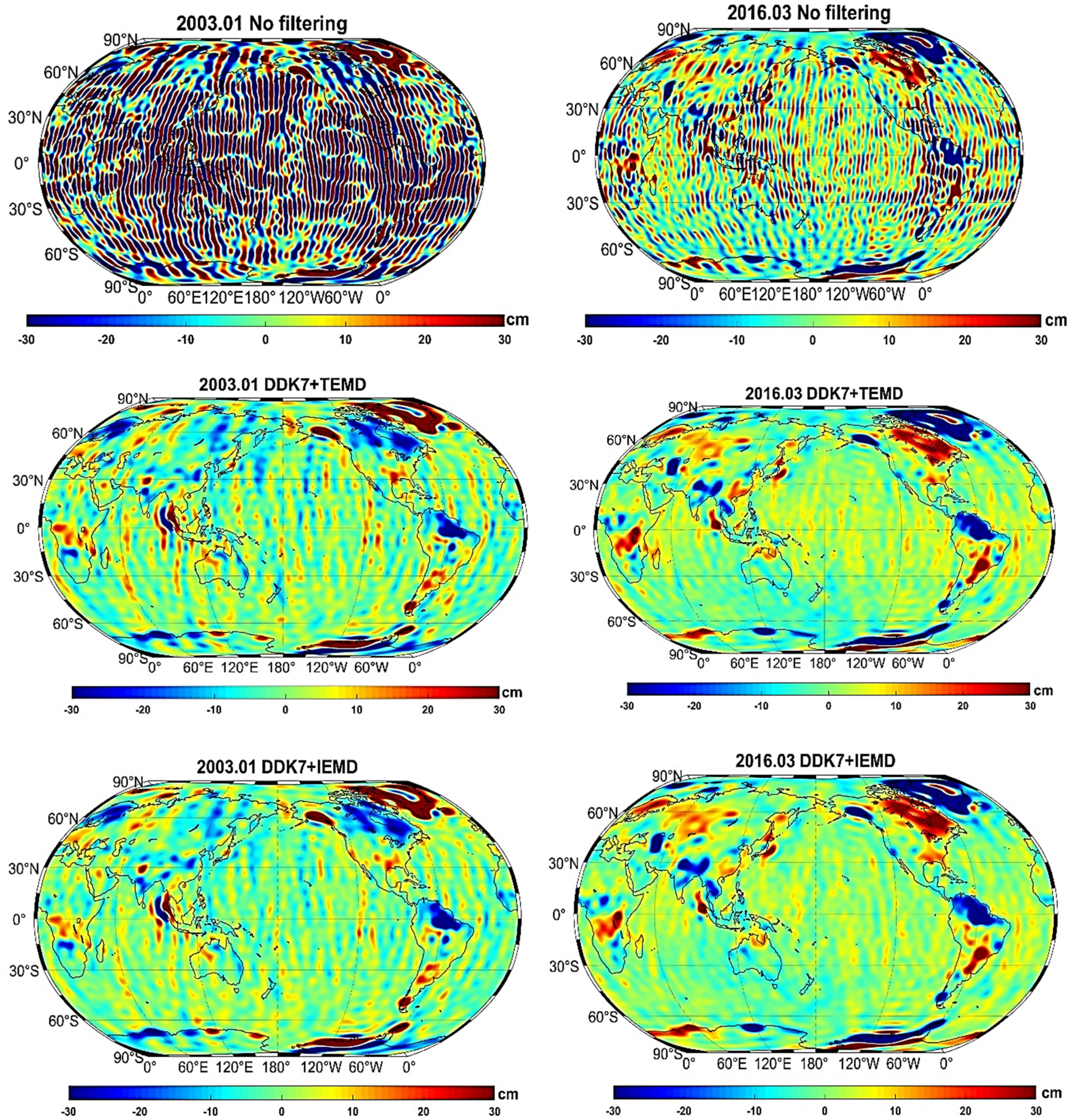


Fig. 4 Global mass change comparison of adopting the traditional EMD and iteration EMD methods in January 2003, March 2016 (TEMD:Traditional EMD; IEMD:Iteration EMD).

available months from April 2002 to August 2016 are shown in Figure 5, which reveals that almost all the RMS ratios of the iterative EMD method are greater than those of the traditional EMD method (shown in the two subplots).

The mean RMS ratios in all available months from April 2002 to August 2016 for processing different degrees of truncation and the corresponding *IMPs* are provided in Table 2. Table 2 indicates that the mean RMS ratios of the traditional and iterative EMD methods when using all degrees of SH are 3.34 and 3.54, respectively. However, for the SH coefficients truncated to degree 40, the mean RMS ratios are 3.06 and 3.08, respectively, and for the SH coefficients truncated to degree 20, the values are 2.85 and 2.86, respectively. The corresponding IMPs for the three processing strategies are 6.17 %, 0.49 %, and 0.31 %. Notably, the RMS ratios of the traditional and iterative EMD methods in January 2003 and March 2016 are provided in Table 3, at 2.46 and 2.93 and 4.07 and 4.60, respectively. Thus, considering all the above experimental analysis results, we can conclude that the iterative EMD method can filter noise and extract real geophysical signals more effectively than the traditional EMD method.

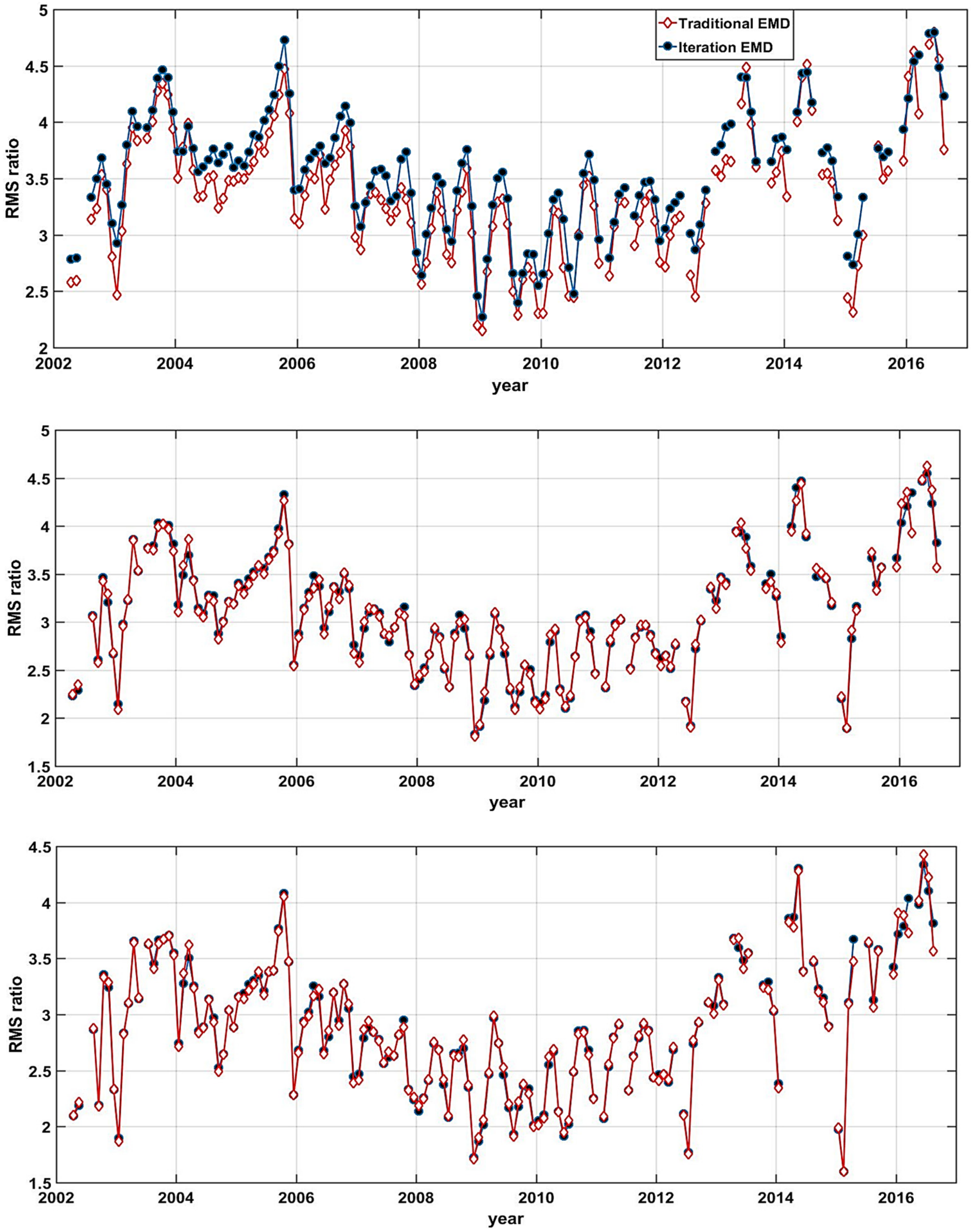


Fig. 5 The RMS_ratios for all available months by traditional EMD and iteration EMD methods from April 2002 to August 2016 (First row: processing all degrees; Second row: only processing before degree 40; Third row: only processing before degree 20).

Table 2 The mean RMS_ratios of all available months by traditional EMD and iteration EMD methods and corresponding *IMPs*.

Index	Traditional EMD	Iteration EMD	IMP (%)
All degrees	3.34	3.54	6.17
Degree 40	3.06	3.08	0.49
Degree 20	2.85	2.86	0.31

Table 3 The RMS_ratios by traditional EMD and iteration EMD methods in January 2003 and March 2016 and corresponding *IMPs*. (All degree).

Index	Traditional EMD	Iteration EMD	IMP (%)
2003.01	2.46	2.93	19.11
2016.03	4.07	4.60	13.03

3.3. REGION RIVER BASINS SIGNAL EXTRACTION VERIFICATION AND ANALYSIS

To verify the noise filtering performance and signal extraction capability of the iterative EMD method, two river basins (Yangtze and Amazon) are selected to validate the estimated mass changes derived from the traditional and iterative EMD methods compared with official GRACE mascon data. As shown in Figure 6, the estimated mass change series after filtering by the traditional and iterative EMD methods are consistent with those from the official GRACE mascon data. However, there were slight differences during various periods. Table 4 provides Pearson's correlation coefficient, RMSE and MAE values for the estimated mass changes filtered by the traditional and iterative EMD methods with respect to the GRACE mascon data. The Pearson correlation coefficients of the iterative EMD method are higher than those of the traditional EMD approach, and the RMSEs and MAEs are smaller than those of the traditional EMD method in the two river basins, which indicates that the iterative EMD method can extract geophysical signals and filter noise more accurately than the traditional EMD method.

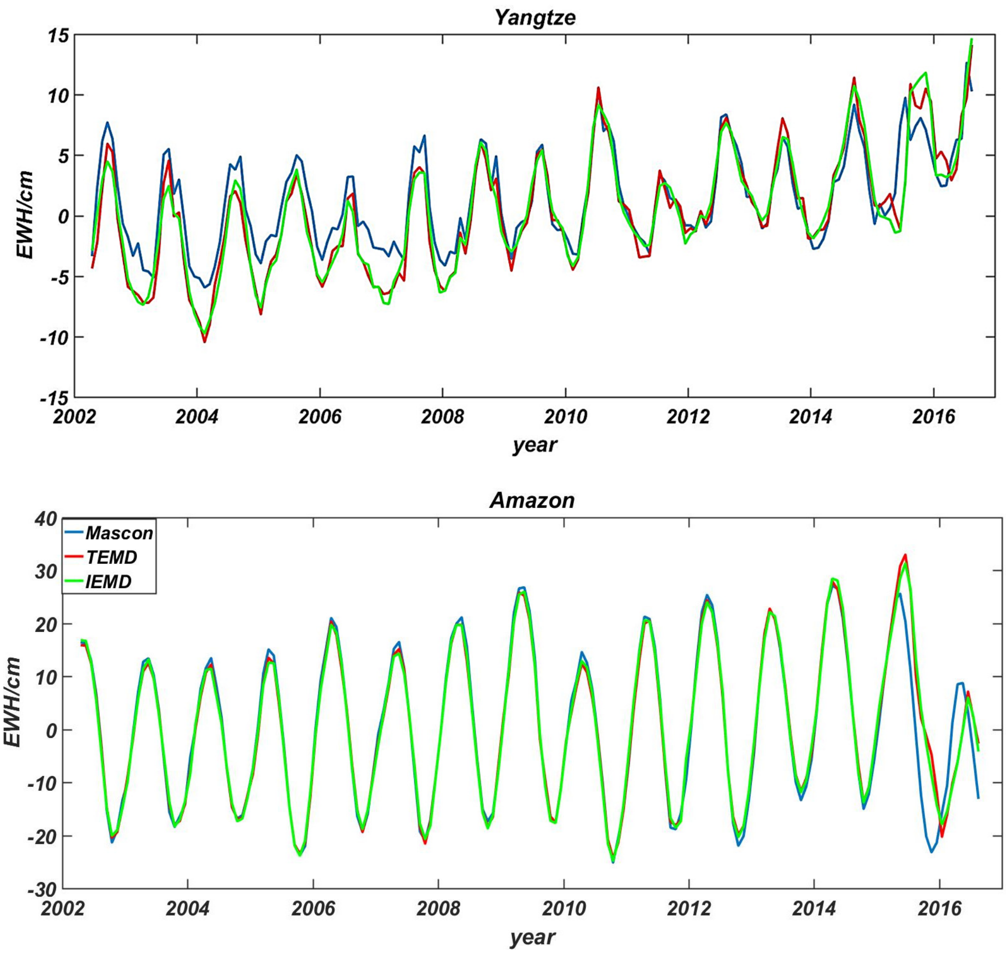


Fig. 6 Mass change series comparison of Amazon and Yangtze.

Table 4 Pearson correlation coefficient, RMSEs and MAEs of traditional EMD (TEMD) and iteration EMD (IEMD) in Amazon and Yangtze.

Index	Pearson correlation		RMSE/cm		MAE/cm	
	IEMD	TEMD	IEMD	TEMD	IEMD	TEMD
Amazon	0.97	0.96	3.58	3.71	1.77	1.81
Yangtze	0.92	0.91	2.17	2.23	1.72	1.76

4. CONCLUSIONS

In this research, we proposed a new EMD-based processing strategy, namely, the iterative EMD method. GRACE SH coefficient models from April 2002 to August 2016 were used for comparison and analysis. The experimental results were analysed in the spectral domain and spatial domain, and all the SH coefficients were analysed regarding their filtered correlation with the original data, which indicates that the correlation between the SH coefficients and the original data after iterative EMD processing is lower than that after traditional EMD filtering. Combined with full-text research, the above low correlation with the original coefficients after iterative EMD filtering was explained via a comparison with the traditional EMD method, which can be used to filter out more useless information and retain more signals. According to the spatial inversion graph, both the traditional and iterative EMD methods can effectively remove stripe noise, and the iterative EMD method can remove noise in some areas while more accurately retaining more signals; notably, the signal strength is greater. The RMS ratio was used to demonstrate the ability of the proposed method to extract signals accurately. The mean RMS ratios of the traditional and iterative EMD methods for all available months were 3.34 and 3.54, respectively. Almost all the RMS ratios in the available months of the iterative EMD method were greater than those of the traditional EMD method. To prevent incidental occurrences, we chose different degrees of the SH coefficient model for the experiments, and the results showed that the mean RMS ratio of the iterative EMD method was greater than that of the traditional EMD method. Finally, we adopted official GRACE mascon data for two river basins with intense hydrological activity to compare the mass changes after filtering by the two methods, and the results indicated that the geophysical signals extracted by the iterative EMD method are closer to those extracted from the GRACE mascon data. Therefore, we can conclude that the iterative EMD method can better reduce strip noise and retain more geophysical signals than can the traditional EMD approach.

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