Dear Referee

Thanks for your in-depth review of the manuscript and relevant comments, which helps us to improve our manuscript indeed. Below is the response to the comments point by point.

Interactive comment on "Response of Antarctic Ice Sheet Mass Balance to Climate Change" by Jingang Zhan et al. Anonymous Referee #2 Received and published: 5 December 2018

General Comments:

- This paper uses complex principal component analysis and wavelet amplitude-period spectrum analysis to examine the main drivers of Antarctic mass change. While the study of the effect of quasi-periodic climate patterns such as the El Nino on Antarctica are important, it is misleading to mostly attribute Antarctic mass balance to such events. Furthermore, the GRACE analysis in the paper suffers from some inadequacies. These issues are explained below. Overall, the paper in its current state is not suitable for publication as it provides misleading conclusions. Significant major revisions are required before potential further review.

  The paper assumes that Antarctic changes are caused by low-frequency quasi-periodic climate phenomena and atmospheric circulation patterns, and attempts to divide the attribution of ice sheet mass balance change to such events. However, no evidence is provided for this assumption and yet this is a major underlying assumption of the study. This is misleading, as these events play a much smaller role in the mass balance of the AIS compared to non-cyclic long term patterns such as enhanced ice-ocean interaction and ice discharge, intrusion of warm saline water on retrograde slopes, etc. The assumption of this paper can lead to misleading conclusions as the oscillatory climate events play a much smaller role in the recent mass balance. Yet the authors attribute the components of the CPCA to climate change as far as its effects on periodic climate phenomena such as the El Nino. For example the authors claim "This result shows that changes in the low-frequency signal of the sea surface temperature anomaly in the Niño1+2 region of the equatorial Pacific Ocean may be the main reason affecting the mass change of the ice sheet in Antarctica." Again it is misleading to attribute cyclic SST anomalies from El Nino to the main driver of AIS mass balance change.

  Response:

Based on your suggestion, we have added content to improve the manuscript. Supplemental content includes: (1) Literature and words were added in the discussion section to increase the interpretation of the results and to help readers extract information from the results. (2) Discussion sections 5.2 and 5.3 were reorganized and the statements were also revised with more appropriate words; the theoretical formulas of CPCA and additional explanations on how to read the data were also supplemented respectively in the Methods and the Discussion. (3) Conclusion were reorganized and the statements were also revised with more appropriate words. (4) The method of mask was used with the drainage basins boundary data to remove the effect of signals leakage. (5) The related literature are also supplemented in the reference section.

The mass balance of the Antarctic ice sheet, in addition to being affected not only by the quasi-periodic climate phenomena and atmospheric circulation, but also exposed to the influences of non-cyclic long term patterns, such as enhanced ice-ocean interaction and ice discharge, intrusion of warm saline water on retrograde slopes. The expression of these issues in the manuscript may be ambiguous and we have edited them in the revised manuscript.

In recent decades, various techniques have been developed to measure changes in ice-sheet mass, based on satellite observations of their speed (Rignot et al., 2002), volume (Wingham et al., 1998) and gravitational attraction (Velicogna et al., 2006) combined with modelled surface mass balance (Van et al., 2018) and glacial isostatic adjustment. There also have been more than 150 assessments of ice loss from Antarctica based on these approaches since 1989, which provide similar results over the period 1992–2011. Shepherd et al. (2018) extended this assessment to include twice as many studies, doubling the overlap period and extending the record from 1979 to 2017. They also found that there has been a large mass loss in West Antarctica with 159 ± 26 billion tons per year and attributed this mass loss to be ocean-driven.

Raphael et al. (2016) studied the Amundsen Sea low (ASL) and found that the Amundsen–Bellingshausen Sea (ABS) region exhibits some of the largest inter-annual atmospheric circulation variability, due in part to orographic forcing and in part to its location in the South Pacific, where atmospheric Rossby waves associated with ENSO variability have a year-round influence. The ENSO plays a significant role in determining the depth of the ASL. The most energetic Rossby waves associated with ENSO variability in the Southern Hemisphere occur in spring, and hence the strongest correlations between ENSO variability and the ASL generally occur in spring. In its La Niña phase, in spring, ENSO is associated with a deeper ASL and with warm air advection toward the Antarctic Peninsula and West Antarctica. However, from spring to summer the sign of the correlation of the phase of ENSO with respect to air temperature anomalies over Antarctica reverses in many locations. They pointed out that the ASL is an important circulation feature that influences West Antarctic climate variability. The ASL has deepened in recent decades with potential impacts on the regional climate through its influence on the meridional wind field. Some research has suggested that tropical teleconnections have contributed to atmospheric warming in West Antarctica and across the peninsula (Ding et al. 2011; Schneider et al. 2012a), and to sea ice loss in the Bellingshausen Sea (Li et al. 2014). The ASL may be related to the variability of the SAM (e.g., Fogt et al. 2011) and ENSO (e.g., Lachlan-Cope and Connolley 2006). Paolo et al. (2018) pointed out that studies correlating ENSO tropical forcing with Pacific sector climate indicators, such as the Amundsen Sea Low strength, sea-ice extent, and AP temperature, found that correlations with ENSO are significant for some seasons but not for others, with reversals of the sign of the correlation from season to season in some cases. The dominant effect of El Niño on the Amundsen Sea ice-shelf mass is the increased basal melting associated with the onshore flow of Circumpolar Deep Water and coastal upwelling as westerly wind stress intensifies.

Paolo et al. (2018) also pointed how the El Niño /Southern Oscillation affects the height and mass of ice shelves in the Amundsen Sea sector of the West Antarctic Ice Sheet. The response in height is the combined effect of two opposing processes, which are both intensified during El Niño events: surface snow accumulation and ocean-driven basal melting. The result is an overall height increase, but net mass loss, since the ice lost from the base has higher density than the fresh snow being gained at the surface. Ice-shelf response to ENSO variability is strongest between the Dotson and Ross ice shelves, with a weak response in Pine Island Bay, the Bellingshausen Sea and west of the Ross Sea. Given expected increases in total precipitation and frequency of extreme ENSO events as Earth’s atmosphere warms, their results imply that interannual variability of ice-shelf height and mass will also increase, stressing the need to quantify surface accumulation relative to basal melting to project future changes in Antarctic ice shelves.

Therefore, ocean-driven factors do not contradict the climate change and atmospheric circulation. The factors of enhanced ice-ocean interaction such as intrusion of warm saline water on retrograde slopes is also the result of global climate changes, for the interaction of the ice-ocean has existed since the formation of the ice sheet on the edge of the Antarctic. Changes in the global climate have caused interactions such as ice discharge, intrusion of warm saline water on retrograde slopes enhanced.

Principal component analysis (PCA) is based on the idea of using an orthogonal transformation to convert a set of possibly related variables into a set of linearly independent variables, and display patterns of similarity of the observations and variables as points in maps. This transformation is based on the guideline that the first principal component has the largest possible variance and therefore accounts for as much of the variability in the data as possible. Each succeeding component in turn has the highest overall variance possible under the constraint that it is orthogonal to the preceding components. The highest variance refers to the observation data from Antarctica taken as a whole, rather than only a smaller amount of observation data collected along the coast.

With the accumulation of observation data (for example, over 30-50 years or longer), the non-cyclic long term patterns may be a principal component and have the largest possible overall variance of the observed data. Regarding the present GRACE data, the results do not reflect this phenomenon very well.

In this manuscript, PCA was used to obtain the major principal components, which have the largest possible variance of the observed data and therefore account for the maximum amount of variability in the data. The wavelet analysis shows a time-frequency correlation between principal components and various possible affecting factors. The results indicate that there is a strong correlation between changes in the low-frequency signal of the sea surface temperature anomaly in the Niño1+2 region of the equatorial Pacific Ocean and the first component of mass change in Antarctica.

In addition to the long term ocean driven factors, based on GRACE data during 2003-2016, we also found that low-frequency quasi-periodic signals appeared in the first principal component, which could be important factors affecting the mass balance in Antarctic. The expressions in the manuscript may be ambiguous and so we have replaced them in the revised manuscript.

Revised include:

Pg2 line 56-59:

"The mass change of the ice sheet is the result of interactions between the ocean, ice sheet and the atmosphere. These interaction are closely related to the changes in air humidity, atmospheric temperatures, atmospheric circulation, and other climatic factors in the Antarctic region. "

Pg4-5 lines 109-138:

"Before CPCA, a complex observation sequence should first be constructed using a real observation series. For a time varying observation vector $u_j(t)$, its Fourier expansion is:

$$u_j(\mathrm{t}) = \sum_{\omega} \left[a_j(\omega)\cos(\omega t) + b_j(\omega)\sin(\omega t) \right]. \tag{1}$$

In the above expansion, *j* stands for the location of the observation point, ωis the Fourier frequency and *t* is the observation time. In order to describe the propagation characteristics of a time series, it is necessary to construct the imaginary part and convert it into a complex observation sequence. The complex observation sequence can be expressed as:

$$U_j(t) = \sum_{\omega} c_j(\omega) e^{-i\omega t} . \tag{2}$$

Here, we define $c_j(\omega) = a_j(\omega) + ib_j(\omega), \mathrm{i} = \sqrt{-1}$. Then the Eq. (2) can be expanded as:

$$\begin{aligned} U_j(t) &= \sum_{\omega} \left[a_j(\omega)\cos(\omega t) + b_j(\omega)\sin(\omega t) \right] + i\left[b_j(\omega)\cos(\omega t) - a_j(\omega)\sin(\omega t) \right] \\ &= u_j(t) + i\mathrm{v}_j(t) \end{aligned} . \tag{3}$$

The real part of Eq. (3) is the original observation sequence and the imaginary part is the Hilbert transform of the real part, which does not change the amplitude of each component of $u_j(t)$.

However, the phase of each spectral component is advanced by $\pi / 2$.

The traditional PCA is the principal component analysis of the real observation vector, whereas the CPCA analysis is the principal component analysis of the complex vector constructed. After the normalization of the complex observation vectors, that is the average value is subtracted from the complex observation vector of each observation point, and then divided by the standard deviation the complex correlation matrix of the observation point can be expressed as:

$$\begin{bmatrix} r_{11} & r_{12} & \cdots & r_{1n} \\ r_{21} & r_{22} & \cdots & r_{2n} \\ \vdots & \cdots & \cdots & \vdots \\ r_{n1} & r_{n2} & \cdots & r_{nn} \end{bmatrix}. \tag{4}$$

Here r_{jk} represents the multiple correlation coefficients between the *j*th and *k*th observation points. CPCA compresses information using the least complex eigenvector e_{jn} of correlation matrix (Eq. 4) and the complex principal component $p_n(t)$, because the correlation matrix (Eq.4) is a Hermitian matrix including n real eigenvalues λ. $\lambda_j / \sum_{i=1}^{n} \lambda_i$ denotes the contribution percentage of the *j*th principal component.

Observation vector $U_j(t)$ can be expressed as the sum of N principal components,

$$U_j(t) = \sum_{n=1}^{N} e_{jn}^{*} p_n(t), \tag{5}$$

where * stands for the complex conjugate, and both complex principal components and complex eigenvectors are orthogonal. The *n*th complex eigenvector element e_{jn} can be expressed as

$$e_{jn} = \left[U_j(t) * p_n(t)\right]_t = s_{jn} e^{i\theta_{jn}}. \tag{6}$$

Where, e_{jn} indicates the multiple correlation relationship between the jth time sequence and nth principal component. s_{jn} and θ_{jn} are respectively correlative order of magnitude and phase. $\left[\cdots\right]_t$ signifies the average of times. The time sequence elements of principal components can be expressed as the functional form of amplitude T_n and phase Φ_n.

$$P_n(t) = T_n(t)e^{i\Phi_n(t)}. \quad (7)”.$$

Pg6 line 148：

“The mass balance of the ice sheet in Antarctica is the result of interactions of many factors such as the ice sheet, atmosphere, ocean and other factors. Ice sheet changes in mass balance are the result of variations in time of specific climate factors represented by different frequency signals as well as long-term non-periodic changes. ”

Pg8 line 218：

“The Response of the Antarctic Ice Sheet Mass Balance to the behavior corresponding the first principal component”

Pg8 lines 219-226：

“Figure 2 shows the time evolution of the principal component, its corresponding spatial mode, and the phase distribution (arrows) of the first three components derived by CPCA. The spatial mode shows where the mass balance is the most sensitive to the change of its corresponding principal component, the phase distribution indicates the source direction of the possible factors that affected mass balance and the length of the arrow reflects the extent to which the mass in this region responds to the variation of these possible factors. From the phase distribution of first principal component (Fig 2b.), we can see that the factors affecting the mass balance mainly come from the direction of the eastern South Pacific. The ice sheets in the AP and West Antarctica (basins B20 to B27), Wilkes Land (basin B13), and Dronning Maud Land and Enderby Land (basins B4 to B8) (Fig. 2b) areas are the most sensitive to the first principal component change.”

Pg9 lines 240-260：

“The Antarctic Oscillation Index (Antarctic Oscillation, AAO. http://www.cpc.ncep.noaa.gov/products/precip/CWlink/daily_ao_index/history/method.shtml .), Southern Annular Mode (SAM, https://legacy.bas.ac.uk/met/gjma/sam.html), air temperature in the Antarctic region (ftp://ftp.cdc.noaa.gov/pub/Datasets/ncep.reanalysis/), and the meridian wind speed in the South Pacific region (−80° S− −40°S) at a height of 700 hPa (ftp://ftp.cdc.noaa.gov/pub/Datasets/ncep.reanalysis/pressure/) were also analyzed using wavelet amplitude-period spectrum method to study the possible relations of this low-frequency signal between different data set. The results of their wavelet amplitude-period spectrum are presented in Fig. 4 and Fig. 5. Both the Antarctic Oscillation (Fig. 4d) and the Southern Annular Mode (Fig. 4f) have significant annual and 2-year periodic signals, the amplitude of the 2-year periodic signal is comparable to that of the annual periodic signal. The Antarctic Oscillation Index and the Southern Annular Mode may be greatly affected by the low-frequency signal during a period during 2 years in the change of ENSO and have a smaller correlation with the first component of ice sheet. However, the results of the first two principal component of meridian wind speed (Fig. 5a and 5b) show that the meridian wind in the South Pacific region has 8.5-year and 6.5-year periodic signals. The correlation coefficient of the low-frequency signal between the meridional wind field and sea surface temperature anomaly in the equatorial Pacific is 0.77. These results indicate that changes in the low-frequency signal of the sea surface temperature anomaly in the Niño1+2 region of the equatorial Pacific Ocean may be the possible factors affecting the mass change of the ice sheet in Antarctica. The phase distribution information (arrows in Fig. 2b) also indicates that the factors affecting the mass balance mainly come from the direction of the eastern South Pacific, and it is more likely that the sea surface temperature anomaly causes changes in atmospheric pressure and meridional wind, and conducts its effect (such as changes in atmospheric circulation, precipitation, enhanced ice-ocean interaction, ice discharge, intrusion of warm saline water on retrograde slopes and etc.) to the Antarctic ice sheet, because the change of the first principal component of ice sheet lags behind that of the low-frequency signal of the sea surface temperature anomaly by a month (Table 2).

Pg10 line291：

"5.3 Effect of the second and third principal components on Antarctic Ice Sheet Mass Balance"

Pg10-11 lines 299-331：

“The phase distribution information (arrows in Fig. 2d) indicates that the factors affecting the mass balance mainly come from the South Pole. This allows us to relate to the temperature changes, as the Antarctic Central area is the source of cold and high pressure air in the region. The wavelet amplitude-period spectrum (Fig. 4h) also shows that the air temperature in the Antarctic region has similar periodic signals.

Figure 2f shows the spatial mode and phase distribution (arrows) of the third components. The phase distribution of the third principal component shows that the factors affecting the mass balance are mainly along the latitude line. The ice sheets in the basins B21–23 and basin B1 areas are the most sensitive to third principal component change. The wavelet amplitude-period spectrum of the third principal component time series (Fig. 3c) shows that the principal component contains significant periodic signals of 8.5 years, 4 years and 5 years. The energy of the 8.5-year periodic signal is the largest, followed by that of the 4-year periodic signal and the 5-year periodic signal, the energy of the signals with period below 2 years is unstable. From the perspective of phase distribution and cycle components, these factors that affect the third principal component may be correlated with the Southern Annular model index (Fig. 4b and Fig. 4f) as well as the sea surface temperature anomaly in the Niño 1+2 region during this period. The direction of phase in the basins B21–23 is counterclockwise, while in the basin B18 and the northern of basin B1, the phase is in a clockwise direction. This data suggests that the impact factors may come from the disturbance of small scale local atmospheric circulation.

Raphael et al. (2016) studied the Amundsen Sea Low (ASL) and found that the Amundsen–Bellingshausen Sea (ABS) region exhibits large inter-annual atmospheric circulation variability. This is due, in part, to orographic forcing and in part to its location in the South Pacific, where atmospheric Rossby waves associated with ENSO variability have a year-round influence. The ENSO plays a significant role in determining the depth of the ASL. The most energetic Rossby waves associated with ENSO variability in the Southern Hemisphere occur in spring, and hence the strongest correlations between ENSO variability and the ASL generally occur in this season. In its La Niña phase, in spring, ENSO is associated with a deeper ASL and with warm air advection toward the Antarctic Peninsula and West Antarctica. However, from spring to summer the sign of the correlation of the phase of ENSO with respect to air temperature anomalies over Antarctica reverses in many locations. The ASL is an important circulation feature that influences West Antarctic climate variability. Observations reveal that the ASL has deepened in recent decades with potential impacts on the regional climate through its influence on the meridional wind field. Some studies have suggested that tropical teleconnections have contributed to atmospheric warming in West Antarctica and across the peninsula (Ding et al. 2011; Schneider et al. 2012), and to sea ice loss in the Bellingshausen Sea (Li et al. 2014). The ASL is probably related to the variability of the SAM (e.g., Fogt et al. 2011) and ENSO (e.g., Lachlan-Cope and Connolley 2006). Paolo et al. (2018) noted out that studies correlating ENSO tropical forcing with Pacific sector climate indicators, such as the Amundsen Sea Low strength, sea-ice extent, and AP temperature, found that correlations with ENSO are significant for some seasons but not for others, with reversals of the sign of the correlation from season to season in some cases. The dominant effect of El Niño on the Amundsen Sea ice-shelf mass is the increased basal melting associated with the onshore flow of Circumpolar Deep Water and coastal upwelling as westerly wind stress intensifies. ”

Pg12 lines 354-365：

“The effect of the specific factor represented by annual periodicity signals on the Antarctic ice sheet mass balance accounts for 2.57% of the total change in the ice sheet mass in Antarctica. The effect of the third component, which contains significant periodic signals of 8.5 years and 4-5 years, on the Antarctic ice sheet mass balance accounts for 1.87% of the total change in the ice sheet mass in Antarctica. The factors represented by the third component may be related to the small scale local atmospheric circulation change Southern Annular model index and westerly wind from the periodicity of signals and phase distribution.

There are many factors that affect the mass balance of the ice sheet in Antarctica. In addition to the factors of long term ocean driven, we also found that the low-frequency quasi-periodic signals appears in the first principal component based on GRACE data during 2003-2016, which is also maybe another important factors affected the mass balance in Antarctic. To fully understand the causes of changes in ice sheet mass, other phenomena such as enhanced ice-ocean interaction and ice discharge, intrusion of warm saline water on retrograde slopes should be included in the analysis and eventually excluded from the list of possible effects.”

The related reference were also supplemented.

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(15) Lachlan-Cope, T. A., and W. M. Connolley: Teleconnections between the tropical Pacific and the Amundsen-Bellingshausen Sea: Role of the El Niño/Southern Oscillation. J. Geophys. Res., 111, D23101, 2006.

- Also one has to be careful about correlations. The authors admit that the mechanisms of this proposed relationship have to be explored further in future studies, but one has the be careful with correlations between 5+ year low-frequency SST changes associated with the El Nino and Antarctic mass balance. The conclusion that air temperature is the second dominant effect on the mass of AIS is also based on the correlation between the components of quasi-periodic atmospheric circulation patterns and AIS mass balance, and the same issues and assumptions arise here. The claims of the paper should not be generalized outside of the scope of the study.

Response:

We want to stress that there is a strong correlation between changes in the low-frequency signal of the sea surface temperature anomaly in the Niño1+2 region of the equatorial Pacific Ocean and the first component of mass change in Antarctica. However, the interaction (such as precipitation change, enhanced ice-ocean interaction, ice discharge and intrusion of warm saline water on retrograde slopes) between the low-frequency signal of the sea surface temperature anomaly in the Niño1+2 region and mass change in Antarctica is unclear and requires additional study. To avoid ambiguity, we removed the sentence “The detailed influential mechanism still needs further study.” We have also reorganized the sections 5.2 and 5.3; the related statement sentences were also revised so that the manuscript conclusions are not outside of the study scope.

- As noted in the paper, the 1x1 grid does not represent the true GRACE resolution. Given that the mass change is obtained by simply fitting the time-series for each grid on a smoothed field, it must be noted that the grids are spatially correlated and the trends of nearby basins (particularly small basins) cannot be considered separately from each other. Furthermore, there is amplitude loss in spatial smoothing so the smoothed spatial field is not the optimal way of getting regional estimates. The authors should use a synthetic field to justify their results (compare true vs. retrieved signal) or alternatively use a mascon solution, which is linked in the paper but never used. The overall loss trend of 248.6 Gt/yr seems really high with respect to other estimates.

Response:

We agree that the mass changes in grids are spatially correlated and the trends of nearby basins (particularly small basins) cannot be considered separately from each other. Furthermore, the amplitude of the signal will decrease to different degrees when using different filters.

We compared our filter with the classical filter such as Gaussian filter, Correlated-Error Filter and the combined filter (Gaussian with 300 km smoothing + Correlated-Error) in the literature of Zhan et al. (2015). The literature of Zhan et al. (2015) describes how the smoothness priors method works in removing the noise of GRACE data, and compared the results of this filter with that of Gaussian smoother, Correlated-Error filtering and the combined filter (Gaussian smoother + decorrelation filtering) with the "Real signals." The results demonstrate that the smoothness priors method has the advantages of less reduction in amplitude of signals in high latitudes, preserved more details of short-wavelength components in the results and has less signal distortion at low latitudes. The statistical results of the filtered field show that the result of the smoothness priors method is closest to the actual value of the original field in the minimum value, maximum value and the RMS value. Please refer to Figure 1 and Figure 2 and Table 1 listed in Zhan et al. (2015).

Figure 1a is the simulation of the numerical model of mass change trend (as true signal), Figure 1b is the simulation of stripe noise model, and Figure 1c is the synthesis signal of mass change trend of Figure 1a add Figure 1b. Then convert this synthetic field of Figure 1c into normalized spherical harmonic (SH) coefficients, to degree and order 60. We then applied the smoothness priors method (SPM), Gaussian filter, the correlated error filter and the combined filter (Gaussian + the correlated error filter) on the synthesis signal.

Figure 2 shows the filtering results of different filters. They indicate that the smoothness priors method (Figure 2d) produced less reduction in amplitude of signals in high latitudes, preserved more details of short-wavelength components in the result and has less signal distortion in low latitudes.

Table 1 illustrates statistics results of the numerical model of mass change (Figure 1a), and the filtering results of mass change (Figure 2) by applying different filters on the synthetic mass change model. The statistics results of the filtered field shows that the result of the smoothness priors method is closest to the truth value of the original field (Figure 1a) in the minimum value, maximum value and the RMS value.

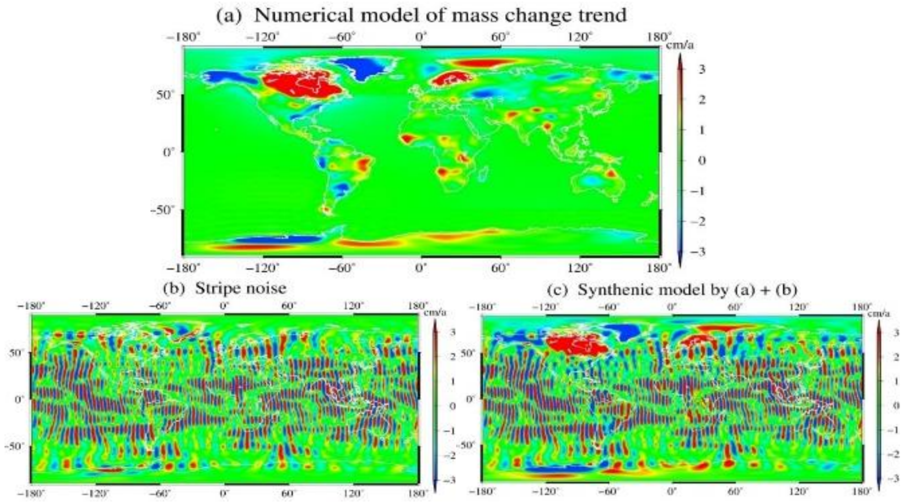

Figure 1. (a) The numerical model of mass change trend,
(b) the stripe noise model; (c) synthetic model by (a) + (b).

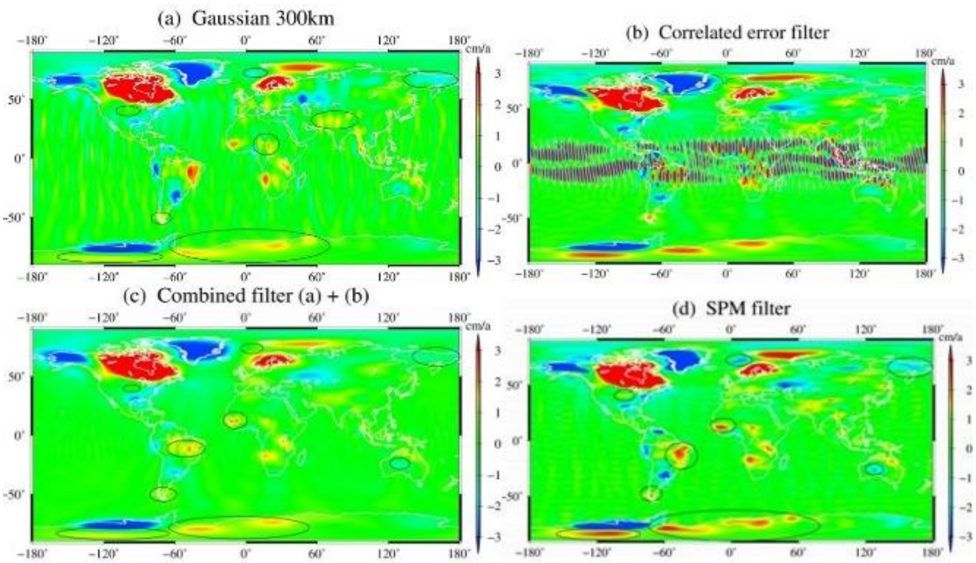

Figure 2. Results by applying different filters on the synthetic model. (a) The Gaussian filter with a smoothing radius of 300km; (b) the correlated error filter; (c) a 300km Gaussian smoothing after the correlated error filter; (d)the SPM filter.

Table 1.The grid statistics results of the numerical mass change trend model and the filtered mass change results by applying different filter on a synthetic mass change model. Unit: cm.

by applying different filter on a synthetic mass change model. Unit: cm.

Filter	Minimum value (cm)	Maximum value (cm)	Mean (cm)	RMS (cm)
Real signal	−11.45	13.15	−0.0396	1.448
Gaussian 300 km (A)	−6.78	11.06	0.0349	1.231
De-correlation (B)	−11.53	11.69	−0.0399	1.727
A+B	−6.53	11.10	−0.0349	1.196
SPM filter	−8.81	11.88	−0.0399	1.371

Second, we found that the reason for this difference of mass balance is mainly due to signal leakage errors. When estimating the Antarctic mass balance, the mask method was not used causing the signals leaking into the ocean to be added to the Antarctic ice sheet mass change. This enlarged the area and resulted in over estimation. We corrected this error with the mask method by using the drainage basins boundary data definitions by Zwally et al. (2012), and this does not affect the result of CPCA.

- The only agreement was with a selected altimetry estimate. The authors claim the discrepancies with previous studies such as Velicogna and Wahr (2006) are partly due to previous releases of GRACE data and signal attenuation due to smoothing. However, more recent results are also in disagreement (such as Velicogna et al 2014), which use newer releases and a mascon approach. Furthermore, scaling factors were calculated for previous studies using synthetic fields to account for signal attenuation. And such approaches such as the spherical cap approach are in close agreement with other mascon solutions such as the JPL or CSR mascons. The authors should also consider the official mascon solutions of the processing centers as a point of comparison. While previous studies that are claimed here to be suffering from signal attenuation due to smoothing looked at scaling and gain factors, this study does not make an attempt on quantifying any attenuation with a synthetic field.

  Response:

  We found that the reason for the mass balance difference is mainly signal leakage errors. When estimating the Antarctic mass balance, the mask method was not used in the manuscript, causing the signals leaking into the ocean to be added to the Antarctic ice sheet mass change (enlarged the area), making the estimation result too large (as shown in Figure 3a). We have corrected this error with the mask method using the drainage basins boundary data definitions by Zwally et al. (2012). We also replaced the previous data set with the RL06 data in the revised manuscript and re-estimate the Antarctic ice sheet balance (as shown in Figure 3b), and the estimated value is consistent with the results of Nagler et al. (2017) and Shepherd et al. (2018). The mass loss in basins B19 to B27 should be −182.9 ± 12.6 Gt/yr. The following is the mass balance trend figure and the table of mass balance of the different drainage basins in Antarctica.

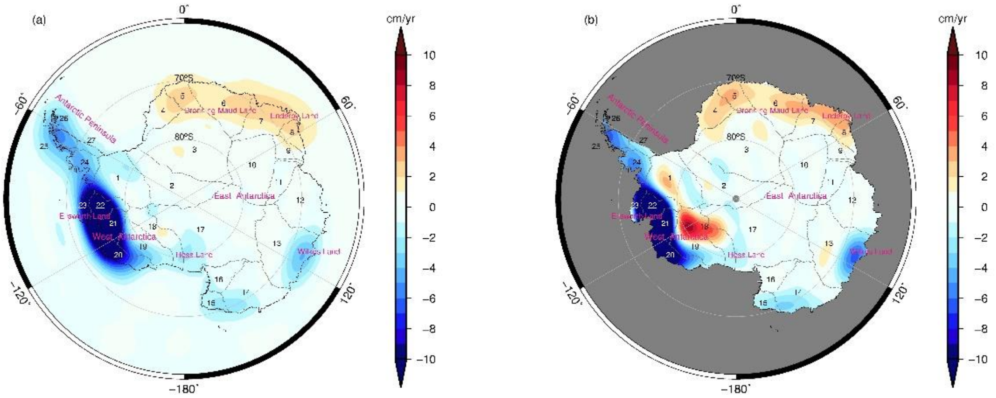

Figure 3. Mass trend of ice sheet in Antarctic. RL05- ICE-6G model (a);
RL06- GIA model of Caron (2018) (b);

Mass balance of different drainage basins in Antarctica of our result:

Basin	Mass balance	Basin	Mass balance
AIS1 basin 1	-3.4 ± 11.6	AIS14 basin14	-8.9 ± 5.4
AIS2 basin 2	-2.0 ± 5.8	AIS15 basin15	-3.5 ± 1.0
AIS3 basin 3	9.7 ± 14.3	AIS16 basin16	-0.5 ± 1.3
AIS4 basin 4	7.9 ± 2.9	AIS17 basin17	1.9 ± 14.3
AIS5 basin 5	7.0 ± 1.2	AIS18 basin18	9.6 ± 3.7
AIS6 basin 6	16.2 ± 1.8	AIS19 basin19	-1.3 ± 5.0
AIS7 basin 7	16.8 ± 2.8	AIS20 basin20	-37.7 ± 6.7
AIS8 basin 8	6.3 ± 1.3	AIS21 basin21	-58.4 ± 6.3
AIS9 basin9	0.5 ± 1.7	AIS22 basin22	-49.3 ± 6.9
AIS10 basin10	-1.8 ± 7.9	AIS23 basin23	-12.5 ± 2.6
AIS11 basin11	-1.4 ± 3.2	AIS24 basin24	-9.7 ± 4.4
AIS12 basin12	-1.0 ± 4.0	AIS27 basin27	-1.5 ± 0.9
AIS13 basin13	-13.4 ± 2.5	AIS28NAP(b25-26)	-12.5 ± 2.6

Revised include:

Pg6 lines 155-159:

“In this way, we obtained the time sequence of mass changes from January 2003 to August 2016 at each grid point. However, some monthly GRACE gravity solutions were not available due to the data quality. Therefore the time series of mass change at one point shows discontinuous and sudden transitions. Before applying the CPCA analysis, we need to interpolate the missing data to make the time sequence continuous. We used a spline function to interpolate missing data in the time series.”

Pg6 line 161：

“At last, the method of mask was used to remove the effect of signals leakage.”

- Analysis is up to September 2015. Is there a reason for this? Even with the presence of accelerometer issues near the end of the mission, at least another year can be added.

  Response:

  We have replaced the old data set with the new released RL06 data, and extending the record to August 2016.

Specific Comments:

- Line 62: “The mass change of the ice sheet in Antarctica is the result of interactions between the atmospheric vapor and the surface water resources;” this is a misleading statement. While ultimately the mass balance is the result of surface mass balance (including precipitation) and discharge, this is the interaction of many factors such as ice-ocean interaction, bathymetry, etc. Needs to be clarified.

  Response:

  Based on this suggestion, we replaced the “The mass change of the ice sheet in Antarctica is the result of interactions between the atmospheric vapor and the surface water resources;” with “The mass change of the ice sheet is the result of interactions between the ocean, ice sheet and the atmosphere.” (**Pg2 lines 53-54)**

- Line 72: Mission ended after 15 years.

  Response:

The sentence was changed to "It successfully operated for 15 years and ended its mission in August 2016." (**Pg3 line 63)**

- Equation 1: If solving for surface density on the left hand side, the coefficient should not be divided by the density of water. Refer to equation (14) of Wahr et al (1998). The coefficient also needs to be in surface density units.

  Response:

  This comment is correct. If solving for surface density on the left hand side in Equation 1, the coefficient should not be divided by the density of water. Here the expression of equation (1) is the equivalent water height (EWH). We have removed this section based on the reviewer's suggestion.

- Lines 121-125: this assumes all changes in Antarctica are caused by periodic climate events (such as El Nino etc.). This is not necessarily true and is unjustified. There could well be significant long-term non-periodic changes that are the main drivers of change.

  Response:

  We have revised it to read "… changes in mass balance are the result of variations in time of specific climate factors represented by different frequency signals as well as long-term non-periodic changes. Thus, after obtaining the temporal change series of principal components of mass change in Antarctica, the time-frequency information of quasi-periodic signals from the time series required analysis." (**Pg6 lines 141-145)**

Technical Comments:

- Line 64: sentence is not very clear. And careful with tense. Maybe "the mass change record contains global and local climate change information across time".

  Response:

  The sentence was changed to "The mass change recorded the global and local climate change information varying in time." based on the suggestion (Pg2 line 56).

- Line 115: delete "the" in front of phase information.

Response:

We have delete it based on the suggestion (Pg4 line 101).

- Lines 147,150: change to “basins B19 to B27”, and the corresponding numbers in line 150.

Response:

We have edited this sentence here and in other parts of the manuscript (Pg7 lines 172-178).

- Line 237: “in analyzing the influence of: : :” makes the sentence longwinded and hard to follow. I think that segment can be removed.

Response:

We have removed it based on the suggestion (Pg9 line 261).

- Line 238: “had a certain impact” is very vague. You need to be more clear as to their conclusion.

Response:

The sentence was changed to “… in the AP during a strong El Niño event cause precipitation changes and sea ice accumulation in the region.” (Pg9 line 261)

- Line 272: Delete “the” before West Antarctica.

Response:

We have removed it based on the suggestion and reorganized this section (Pg8-10 lines 219-289).

- Line 345: “i.e.” is not appropriate here as the acceleration does not follow from the trend magnitude, it is a separate fact (and it would be helpful to also report the acceleration value if this is the case).

Response:

We have removed it based on the suggestion and rewrite this section (Pg12 lines 345-352).