Ocean mass changes from the lower degree harmonics.

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Note that a few issues have been fixed after the meeting: The rates have been updated using the residual fields and they agree.

Abstract.
The study is based on the low degree harmonics to focus on the accurate long wavelength parts of the GRACE/GFO gravity fields. To reduce the contamination of mass changes on land a set of point masses are estimated and analyzed to verify estimates of the melting of the major ice sheets. Subsequently, residual gravity fields are used to recover characteristics and regional patterns of changes in the ocean mass.
Initially, ocean mass changes are computed using the direct approach (Uebbing, et al., 2018) using coefficients filtered at harmonic degree and order 20, 40 and 60.

The data.
For this study the following data sources were used:

- GRACE: JPL GSM rel. 6.0,
- GFO: JPL GSM rel. 6.3,
- Degree-1 terms from TN-13,
- C20 terms from TN-14,
- GIA: Caron et al. (2018), and
- OA background: GAB ocean model only.

Coefficients up to d/o 60 were used, though filtered by a gaussian function at harmonic degree 20, 40, and 60.

EWH were computed by multiplying the coefficient by: a/3*rho_ave/rho_w*(2n+1)/(1+k_n) according to Wahr and many others.
Finally, a grid of distances to land for masking out data in the coastal buffer zones were constructed using a smoothed version of ETOPO5.

Table 1. Global ocean mass trends in mm/y obtained using Gaussian filtering at harmonic degrees 20, 40, and 60 (n_filter), and buffer zones of 300 km, 500 km, and 1000 km, and data from the period 2002.6-2024.5.

		Buffer zone (km)		
Models	n_filter	300	500	1000
GSM+GAB	20			2.40
GSM+GAB	40		2.29	2.41
GSM+GAB	60	2.27	2.29	2.41
GAB	20			-0.11
GAB	40		-0.11	-0.11
GAB	60	-0.11	-0.11	-0.11

The direct approach.
The computation of ocean mass changes using the direct approach is nicely described by Uebbing et al. (2018): Use GSM coefficients to d/o 60 and compute Equivalent water heights (EWH), apply a GIA model and restore the monthly means of the ocean atmosphere de-aliasing models compiled in the GAC or GAD products. When analyzing the results over the oceans it is important to mask out data in the coastal areas to avoid land contamination, typically using a buffer zone of 300 km. There are more details, but essentially this procedure was followed. It was decided, though, to restore the ocean model means only, using the GAB product.

Initially, global ocean mass changes were computed using coefficients up to d/o 60 vaguely filtered by a Gaussian function at degree 60. Using a coastal buffer zone the global mean ocean mass trend is 2.27 mm/y (Table 1).

Buffer zone
At this stage, the effects of changing the width of the buffer zone was tested by changing the buffer zone from 300 km to 500 km and 1000 km, respectively. The results show minor effects, only, around a few percent (Table 1).

Increased smoothing
To focus on the more accurate lower harmonics, the Gaussian filtering was strengthened by reducing the filtering to degree 40 and 20, respectively. It is important to adjust the buffer zone as the wavelengths increase. 300 km corresponds roughly to the half wavelength associated with harmonic degree 60. For harmonic degrees 40 and 20 the corresponding half wavelengths are 500 km and 1000 km, respectively. Hence, the buffer zones should be adjusted accordingly. The maps of the ocean mass trends are shown in Figure 1.

The global ocean mass trends were computed (shown in Table 1 and for the reduced time period also in Table 2). The results are remarkably consistent. The associated time series are shown in Figure 2.

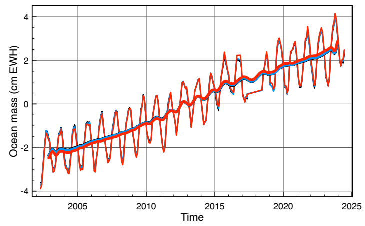

Figure 2. Time series of global ocean mass changes using data smoothed at degree 60, 300 km buffer zone (Black),data smoothed at degree 40, 500 km buffer zone (Blue), and data smoothed at degree 20, 1000 km buffer zone (red).

In all cases the GAB fields were smoothed in a similar way as the GSM coefficients and the contribution computed using the same buffer zones as used for the GRACE/GFO EWH contribution. The trends associated with the GAB fields all became -0.11 mm/y.

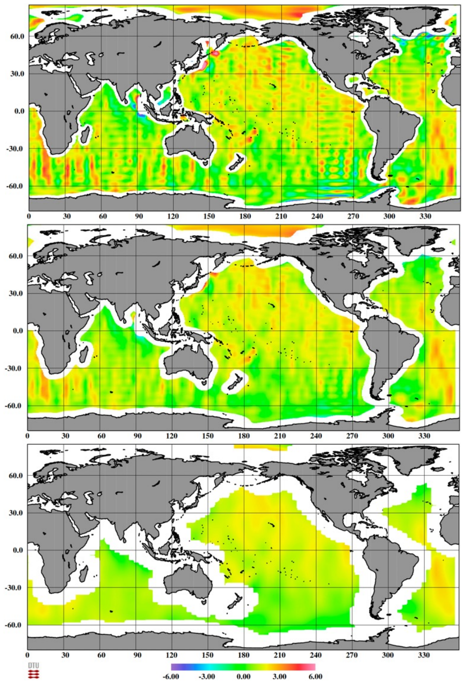

Figure 1. Maps of global mass trends (in cm/y) using data smoothed at degree60, 300 km buffer zone (upper panel),data smoothed at degree 40, 500 km buffer zone (middle), and data smoothed at degree 20, 1000 km buffer zone (lower)..

Regional ocean mass changes using lower degree harmonics
The results described above show that it does not have significant impact to apply smoothing or not.; at least when global mean trends are computed. For assessing regional ocean mass changes; e.g., in the Arctic ocean, the situation may be different. From the maps in Figure 1 it appears that striation is present when filtering at harmonic degree 40 and 60. Such features may affect the computation of regional changes. When filtering at degree 20 the striation have been very much reduced. Hence, it may be an advantage to used the more smoothed version. However, the wider buffer zone that is needed to avoid land contamination, may eliminate most of the area, so that very little data are left for the analyses. Hence, in order to reduce the width of the buffer zone a procedure for removing the land signal is tested.

Removal of land signals
A removal of signals originating from mass changes on land may be carried out using mascon solutions that are available. In this study, a mass distribution approximated by point masses located on land only, were tested. The point masses are located in a 2° by 4° grid and estimated using constrained inversion where point masses on land only, are free parameters and data over land is used only.

The response from a point mass is calculated using a sum of a series of Legendre's polynomials allowing to truncate the series and apply gaussian filtering consistently.

Then, such land-land solutions were computed for each month there is a GSM file. The response are subtracted from EWH files forming a new data set of EWH values from which all land signal (hopefully) is removed. The new data sets may be used for analyzing ocean mass changes.

Results

The preliminary results are obtained using EWH values that were filtered at harmonic degree 20. Subsequently, trend maps (as in Figure 1) and time series (as in Figure 2) were produced.

The maps shown in Figure A1 below show how well the land signal is estimated and subsequently removed. To focus on the ocean outside the buffer zone, it is shown in Figure 3 how the estimated signal compares to the data shown in Figure 1 lower panel. The estimated signal is, as expected, close to zero. Hence, the residual trends (Figure 3, lower panel) show the same features as the data (Figure 1. lower panel).
The time series are shown in Figure 4. The red curve is the same as the red curve in Figure 1. The time series computed from the point mass responses is as expected close to zero. Hence, the residuals are not affected by the land signal outside the buffer zone and become very similar to the original data.

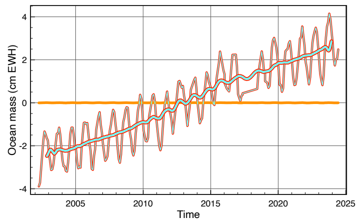

Figure 4. Time series of global ocean mass changes using data smoothed at degree 20, 1000 km buffer zone (red), the response from the point mass solutions (orange) and residuals (cyan)

Discussion
The first part of this study show results that are pretty consistent with what others had found already. Also, it is shown that smoothed GSM fields may be used as well, though a wider buffer zone is required. In all cases, values for the global mean ocean mass trends of 2.27-2.41 mm/y were found.

The second part focus on using the lower degree and more accurate parts of the GRACE/GFO gravity fields. A method for removing land signals contaminating the ocean signal, is tested. It is based on point masses. Though the locations of the point masses at fixed grid nodes may not be optimal, the method seems to work well.
In Greenland and Antarctica the mass changes reflect the mass loss of the ice sheets. Adding up the changes of the point masses should reproduce the well-known values around 269 Gt and 142 Gt, respectively (NASA website). In this case the values are 234 Gt and 130 Gt, respectively; hence slightly smaller than the NASA values. The total mass loss on land is about 670 Gt corresponding to 1.86 mm/y ocean sea level gain which is on the low side compared to the values in Table 1. However, using the residual fields from where the continental signals have been removed and no buffer zone, a trend of 1.84 mm/y is obtained. Hence, there is a very good agreement with the corresponding land value. The trend of the associated GAB fields reduced to -0.04 mm/y when no buffer zone is applied. The time series land vs ocean (shown in Figure 5) show very well how the changes are inter-connected.

The results show that the method is very successful in removing land signal from the GRACE/GFO monthly fields and facilitates further studies of the changes in the ocean masses.

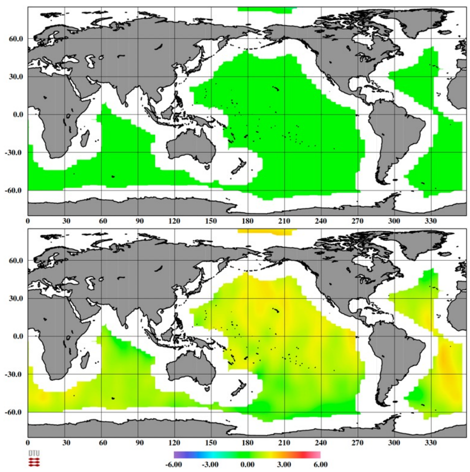

Figure 3. Maps of global mass trends (in cm/y) using data smoothed at degree 20, 1000 km buffer zone as modeled by continental point masses (upper) and residuals (lower).

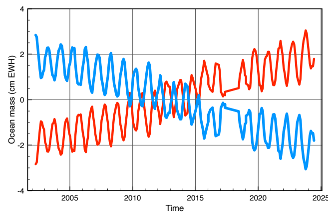

Figure 5. Time series of global ocean mass changes using residual data smoothed at degree 20, 0 km buffer zone (red) and the total mass change on land converted to global sea level change (blue).

Figure A1. Maps of global mass trends (in cm/y) showing data without the buffer zone masking:
The EWH data smoothed at degree 20,
The corresponding response from the continental point masses, and
The residuals.