Heterogeneous oceanic mass distribution in GRACE observations and its leakage effect

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1. Motivation

Gravity models reconstructed from spherical harmonics present skewed patterns extending beyond the region of real signals, usually with diminished strength. This is known as the leakage. Fig. 1 illustrates this problem with a profile across the equator of a simplified land-ocean model. Considering global conservation of water mass, a decrease of water mass storage on land would result in an increase of the ocean mass by the same amount (Fig. 1a). The realistic distribution of mass anomalies is highly heterogeneous (Fig. 1b). Usually, the mass anomalies concentrate in regions near (less than hundreds of kilometers from) the coast, where more precipitation and ice melting take place.

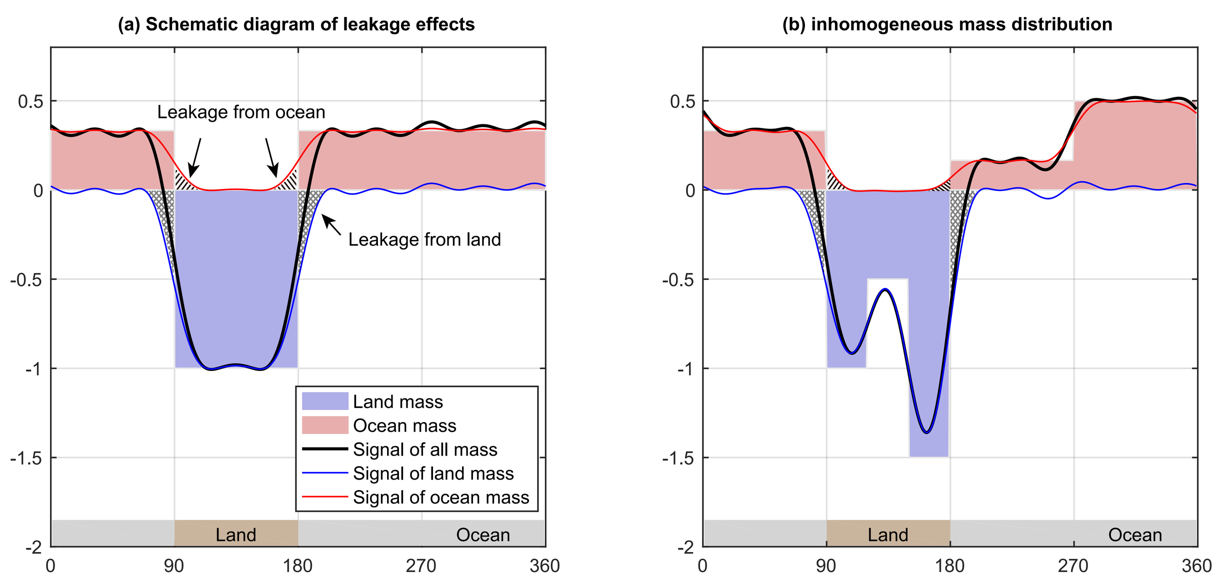

Figure 1: *Schematic diagrams along the equator showing leakage effects of a simple mass distribution (a) and a more complex distribution (b). Here we assume a simple earth composed of only one land and ocean.*

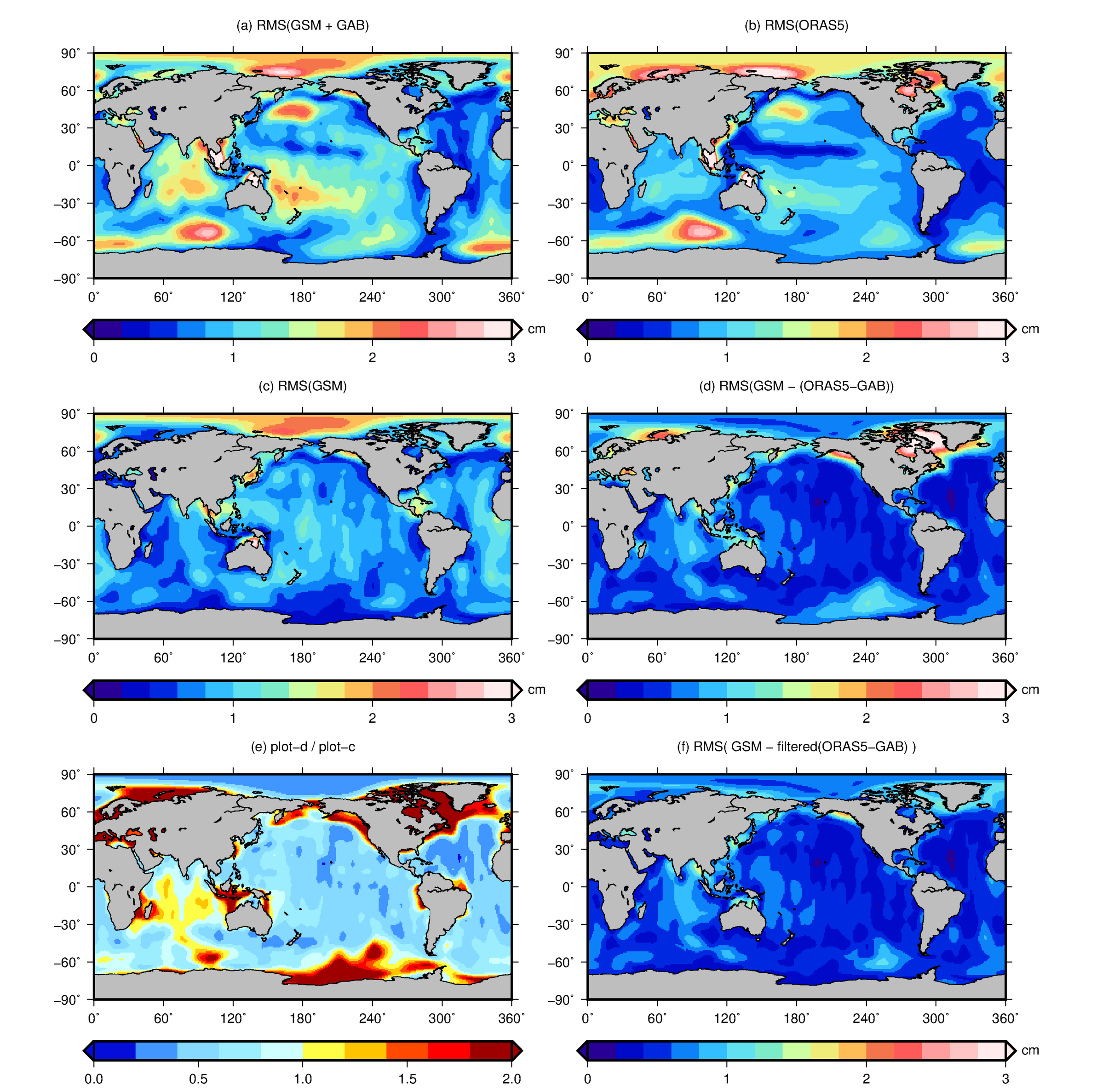

Figure 2: *Seasonal ocean mass variabilities (RMS) in various datasets. RMS of ocean mass without atmospheric mass contribution is observed by GRACE (a) and derived from the ORAS5 model (b). The RMS of the residuals after removing GAB and ORAS5 are shown in (c) and (d), respectively, and their amplitudes are compared in (e). The RMS of the residual after combined reduction from GAB and ORAS5 is given in (f).*

Gravity signals of land/ocean mass anomalies will leak into ocean/land regions and let us underestimate the mass changes on land/ocean in two mechanisms. On one hand, the gravity signal on the land/ocean is reduced because a part of the coastal mass changes leaks out. On the other hand, the signals leaking in from the other regions always have the opposite sign. Therefore, both leakage effects should be corrected to avoid the underestimation. However, only the leakage from the land (land-to-ocean leakage) is well recognized until now, and the leakage from the ocean (ocean-to-land leakage) were either neglected or averaged from nearby ocean grids.

Root mean square (RMS) of seasonal mass variation in ocean regions in GSM plus GAB and GSM are shown in Fig. 2a and c, respectively. Although GAB is capable of removing most oceanic mass variations, some strong residuals can still be identified in the Arctic Ocean, the Gulf of Carpentaria, the Sea of Japan and some other coastal regions. Besides, GAB always has zero net mass change in the entire ocean region, so annual mass exchange of 4000 Gt between the land and ocean is retained in GSM. Therefore, significant regional and overall ocean mass variations exist in GSM and their leakage needs to be considered in the estimation of land mass.

2. Data and method

GRACE product

We adopt the GRACE RL06 dataset from January 2005 to December 2016 generated by CSR for presentation. The C20 term is replaced by more precise SLR one and the geocenter ones are added back. Note that the GAB product is not available from CSR (while it is available from GFZ and JPL, but they are not interchangeable). However, it is easy to derive the GAB product by the Inverted Barometer correction from their GAD product, which is always released with the GSM product.

Ocean product ORAS5

ORAS5 is the production of the ECMWF OCEANS reanalysis-analysis system, a global eddy-permitting ocean-sea ice ensemble system of five members. Its data assimilation system includes temperature and salinity profiles, altimetry derived sea level anomalies, sea-ice concentration and sea surface temperature. Its spatial resolution is down to 0.25 degree by 0.25 degree (here we only use the version of 1 degree by 1 degree) in global oceans and contains 75 layers of ocean water temperature and salinity down to 5902.1 m at depth.

Non-uniform forward modeling method

We correct the ocean mass variation with the help of the ocean mass model ORAS5. The relationship between ocean mass variation and the products is described in equations below.

$$\Delta OBP = \Delta OM + \Delta Atm = \Delta GSM' + \Delta GAD$$

$$\Delta OM = \Delta GSM' + \Delta GAB = \Delta SSH - \Delta Steric = \Delta ORAS5$$

Global land mass is estimated by a non-uniform forward modeling method from GRACE as described in Fig. 3. To find out how important the ocean-to-land leakage can be, we compare the results by three methods:

- M1: the FM method without ocean mass correction, i.e., only the fourth step is applied
- M2: the uniform ocean layer is used.
- M3: the non-uniform ocean layer is used, which is the method proposed in this study.

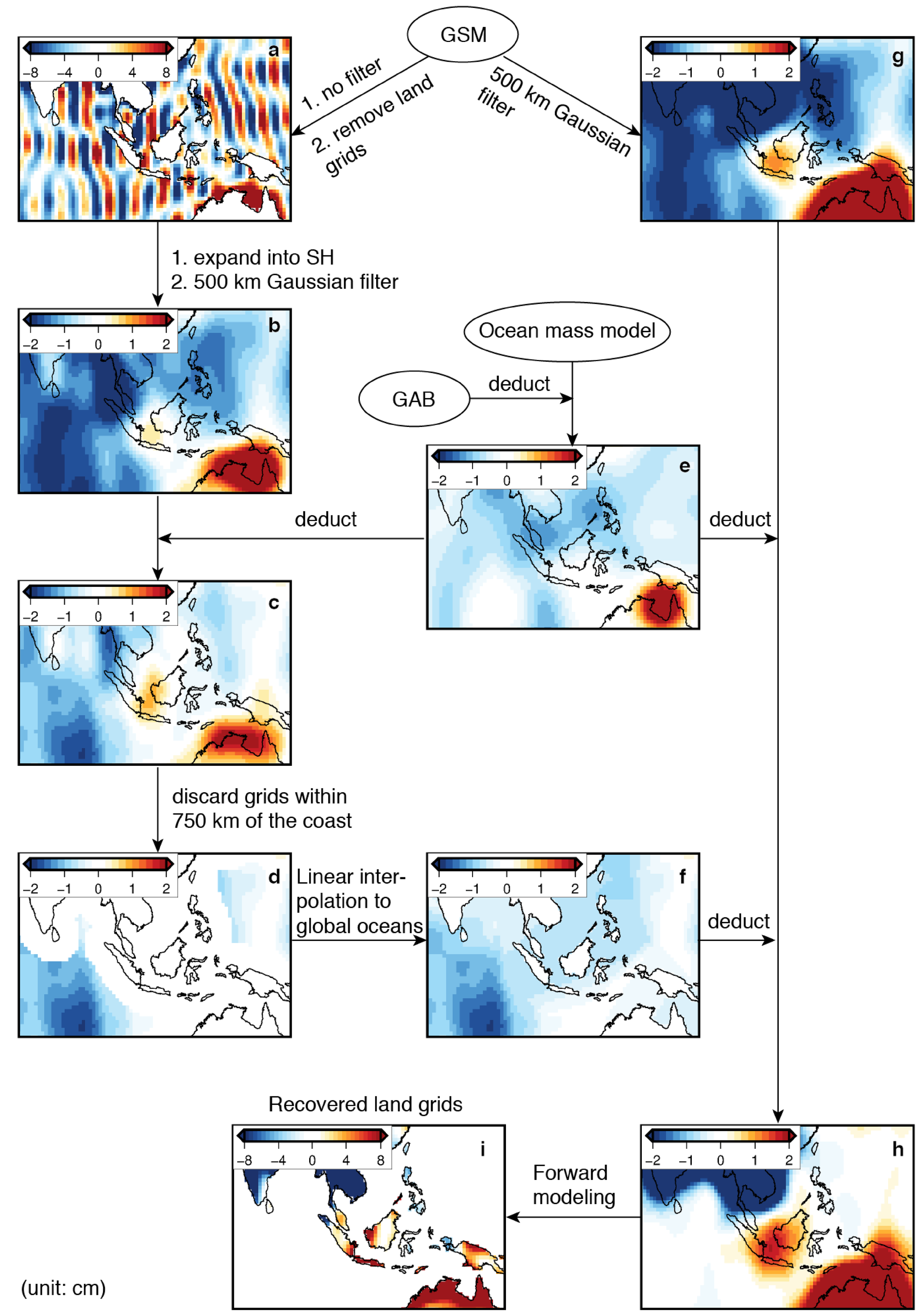

Figure 3: *Flow chart of the non-uniform forward modeling (FM) method. Note that the method has a global coverage, while the Southeastern Asia is shown as a regional demonstration.*

3. Results

Seasonal variation

The global-mean result of three methods in the seasonal variation are shown in Fig. 4. The ocean-to-land leakage, up to 2.4 mm, always accounts for ∼20% of the total mass anomaly, so failing to consider it will always underestimate the total mass anomaly by ∼20% compared to a uniform ocean layer correction. The non-uniform effect is not significant at the global scale, and the difference between a uniform and non-uniform is always smaller than 0.5 mm. Therefore, it's acceptable to not consider the non-uniform distribution in ocean mass if only the global mean is targeted.

The example of mass loss in the Central Valley

The influence of the ocean-to-land leakage in the secular trend varies from place to place. Here we present the case in the Central Valley as an example (Fig. 5). The Central Valley play an important role in the food production in the U.S. and its irrigation depends heavily on groundwater especially during droughts. The total mass change in the Central Valley between 2005–2016 by M1, M2, M3 is -10.9 Gt, -12.5 Gt, -13.3 Gt, respectively. Therefore, ocean-to-land leakage will bring a positive bias of 2.4 Gt, and a uniform ocean layer only corrects 65% of this bias, because the part of Pacific Ocean adjacent to the Central Valley has a mass increase rate faster than the global average (0.34 cm compared to 0.21 cm).

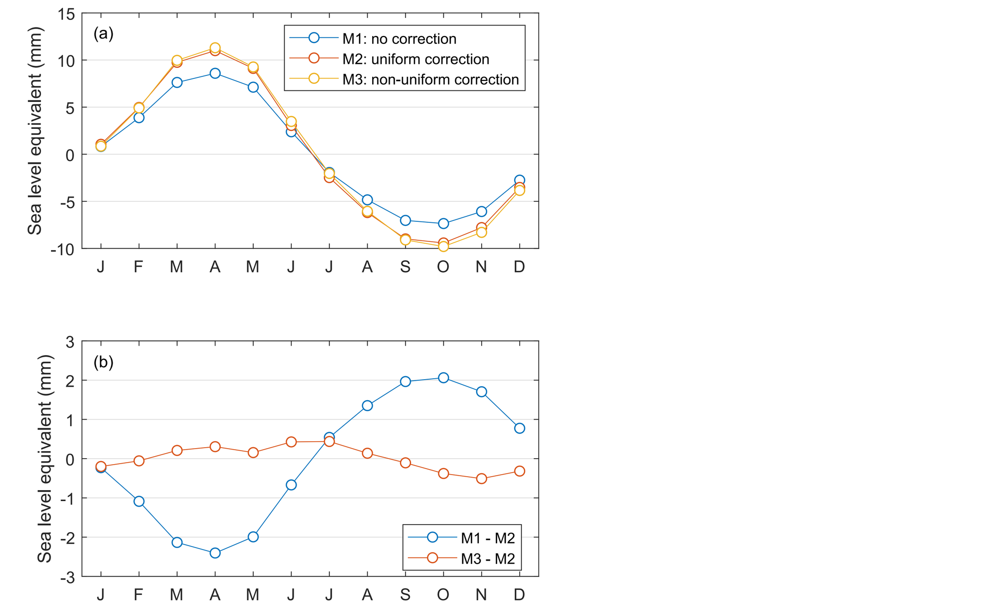

Figure 4: *Global mass change by three strategies of ocean mass correction. The individual results and their differences are given in (a) and (b), respectively.*

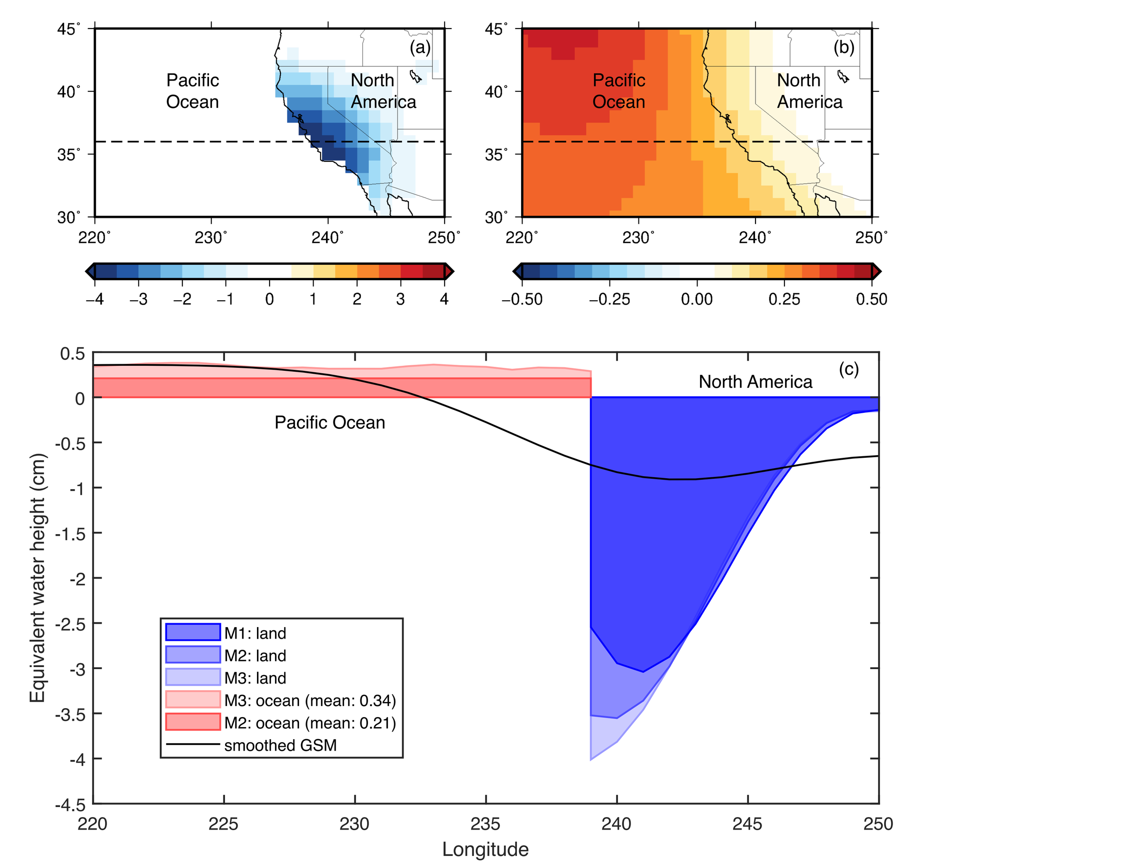

Figure 5: *Terrestrial (a) and smoothed ocean (b) mass trends from the GSM estimated by M3. (c) Comparison of mass trends by three methods along the profile marked by the dashed line in (a). The unit is cm.*

4. Conclusions

1. Ocean-to-land leakage is non-uniform and non-negligible in GSM.
2. One model-based method is proposed to correct the ocean-to-land leakage.
3. Failing to consider the ocean-to-land leakage will cause an underestimation of ∼20% in the seasonal variation, a bias of several giga-tons in the secular trend. A globally uniform model performs badly in most places.

Acknowledgement

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