## 2.2. Cumulative TMB anomaly

For the whole GrIS or a complete basin from ice sheet maximum height to the coast, the total mass balance is:

**( 1 )**

In this study, we further separate each GrIS basin in a downstream (I) and upstream (II) region separated by the 2000m surface elevation contour line. Thus, for the sub-divided regions Eq. (1) becomes:

**( 2 )**

Where

**( 3 )**

And

**( 4 )**

in which refers to the ice flux across the 2000 m elevation contour, and refers to the ice flow across the flux gate. Note that is cancelled if the study area includes both the regions below and above the 2000m contour, but has to be considered when the upstream and downstream regions are considered separately. As described above, we assume that SMB changes downstream of the Enderlin-14 flux gates are negligible and that .

In order to fit the temporal resolution of the modeled SMB data, we interpolate the yearly D on a monthly basis. Significant seasonal variations in ice velocity have been observed along Greenland’s marine-terminating outlet glaciers (Moon et al., 2014). However, since we focus mostly on long-term changes in mass in this study, monthly variations in D should have a negligible influence on our analysis and we assume that D is approximately constant throughout the year. The monthly GRACE data represent the gravity field of Earth at that particular month. By subtracting the gravity field from a reference period (e.g. the 2003 – 2014 average), the gravity variations with respect to this reference can be obtained. These can be converted to mass variations assuming that all mass variation takes place in a thin layer near to the Earth’s surface. Contrary to the GRACE data, the SMB, D and TMB are estimates of rates of mass change (i.e., mass flux) in Gt per month. Hence in order to compare with GRACE, one has to integrate the SMB and D from a certain month (or year), which yields:

**( 5 )**

where is the cumulative mass change at month *i* in IOM (unit is Gt) and the integration time period is from a certain initial month to month .

In previous study of mass balance IOM, when estimates of D are not available for some regions (Rignot et al., 2008), the 1961 to 1990 reference SMB is used to approximate the missing regional D (Sasgen et al., 2012). Also, due to the uncertainties in the SMB model, accumulating the TMB over a long time period may also lead to unrealistic mass gains or losses (van den Broeke et al., 2009). By removing the reference, the influence of the large uncertainties and inter-annual variability in SMB and D can be reduced (van den Broeke et al., 2009), for instance the uncertainties due to model configurations could be the similar in very month SMB estimate, and cumulating over long period may result to a large uncertainty. The reference period is chosen based on the assumption that the mass gain from the surface mass balance during that period is compensated by ice discharge, so the GrIS was in balance (i.e. no mass change).

For the reference period we defined the month index to run from *i0* to *i1*, from *i2* to *in* afterwards. Since we assume the GrIS was in balance during this period, . By removing the reference SMB and D (i.e. and ) Eq. (5) becomes:

**( 6 )**

where , and . Note that and are both rates of mass change, similar to the discharge.

As explained before, when Eq. (6) is used to compute the mass balance for the regions below and above 2000m separately, the ice flux across the 2000m contour () has to be considered. Therefore we introduce two assumptions, i.e. 1) is constant over time, which means ( is the during the reference period), so , and 2) the separate GrIS interior and coastal regions are all in balance during the 1961 – 1990 reference period, i.e. and Assumption 1) is necessary since there is a lack of yearly measurements of ice velocity across the 2000m contour. An estimate of decadal change by Howat et al. (2011) suggests it is reasonable to assume a constant for the entire GrIS, except for a few glaciers, such as the Jakobshavn glacier in basin 7 where the may be higher than after 2000. In Andersen et al. (2015), the mass balance of the interior GrIS (in their study defined as the ice sheet above the 1700 m elevation contour) was 41±61 Gt/yr during the 1961-1990 reference period and in Colgan et al. (2015) the ice flux across the 1700m contour was estimated to be 54±46 Gt/yr for the same time period, indicating the assumption of balance approximately holds within the uncertainties.

Based on these two assumptions, we apply Eq. (6) for the interior and coastal GrIS regions, yielding:

**( 7 )**

And

**( 8 )**

We quantify the combined uncertainties of assumptions 1) and 2) by comparing the results from Eq. (8) to the regional mass balance derived from GRACE by Wouters and Schrama (2008) and derived from ICEsat by Zwally et al. (2011), resulting in ~±15 Gt/yr uncertainties for the entire interior GrIS. The regional uncertainties are summarized in Table A2. Note that for each region, the same uncertainty is applied to both the interior and coastal areas. For the whole basin the uncertainties associated with assumption 1) and 2) will vanish, because these two assumptions are needed only when we separate the coastal and interior regions.