Temporal Variations in Ice Thickness of the Shirase Glacier Derived from Cryosat-2/SIRAL Data

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Supplementary Materials

S1. Conversion of CryoSat-2/SIRAL Data into Height

The data measured by CryoSat-2/SIRAL are ellipsoid heights using the WGS-84 as the ellipsoidal model. The SIRAL measures the distance (r) from the antenna to the surface of the observation target, and then the surface height measured by the SIRAL (h_s) is calculated using Equation (S1):

$$h_s = H - r, \tag{S1}$$

where H is the satellite height on the ellipsoidal surface.

h_s is also defined by the ellipsoidal surface and includes a geoid height (h_g); therefore, the elevation (h) at the target is calculated using Equation (S2):

$$h = h_s - h_g, \tag{S2}$$

where the geoid is a model of global mean sea level surface, for which this study adopted the Earth Gravitational Model 2008 (EGM2008) [36], as the most recent. The height obtained by the CryoSat-2/SIRAL is hereafter referred to as the CryoSat-2 height.

S2. Screening for Outlier Data of the CryoSat-2 Height

The procedure employed for screening for outliers in CryoSat-2 height employed in this study was as described below. First, CryoSat-2 heights lying outside the analysis area shown in Figure 1 were not used in this study. Next, CryoSat-2 heights below 1 m were also not used in order to be able to apply the method for estimating ice thickness as described in Section S3. Then, CryoSat-2 heights above 140 m were excluded as outliers, since the maximum height on the grounding line of the Shirase Glacier is approximately 130 m, as derived from the AW3D30. Furthermore, CryoSat-2 heights greater than the maximum heights obtained by the AW3D30 for each of the exposed rock areas, which were 54 m, 296 m and 84 m for Rundvågshetta, Skallevikshalsen and Skallen, respectively, were excluded.

Finally, prior to the CryoSat-2 height gridding, described in Section S3, outlier removal was applied the CryoSat-2 heights for each grid in the five-number summary. The closed interval of the five-number summary can be expressed as shown in Equation (S3):

$$[Q_{1/4} - 1.5 \times IQR, Q_{3/4} + 1.5 \times IQR], \tag{S3}$$

where $Q_{1/4}$ is the lower quartile, $Q_{3/4}$ is the upper quartile and IQR is the interquartile range ($Q_{3/4} - Q_{1/4}$)). When the CryoSat-2 height was outside the closed interval in a grid, that height was excluded as an outlier. Additionally, our analysis excluded grids with less than three CryoSat-2 heights in order to ensure the representativeness of the CryoSat-2 heights in a grid.

S3. Gridding CryoSat-2 Height and Its Conversion into Ice Thickness

After the preprocessing of CryoSat-2 height, a rasterized image was generated by calculating the mean CryoSat-2 height for each grid. Since this resulted in missing data in some grids due to screening for outlier data (Section S2), the raster images were generated after interpolating the missing values using the inverse distance weighting method [37].

The CryoSat-2 height extracted from the rasterized image was converted into ice thickness using the following procedure. The calving area of the Shirase Glacier is the region downstream from the grounding line, where the ice shelf or the floating ice tongue float into the ocean. Under the assumption of hydrostatic equilibrium, the relationship between the floating ice and the seawater can be expressed using Equation (S4):

$$\rho_{ice} \times S \times H \times g = \rho_{sea} \times S \times (H - h) \times g, \tag{S4}$$

where ρ_{ice} is the density of the ice, ρ_{sea} is the density of the seawater, S is the area of the ice bottom, H is the ice thickness, and g is gravitational acceleration.

This study employed reference densities of ρ_{ice} = 900 kg m^{-3} and ρ_{sea} = 1030 kg m^{-3} [9], which, when used in Equation (S4), resulted in the following:

$$H = 7.92 \times h. \tag{S5}$$

36 Pavlis, N.K.; Holmes, S.A.; Kenyon, S.C.; Factor, J.K. The development and evaluation of the Earth Gravitational Model 2008 (EGM2008). *J. Geophys. Res*. **2012**, *117*, B04406. https://doi.org/10.1029/2011JB008916.
37 Watson, D.F.; Philip, G.M. A refinement of inverse distance weighted interpolation. *Geo-Process.* **1985**, *2*, 315–327.