Response (Anonymous Referee #1)

Comment: This paper presents significant new material by introducing the SDUST2022GRA, a new 1 arcmin global marine gravity anomaly model, along with various comparisons to state-of-the-art global gravity field models and in situ observations. The authors leverage radar and laser altimetry to harness the strengths of individual missions enabled by advanced altimeter technologies. The beam pair configuration of ICESat-2, which allows for the determination of cross-track height slopes, offers an opportunity to enhance the precision and spatial resolution of the gravity anomaly model. This article provides valuable insights into gravity anomaly recovery using along-track and cross-track data. Overall, the paper introduces significant advancements in the field, but addressing the following concerns would enhance its clarity and impact.

Reply: Thanks very much for your valuable suggestions and comments. These comments play an important role in revising the paper and improving the quality of the paper. We have revised our manuscript according to your comments. Below, we describe in detail the changes to the manuscript on a point-by-point basis.

Concerns:

1. Section 4.1 emphasizes the critical role of altimeter data downsampling in mitigating high-frequency noise, which is essential for ensuring data accuracy and reliability. For radar altimeter data, a 1 Hz sampling rate is typically employed. The authors note that ICESat-2 laser altimeter data exhibit varying length scales, ranging from 70 m to 7 km. However, the downsampling method applied to the ICESat-2 laser altimeter data is not specified. Clarification on this method is essential, as it significantly impacts the quality of the SDUST2022GAR model.

Reply: Thanks for your suggestion. Resampling is an important method in altimeter data processing. We have added the introduction about resampled method in Section 3.2 and presented the precision of SSHs before and after resampling in Section 4.1.

Section 3.2 ICESat-2 laser altimeter data processing

The ICESat-2 SSH observations at varying length scales is resampled at 1 Hz for each beam to achieve a uniform distribution of SSHs. In the resampling, SSHs at varying length scales are fitted using a quadratic polynomial in latitude to reduce the effect of the high-frequency noise and outlier. Each 1-s SSHs is used to solve polynomial coefficients and then produced SSHs in the median of the latitude. When the number of observations is less than the minimum number for the solution of polynomial coefficients, the 1-s SSHs are averaged directly to 1 Hz. The used quadratic polynomial function of latitude is (Yu and Hwang, 202)

$$l_i + v_i = a\varphi_i^2 + b\varphi_i + c \tag{6}$$

where l_i is the SSH observation at point i with in a time threshold, v_i is the residual at point i, φ_i is the latitude at point i, and a, b, c are the coefficients of the quadratic polynomial.

Section 4.1 Gravity anomalies recovered from ICESat-2

For the recovery of gravity anomalies from ICESat-2 altimeter data, SSHs at varying length scales from ICESat-2 are resampled to 1 Hz to integrate into radar altimeter data. The quality of SSHs and the accuracy of gravity anomalies recovered from SSHs at different sampling frequency are listed in Table 3. After resampling, the total number of SSHs is reduced, but the RMS of SSHs crossover discrepancies is improved by about 1 cm. Moreover, assessed by shipborne gravity and SIO V32.1, the RMS of gravity anomalies from SSH at 1 Hz assessed by SIO V32.1 is slightly better than that of SSHs at varying length scales. Thus, SSHs of ICESat-2 resampled at 1 Hz are used to recover global marine gravity anomalies.

Table 3 The quality of ICESat-2 SSHs and gravity models recovered from SSHs at varying length scales and at resampled 1 Hz

SSHs at different sampling frequency	The number of SSHs	The RMS of SSH crossover discrepancies after adjustment (m)	The difference between Gravity anomalies recovered from ICESat-2 and Shipborne gravity (mGal)		The difference between Gravity anomalies recovered from ICESat-2 and SIO V32.1 (mGal)	
			|Max|	RMS	|Max|	RMS
SSHs at varying length scales	1 457 596	0.124	50.02	5.44	52.30	3.06
SSHs at 1 Hz	854 533	0.115	49.54	5.42	52.01	2.89

2. The geoid height is derived from SSH observations, with the dynamic topography removed as the non-geoidal signal. The authors use the MDT_CNES_CLS18 model with a grid resolution of 7.5 arcmin to remove this signal. Given that the average along-track ground distance of altimeter data is about 7 km (1 arcmin), it is crucial to understand how the removal value from MDT_CNES_CLS18 is determined. Detailed methodology on this aspect would enhance comprehension.

Reply: Thank you for your thoughtful comments. The dynamic topography is an essential non-geodetic signal. It should be removed from SSH observations to obtain the geoid height. In general, the mean dynamic topography (MDT) model is used in order to reduce the effect of dynamic topography. The MDT_CNES_CLS18 model (or other model) is a regular grid data of 7.5'×7.5'. The SSH observations is at 1 Hz sampled frequency. The removed value of MDT at corresponding position of SSHs is derived by the bivariate spline interpolation.

The sentence is rephrased:

Secondly, the residual geoid heights are determined by removing the mean dynamic topography model and the reference geoid model from corrected SSHs. The removed valve of MDT_CNES_CLS18 (Mulet et al. 2021) or geoid model at corresponding position of SSHs is derived by the bivariate spline interpolation.

3. Filtering is crucial for the fusion of multi-altimeter data. The filter radius for along-track radar and laser altimeter data is noted as 7 km. However, details regarding the filter radius and its application are missing. Is the filtering applied in the along-track direction or in the spatial domain? Is the purpose to reduce spatial high-frequency error or to mitigate the temporal SSH signal? Clarification on these points is essential for a thorough understanding and accurate interpretation of the results.

Reply: Thanks for your comments. Gaussian filter is applied in along-track SSHs from radar and laser altimeter data in order to reduce the influence of sea surface temporal variability and high-frequency noise. The response function is selected as

$$r(d) = \exp(-\frac{d^2}{2s^2})$$

where d is the spherical distance between two data points. s is the radius of the convolution window and is defined as the filtering parameter. Filtered values are obtained by convolving all SSHs in the window of radius s with the response function.

In section 4.1, we have discussed the filter radius for the gravity anomalies recovered from ICESat-2. According to the average along-track ground distance, the filtering radius with a multiple of 7 km is used to recover gravity anomaly model. To conclude, the filtering radius of 7 km is selected for the gravity anomalies recovery from ICESat-2 along-track SSHs.

For radar altimeter data, the filter radius is generally consistent with the recovery of SDUST2021GRA gravity anomaly model (Zhu et al., 2022). Thus, it is not presents in this manuscript.

Zhu, C., Guo, J., Yuan, J., Li, Z., Liu, X., and Gao, J.: SDUST2021GRA: global marine gravity anomaly model recovered from Ka-band and Ku-band satellite altimeter data, Earth Syst. Sci. Data, 14, 4589–4606, https://doi.org/10.5194/essd-14-4589-2022, 2022.

4. Section 3.2 outlines the steps for determining cross-track geoid gradients. However, merely listing the processing steps can lead to ambiguity. For instance, the phrase "one track with good observation is selected as the reference altimeter data" is unclear. Does "good" refer to accuracy or the number of observations? Providing the corresponding formula or a detailed processing flowchart would greatly improve clarity.

Thanks very much for your valuable comments. We have revised the processing steps for determining cross-track geoid gradients (GGs), and added the corresponding formula to determine the cross-track GGs from any two of three beams observations. The sentence in Section 3.2 is rephrased:

Because three beams of ICESat-2 observations are not exactly simultaneous, the cross-track GG is determined, according to the following steps. (1) One beam with good observations (maximum number) from two beams altimeter data is selected as the reference altimeter data. (2) Based on the reference beam observations, the cross-track GG is determined within an azimuth threshold. (3) If the number of GGs is more than one on each reference observation, only the cross-track GG with an azimuth closet to perpendicular to the orbit inclination is used to recover gravity anomalies. A schematic diagram of determining the cross-track gt13 GGs from ICESat-2 altimeter data is shown in Fig. 3. The cross-track GG determination strategy is defined as follows:

$$\begin{cases} \mathrm{Reference\_beam} = \mathrm{Max}[\mathrm{Num}_{\mathrm{gt1}}, \mathrm{Num}_{\mathrm{gt3}}] \\ \left|T_i - T_{ref}\right| \le T\_Threshold \\ \left|\alpha_{GG,i} - \alpha_{ref\_inc}\right| \le A\_Threshold \\ \mathrm{Cross\_track\_GG} = \mathrm{Min}[\alpha_{GG,i} - \alpha_{ref\_inc}] \end{cases} \tag{7}$$

where $\mathrm{Num}_{\mathrm{gt1}}$, $\mathrm{Num}_{\mathrm{gt2}}$, and $\mathrm{Num}_{\mathrm{gt3}}$ are the number of each beam observations, respectively. T_{ref} is the observation time of reference beam, T_i is the observation time of the other beam, $\alpha_{GG,i}$ is the azimuth of GG derived from two-beam observations at the number i . α_{ref_inc} is a reference azimuth perpendicular to the orbit inclination. $T\_Threshold$ is a time threshold, and 1 s is selected as time threshold to reduce the effect of random errors, $A\_Threshold$ is an azimuth threshold, $\pi/4$ serves as a azimuth threshold to obtain GGs with azimuth toward east-west direction.

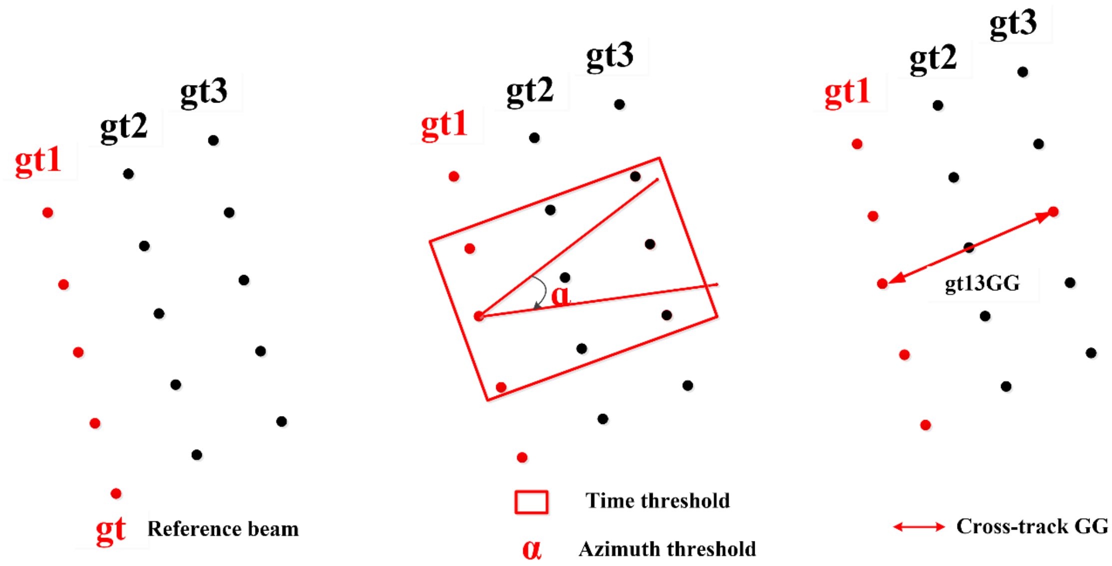

Figure 3 The schematic diagram of determining the cross-track geoid gradients from gt1 and gt3 beams of ICESat-2

5. The precision of the gravity anomaly model is assessed by comparing it to shipborne gravity anomalies. While the RMS is 4-5 mGal in global oceans and low-middle latitudes, it approaches 10 mGal in high-latitude regions. An explanation for the lower precision in high-latitude regions is necessary to understand this discrepancy.

Reply: Thanks for your comments. For this large difference, I think there are two main reasons. First, the number of shipborne gravity data is small, as shown in global shipborne gravity distribution (Fig. 2). The precision of shipborne gravity in high latitude region is probably lower than that of in low-middle latitudes. In some local high latitude regions, the RMS of difference is large than 10 mGal, as shown in the assessment of SDUST2021GRA (Zhu et al., 2022). Second, the reduced quantity and low precision of SSHs also degraded the accuracy of the recovered gravity anomaly model. The average number of GGs from all altimeter data within the $1'\times1'$ grid is calculated, as presented in Fig. 8. In addition, we also compared SDUST2022GRA and shipborne gravity in local high latitude region (140°W-170°W, 80°S-66°S). The statistic of difference is shown in Table 11. The RMS is about 5.14 mGal, which consistent with the assessment in low-middle latitudes.

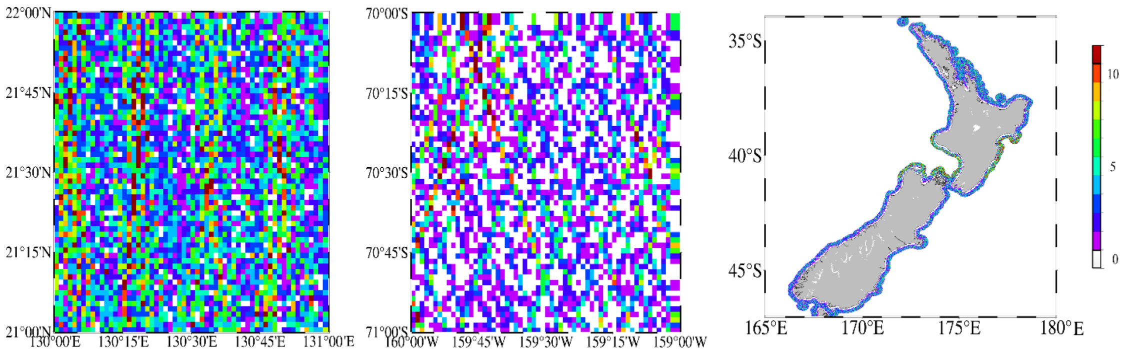

Figure 8 The number of SSHs within the 1′×1′ grid in different local regions. a: open ocean with average number of 3.5. b: the high latitude region with average number of 2.1. c: coastal region with average number of 1.9.

Table 11 The Mean and RMS of difference between gravity anomaly models and shipborne gravity in local regions (Unit: mGal)

Local region		**NSOAS22**		**DTU17**		**SIO V32.1**		**SDUST2022GRA**	
		Mean	**RMS**	**Mean**	**RMS**	**Mean**	**RMS**	**Mean**	**RMS**
Region A1	Open ocean	0.15	3.58	0.10	3.24	-0.10	3.15	0.20	3.04
Region A2		-0.41	5.13	-0.41	4.29	0.14	3.78	0.01	4.01
Region B1	Coastal region	-1.51	8.47	-1.81	7.21	0.10	6.25	-0.16	6.08
Region B2		-0.86	10.66	-1.41	10.33	-0.56	7.85	-0.57	7.69
Region B3		0.10	12.12	-1.24	11.25	-0.67	10.32	-0.68	10.10
Region C1	High-latitude region	0.33	5.86	0.15	5.36	0.12	5.38	0.12	5.14

6. Spatial resolution is a crucial index of the gravity anomaly model. Cross-spectral analysis is typically used to determine the wavelength of the model by comparing it to shipborne gravity. The paper derives three results from shipborne gravity, yet the wavelengths from the gravity anomaly model differ. An explanation for this variance and what determines the spatial resolution of the model would be beneficial.

Reply: Thank you for your thoughtful comments. The spatial resolution is certainly a crucial index of the altimeter-recovered gravity anomaly model. The wavelength derived from SDUST2022GRA with a CMS value of 0.5 is 18.6 km, 20.7 km, and 20.4 in a local open ocean region, high latitude region, and coastal region, respectively. There are two main reasons for the difference. First, the assessment is related to the data interval of shipborne gravity. Three cruises shipborne gravity anomalies are used to determine the spatial resolution of SDUST2022GRA, SIO V32.1, and DTU17, as shown in Fig. 5. In addition, the spatial resolution of gravity anomaly model is mainly determined by altimeter data resolution and density. In different regions, there are also slight variations in the density of altimeter data, as shown in Fig.8.

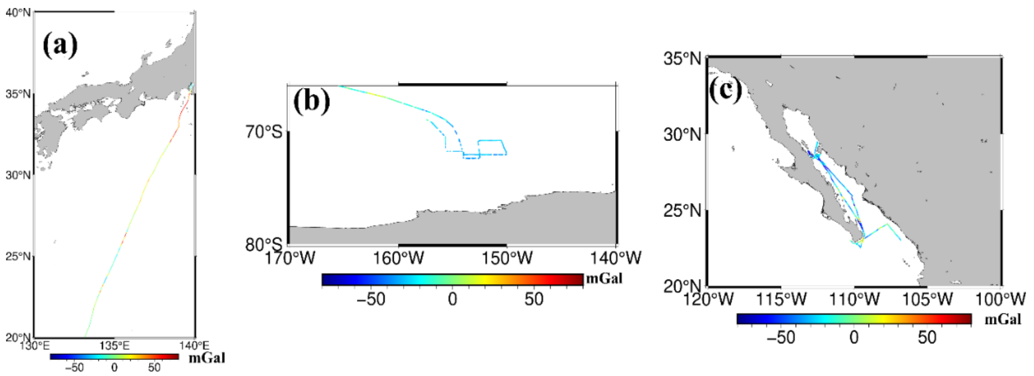

Figure 5 Shipborne gravity (used to determine CMS) of different cruises. a: the jare3311 with average distance interval of 0.45 km. b:. the ew9201 with average distance interval of 0.80 km. c: the moce05mv with average distance interval of 0.22 km.

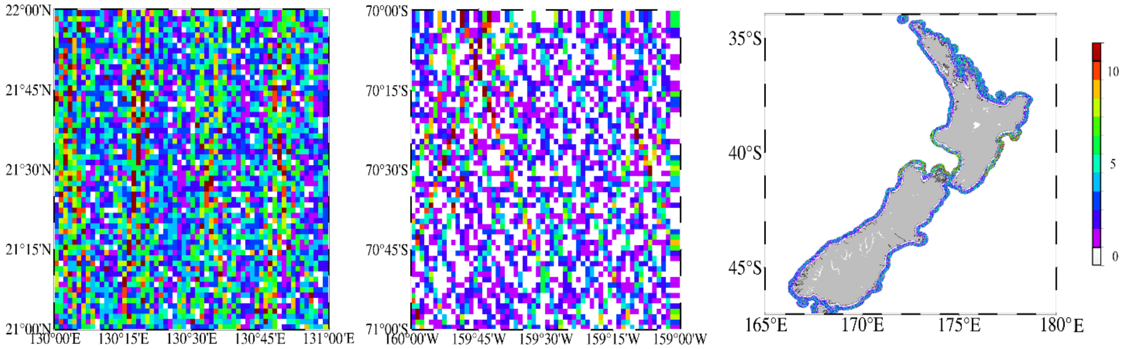

Figure 8 The number of SSHs within the 1′×1′ grid in different local regions. a: open ocean with average number of 3.5. b: the high latitude region with average number of 2.1. c: coastal region with average number of 1.9.

Minor edits:

7. I recommend that the authors improve the clarity and readability of the manuscript by refining the English language usage

   Line 17: "across-track direction" should be "cross-track direction".

   Line 115: SARAL/Altika is operate in Ka-band not Ku-band, please correct it.

Reply: Thanks for your thoughtful comments. This 'across-track' is corrected to 'cross-track' as the suggestion in all sections. And we corrected the sentence 'SARAL/Altika is operate in Ka-band not Ku-band'.

8. Line 146: "a quadratic polynomial was used to correct long wavelength system error". This statement is not accurate. The quadratic polynomial is used for shipborne gravity from each cruise in order to correct system bias relative to the gravity reference field.

Reply: Thank you very much for your suggestion. The sentence is rephrased:

Then, for gravity anomalies from each cruise, the system bias caused by the drift of the gravimeter was corrected by a quadratic polynomial, which is detail in Hwang and Parsons (1995).

9. Line 252: "the maximum distance of along-track …", what is the maximum distance?

Reply: Thanks for your suggestion. The sentence is rephrased:

For SSHs of ICESat-2, the average ground distance of along-track adjacent observations is about 7 km, so the filtering radius with a multiple of 7 km is applied to recover marine gravity anomalies from along-track altimeter data.

10. Line 265: In Table 5, please specify the unit of geoid gradients?

Reply: Thanks for your comment. We scrutinized the unit of geoid gradients. The unit in Table 5 is corrected.

Table 5 The number and STD of residual GGs from ICESat-2

Residual GGs	**gt1**	**gt2**	**gt3**	**gt12**	**gt23**	**gt13**
Number	302407	250988	301138	202492	200312	209769
STD(urad)	1.93	1.88	1.91	2.66	2.75	1.94

11. Line 369: The percentage contribution formula is not explained clearly about the use of the variable

RMS. Please add an description.

Reply: Thank you for your valuable comments. The percentage contribution is redefined as $\frac{RMS_{\mathrm{SDUST2022GRA}} - RMS_{\mathrm{SDUST2021GRA}}}{RMS_{\mathrm{SDUST2022GRA}}} \times 100\%$ and the improvement is recalculated. The sentence is rephrased: the percentage contribution of ICESat-2 to the improvement of gravity anomaly model is 4.3% in low-middle latitude regions, and it is increasing in coastal regions.

12. Line 385: In Table 14, the regions A, B, C, D, E, F are not mentioned in the text. please specify the used region.

Reply: Thanks for your comments. We corrected the description of region in the Table 14.

Table 14 The percentage contribution of ICESat-2 altimeter data in different local regions

Local region	**$RMS_{SDUST2021GRA}$ (mGal)**	**$RMS_{SDUST2022GRA}$ (mGal)**	**△RMS (mGal)**	**Percentage Contribution**
Region A1	3.12	3.04	0.08	2.5%
Region A2	4.07	4.01	0.06	1.5%
Region B1	6.40	6.08	0.32	5.0%
Region B2	7.98	7.69	0.28	3.5%
Region B3	10.51	10.10	0.41	3.9%
Region C1	5.32	5.14	0.18	3.3%