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Ionospheric Corrections for Satellite Altimetry - Impact on Global Mean Sea Level Trends

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Key Points:

- Global Ionospheric Map corrections in altimetry Sensor Geophysical Data Records are not fully scaled to account for plasmaspheric electron content
- Neglecting the plasmaspheric effect leads to trends of up to 1 mm/year in Global mean sea level estimates
- The additional application of a scale factor improves the consistency in trend with respect to dual-frequency satellite altimetry data

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Abstract Atmospheric delay corrections for satellite altimetry measurements are essential for deriving highly accurate sea surface heights and reliable global mean sea level (GMSL) trend estimates. A commonly used method to correct for ionospheric path delays are the usage of GNSS-based Global Ionospheric Maps (GIM). The different orbit heights of GNSS and altimeter satellites require an adaption of GIM corrections to account for free electrons in the Earth plasmasphere. This study shows that the widely used scaling approach based on the International Reference Ionosphere (IRI) is not able to accurately scale the GIM models. The impact of neglecting the plasmaspheric part of the atmosphere strongly correlates with the solar activity of about 11 years. This manifests itself as trend errors in global GMSL. For the Jason period (2002–2021) a trend error of 0.17 mm/year can be shown, which is even larger for smaller periods (e.g., 1.0 mm/year for Jason-1 lifetime). The application of an additional constant scaling factor of 0.886 can reduce the trend differences to below 0.05 mm/year.

Plain Language Summary Global mean sea level (GMSL) rise is an important indicator for climate change. To precisely measure this quantity that is only in the order of about 3 mm/year, satellite altimeters are used. Their observations have to be corrected for influences in the Earth atmosphere. This study shows deficiencies in one commonly used correction data set. These corrections, based on observations from the Global Navigation Satellite Systems (GNSS) are not accounting for the higher part of the atmosphere, the plasmasphere. Neglecting this influence derives systematic errors with a 11 years cycle that impacts the estimation of GMSL by up to 1 mm/year, depending on the period under investigation. It is recommended to apply an additional scaling of the available corrections in order to reduce the trend error to below 0.05 mm/year.

1. Introduction

Monitoring the global mean sea level (GMSL) rise is essential for understanding and predicting global change and its impact on society. Satellite altimetry is providing important information about the global sea level record for about 30 years (Abdalla et al., 2021). In order to be able to provide the rate of GMSL with high accuracy, a careful processing of the altimetry observations is mandatory. One important component is the correction of the data for influences by free electrons in the Earth's ionosphere. Any systematic error in these corrections, especially drifts, directly influences the estimates of global mean sea level rise. According to Ablain et al. (2019), the GMSL rise for the period from 1993 to 2017 of 3.35 mm/year can be determined with an uncertainty of 0.4 mm/year within a 90% confidence level. Within this error estimate, ionospheric corrections errors are assumed as a high-frequency component with a correlation length of 2 months. Possible long-term systematic effects of this correction are not considered in that study (since they are not expected for the dual-frequency altimeter-based corrections used).

Most altimetry missions are operating on two different frequencies that allow for determining and correcting the ionospheric delay of the signals (Chelton et al., 2001). However, not all missions do have a second signal (e.g., Cryosat-2) or lost the second frequency during operational life (e.g., Envisat). Moreover, offsets between different missions are known (Dettmering et al., 2011; Tseng et al., 2010), and the dual-frequency corrections are less reliable in coastal and inland environments due to a required along-track smoothing (CNES, 2010; Fernandes et al., 2014; Imel, 1994) that might be influenced by land contamination in these areas.

Ionospheric information for correcting satellite altimetry measurements can also be derived from external models. A prominent example are the global ionospheric maps (GIM) from terrestrial dual-frequency Global Navigation Satellite Systems (GNSS) measurements (Komjathy & Born, 1999) available from the International GNSS

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Service (IGS) or its analysis centers (e.g., JPL or CODE). Such corrections are available since 1998 (Hernández-Pajares et al., 2009; Wielgosz et al., 2021). They are included in most of the official altimetry data sets (e.g., for the Jason satellites), and they are commonly used for single-frequency altimeter correction and for coastal and inland applications. For their application on satellite radar altimetry data, the different orbit heights between GNSS satellites and altimetry satellites have to be taken in account, since GNSS is influenced not only by the ionosphere but also by the plasmasphere (above about 1000 km). The relative contribution of the plasmaspheric effect is estimated to range between about 10% and 60% (Yizengaw et al., 2008) with largest contribution in the equatorial region (Orús et al., 2002). This is usually taken into account by scaling the GNSS vertical total electron content (VTEC) using the method proposed by Iijima et al. (1999).

Nowadays, physical or climatological models such as the different versions of the International References Ionosphere IRI (Bilitza, 2018; Bilitza & Reinisch, 2008) or the Bent model (Bent et al., 1976) are rarely used to correct altimetry observations due to their relatively low ability to reflect short-term extreme events. Also not often used but developed with focus on altimetry corrections is the NOAA Ionospheric Climatology (NIC09) that fits GPS maps more than twice as well as the IRI2007 model and has a root mean square error of about 18% (compared to 14% for GIM and 35% for IRI2007) (Scharroo & Smith, 2010).

For GMSL applications, highly precise and long-term stable ionospheric corrections are necessary. Moreover, consistency between different missions is important since reliable trends require the combination of different missions that have limited lifetimes of only a few years each. When relative sea level trends should be computed and coastal areas are included in the investigations, satellite missions with single-frequency altimeters come into play, and models for correcting the ionospheric path delay are necessary. The large impact of ionospheric corrections to GMSL from ERS and Envisat have already been discussed and shown by CLS (2012).

This paper assesses the consistency between different ionospheric corrections for satellite altimetry with the focus on long-term stability and application for GMSL estimates. The study only focus on the effect on GMSL trends. Other quantities as regional effects and tides will not be considered, even they are also impacted, as already shown by Jee et al. (2010) and Ray (2020). Only ionospheric corrections freely available to all users are assessed.

The datasets used within this study as well as the methodology used for the assessment are described in Section 2. Section 3 presents the results and the paper finishes with a conclusion.

2. Materials and Methods

This section describes the different ionospheric datasets used within this study as well as necessary pre-processing steps for the comparison. All investigations are based on the TOPEX and Jason-1/2/3 missions covering a period of about 21.5 years from January 1999 to June 2021. These missions are used since they provide dual-frequency ionospheric correction that can be easily compared to the GIM products. The data used (times and locations) are extracted from different versions of Geophysical Data Records (GDR): MGDR for TOPEX (NASA/JPL/PODAAC, 1998), as well as Sensor Geophysical Data Record (SGDR) versions available from AVISO, namely SGDR-E (Jason-1), SGDR-D (Jason-2), SGDR-F (Jason-3) (AVISO, 2021). It should be noted here, that the same information is also included in the standard GDR products, which do not include sensor data, that is, radar waveforms. The data is stored in DGFI-TUM's internal altimetry database MVA, and VTEC data is available through OpenADB (https://openadb.dgfi.tum.de; Schwatke et al. (2014)). Only data collected during the core mission phases are used (without interleaved and geodetic phases). For TOPEX, the first years before 1999 are not considered since no GIM correction is available for this period.

The ionspheric corrections are taken from external datasets (more details below), expect for the IRI95-scaled GIM data, which is directly taken from the SGDR for the Jason satellites (and named GIM SGDR). This information is not available in the TOPEX MGDR files. For this mission, information since 1999 (cycles 232–365) stems from external GIM files using an identical scaling approach. Comparisons for Jason-1 reveals a consistency between corrections derived from external data with internal GIM information down to sub-millimeter level.

2.1. Ionospheric Corrections From GNSS Global Ionospheric Maps (GIM)

Global VTEC maps based on the observation of dual-frequency GNSS are available since 1998 (Hernández-Pajares et al., 2009). Various Ionospheric Associated Analysis Centers (IAAC) are computing maps using different approaches, among them the Jet Propulsion Laboratory (JPL) in US. Their approach is based on interpolating VTEC within triangular tiles that tessellate the ionosphere modeled as a thin spherical shell (Mannucci et al., 1998).

In this study, the final VTEC maps from JPL are used (JPLG), since they perform similar well as the other IGS products (Hernández-Pajares et al., 2009; Orús et al., 2003) and are also used within the altimetry SGDR production and the NIC09 generation. They are available as daily IONEX files with a latency of a few days. The resolution is 2h in time and, 5° and 2.5° in longitude and latitude, respectively. The files are available from September 1998 until today from NASA's Archive of Space Geodesy Data CDDIS (Noll, 2010). For the comparison with dual-frequency altimeter data, these maps are interpolated on the altimetry ground tracks.

GIM provide the VTEC up to the orbit height of the GNSS satellites, that is, about 20,200 km. Thus, not only the ionospheric component is included but also plasmaspheric effects. Iijima et al. (1999) published a method to reduce the plasmasheric content from the measurements using an ionospheric model (IRI95) to extract the relation between the VTEC at altimetry orbit height and the maximum height of the model. Because they considered IRI95 to be realistic only up to an altitude of 1400 km, this upper limit was applied, and consequently, only a small part of the VTEC above the orbit height of the altimeter satellites is reduced. Newer versions of IRI use an upper boundary of 2,000 km, and even extensions to the plasmasphere exists (Gulyaeva & Titheridge, 2006). Nevertheless, this approach with an upper limit of 1400 km is still used for scaling the GIM information that is part of the current altimetry SGDR data of the Jason satellites.

In order to investigate the influence of the scaling approach on the comparability with dual-frequency altimeter measurements, four different GIM corrections are computed, all based on the JPLG GIMs:

1. an unscaled version representing the electron content up to GNSS orbit height
2. a version scaled by the approach of Iijima et al. (1999) (GIM SGDR; not available before 1999)
3. a version scaled by the NIC approach of Scharroo and Smith (2010) (see Section 2.2)
4. an optimal scaled version that minimizes the discrepancies to the ALTI product (see Section 2.4)

2.2. Ionospheric Corrections From NOAA Ionospheric Climatology (NIC09)

Based on about 10 years of JPL GIM, Scharroo and Smith (2010) developed a global ionospheric climatology, called NIC09. They set up a five-dimensional model depending on latitude, longitude, month, and hour of day, as well as a time-dependent global mean electron content (GTEC), which provides VTEC for any location on Earth and for any time for which the GTEC is known. A weighted linear least square solution is used to fit predefined functions (mainly offset and slope of linear variations) for each location and each even hour. While the spatial distribution of VTEC is derived from the GNSS information, the temporal evolution (in terms of global mean total electron content) for the period before the GNSS era is taken from TOPEX dual-frequency measurements (1992–1998) or from a fixed relation fitted between GTEC and the solar flux at 10.7 cm wavelength (before 1992 and for periods without TOPEX data). Even not as accurate as the GIMs itself, NIC09 provides a long-term stable correction with improved accuracy with respect to older ionosphere climatologies (Scharroo & Smith, 2010). The scaling to altimetry orbit height for NIC09 is done based on constant factors depending on the orbit. For the TOPEX/Jason orbit, a factor of 0.925 is recommended. In this study, this approach is also applied to GIM corrections and named as "NIC scaled" in the following.

2.3. Ionospheric Corrections From Dual-Frequency Altimeter Observations (ALTI)

The dual-frequency corrections for the Ku-band of the TOPEX and Jason altimeters is provided in the SGDR datasets. They are derived from a linear combination of both signals. Since the along-track noise level of these observations is quite high - even in 1 Hz data - an along-track smoothing of at least 100 km is recommended (Imel, 1994). In this study, a running median filter with about 150 km filter length is used for smoothing. The pre-processed smoothed correction available only for Jason-3 from the SGDR-F data set is not used to ensure consistent processing of all missions.

2.4. Pre-Processing for Data Comparison

Since the focus of this work is on long-term trends and global mean sea level, for analysis and comparison, global mean ionospheric corrections are used. Thus, the along-track information from a whole cycle (i.e., about 10 days)

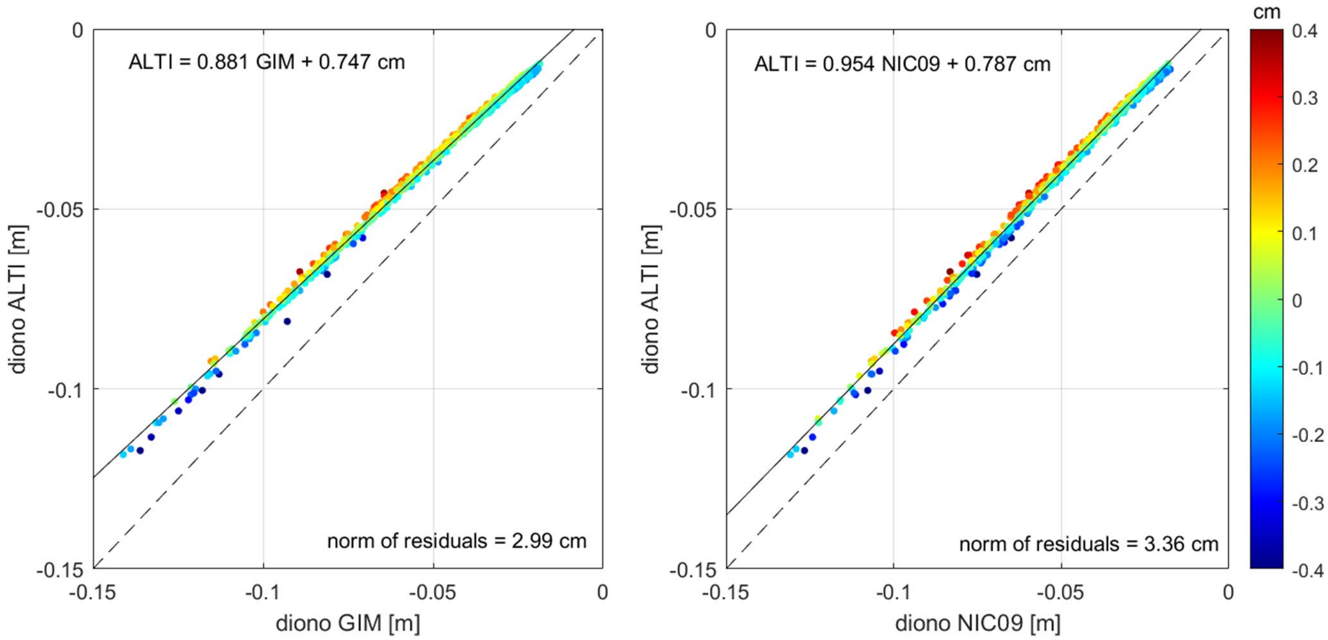

Figure 1. Relationship between dual-frequency altimeter ionospheric correction and (unscaled) Global Ionospheric Maps correction (left plot) and NIC09 corrections (right plot). The colors illustrate the residuals with respect to a linear relationship (in cm).

is average. In order to exclude influences from sea ice contamination, all observations north and south of 55 degrees have been removed from the data set before averaging. Moreover, only open ocean data are used without coastal and shelf areas (bathymetry threshold of 2,000 m).

As known from literature, offsets between different altimetry missions are to be expected (e.g., Bosch et al., 2014). This holds not only for the altimeter ranges but also for the derived dual-frequency ionospheric corrections (Azpilicueta & Nava, 2021). In this study, inter-mission biases are estimated from the overlapping periods (tandem phases; 20–23 cycles) between successive missions. The estimated offsets (−1.4 cm between TOPEX and Jason-1; 0.7 cm between Jason-1 and Jason-2; −0.9 cm between Jason-2 and Jason-3) are used to align all missions to the Jason-1 level. This reference is used since it spans a long period covering different solar activities. However, this choice is somehow arbitrary and not impacting the conclusion from this paper. It only influences the offset of the combined time series to the GIM results. The inter-mission offsets agree reasonable well with the estimates provided by Azpilicueta and Nava (2021) who reported −5.6 TECU (about −1.2 cm) for Jason-1 minus TOPEX, 3.5 TECU (0.7 cm) for Jason-2 minus Jason-1, and −2.5 TECU (−0.6 cm) for Jason-2 minus Jason-3 GDR-D (instead of the newer version GDR-E used for Jason-3 within this study).

Since in-situ as well as relative calibration approaches do not show any systematic drifts in TOPEX/Jason data, it is assumed that the dual-frequency corrections are stable with time. The combined time series of global mean ionospheric correction (called ALTI from now on) is used as reference in the following investigations.

Based on a comparison of the global mean (unscaled) GIM time series and the ALTI time series optimal scaling parameters between both data set are estimated. For that purpose, it is assumed that the ALTI values can be represented by the following equation

$$ALTI = GIM * scale + offset \tag{1}$$

Then, scale and offset can be estimated within a least square adjustment to be $offset = 0.899 \pm 0.008$ cm and $scale = 0.881 \pm 0.001$.

The relation between GIM and ALTI is shown in the left plot of Figure 1. When looking closely, one can see that the assumed linear relationship is not completely valid. This is also revealed when comparing the norm of residuals for a linear fit (2.99 cm) and with a quadratic fit (2.56 cm).

Table 1
Estimated Offsets and Scale Factors (From GIM to ALTI and From NIC09 to ALTI) for the Combined Time Series and for Different Missions

Mission	Offset (cm)	Scale factor	No of cycles
GIM combined	0.747 ± 0.008	0.881 ± 0.001	816
GIM SGDR combined	0.759 ± 0.008	0.886 ± 0.002	713
GIM TOPEX	−0.335 ± 0.047	0.919 ± 0.005	125
GIM Jason-1	0.839 ± 0.012	0.899 ± 0.002	257
GIM Jason-2	0.002 ± 0.012	0.873 ± 0.002	303
GIM Jason-3	0.620 ± 0.013	0.809 ± 0.005	196
NIC09 combined	0.787 ± 0.009	0.954 ± 0.002	816

The estimated scale factor differs from the value of 0.925 computed by Scharroo and Smith (2010) and used in NIC09. This might be related to the different periods used for estimating the scale. However, as visible from the right plot in Figure 1, the NIC09 model (including the NIC-scaling) shows less systematic differences with respect to ALTI (slope of linear fit is 0.954, e.g., closer to 1) even if the data is noisier.

In principle, scale and offset can also be estimated separately for the four missions (to avoid the mission combination), however, due to their different length and coverage of solar cycle (e.g., Jason-3 has not yet flown in high-solar-conditions), not all of the estimated parameter will be reliable. The estimated scale factors and offsets are summarized in Table 1.

As visible from the Table the estimated scale factor for GIM becomes smaller with time. While for TOPEX it is 0.919 (and thus close to the value estimated by Scharroo and Smith (2010) for NIC09), for Jason-3 only 0.809 is estimated. Whether this is related to the different lengths of the time series, to dif-

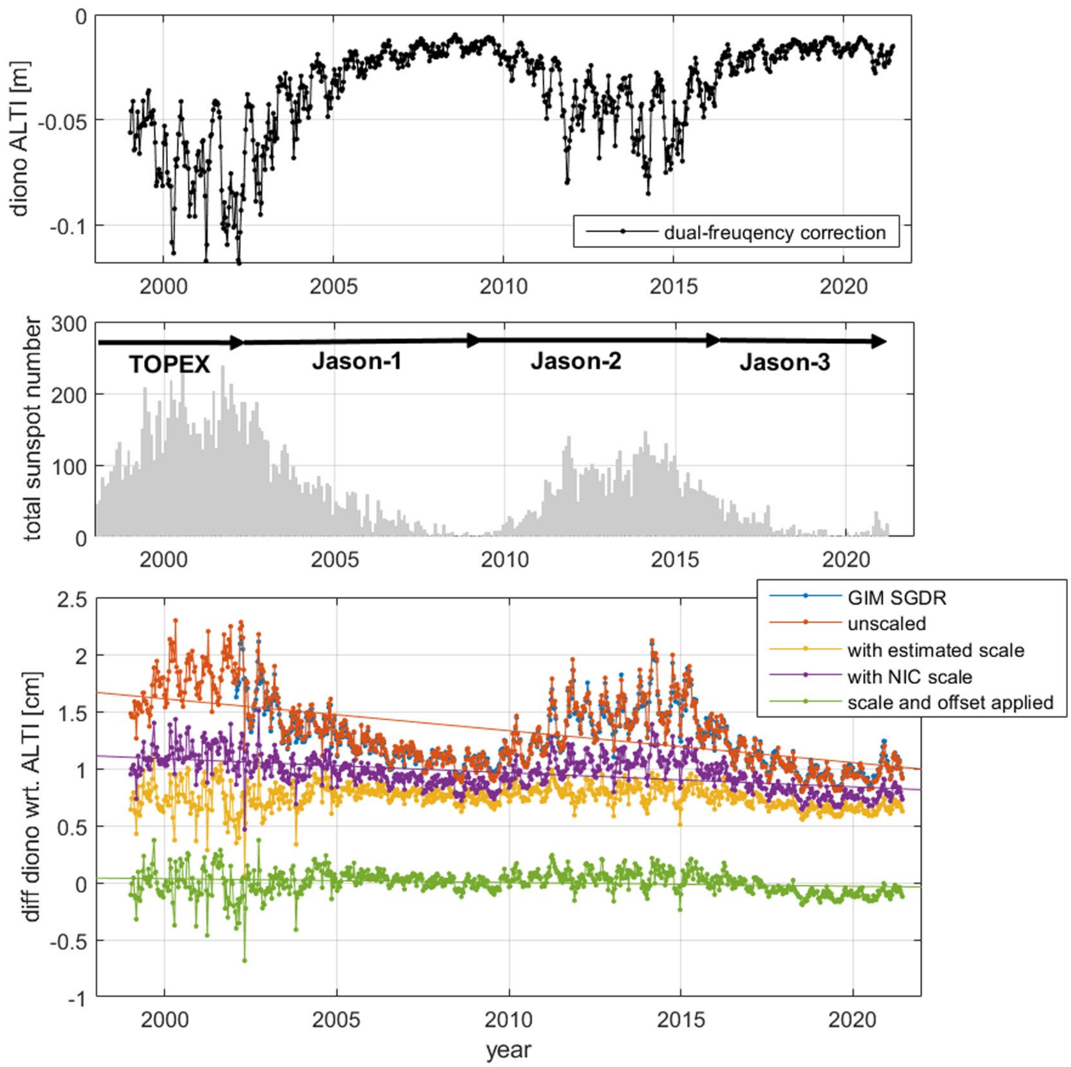

Figure 2. Dual-frequency altimetry ionospheric corrections (top) and its deviations to Global Ionospheric Maps model corrections with different scaling (bottom). The middle plot shows the monthly mean total sunspot number (SILSO World Data Center, Royal Observatory of Belgium, Brussels, 1998–2021) representing the solar activity.

Table 2
Comparison of Different Model Corrections to Dual-Frequency Altimeter Corrections; Standard Deviation of Difference (in mm)

	TOPEX	Jason-1	Jason-2	Jason-3	Combined
GIM unscaled	2.3	2.6	2.6	1.3	3.2
GIM SGDR (w/o TP)	–	2.4	2.4	1.3	2.6
GIM optimal scaled	1.3	0.9	0.7	0.4	1.0
GIM NIC scaled	1.3	1.1	1.3	0.9	1.5
NIC09	1.7	1.1	1.3	1.0	1.6

ferent solar conditions or to increasing impact of the plasmaspheric content is unclear. An analysis of a plasmaspheric model is recommended for further clarification.

3. Results and Discussion

The global mean ionospheric correction strongly depends on the solar activity and shows a clear correlation to the total sunspot number, as can be seen from Figure 2. The lower plot of that figure shows the differences between the ALTI correction and the GIM correction - the latter based on four different scaling approaches as described in Section 2. The unscaled GIM solution (red) as well as the SGDR GIM solution (blue) are very similar to each other and both are still correlated with the solar activity. Moreover, over the full period of nearly 22 years a trend of about 0.2 mm/year in the differences is visible, which is even more significant for some smaller time spans, for example, for the Jason-1 mission between 01/2002 and 01/2009.

When applying the NIC scaling factor to the GIM corrections, correlation and drift become significantly smaller, and the estimated optimal scaling completely removes the time-variable systematic effects. The green curve shows the differences when estimated offset as well as optimal scaling is applied. This solution is dominated by random noise.

As visible from Table 2, the standard deviations of the differences are reduced from 3.2 cm (unscaled) to 1.0 cm with optimal scale factor application. IRI- and NIC-scaling are with 2.6 and 1.5 cm in between. When looking at the different missions separately, it turns out that the scaling used in SGDR only slightly improves the consistency to ALTI corrections, and that the improvement is no longer visible for Jason-3, thus for low solar activity. The NIC scale factor works best (i.e., is closer to the optimal scaling) for TOPEX, thus for higher solar activity. The standard deviations for the NIC09 differences are similar or only slightly larger than for the NIC-scaled GIM differences.

These numbers are at least partly dominated by systematic effects correlated with solar activity. These effects will directly impact the estimation of GMSL, especially decadal variations and trends. Tables 3 and 4 show the trend differences for the combined time series and separately for the different missions. Even in the long time series covering more than 11 years of one solar cycle significant trend differences are visible. GMSL trends relying on the GIM corrections provided in the SGDR of the Jason missions will by biased by 0.17 mm/year with respect to the dual-frequency correction. This value can be reduced to below 0.05 mm/year when introducing an optimized (constant) scaling factor. The impact on shorter GMSL trends is of course much larger, depending on the length and timing within the solar cycle. For example, for Jason-1, the trend difference yields more than 1 mm/year due to fact that this mission covered about half a solar cycle starting in high solar activity and ending in low solar activity. When trends are computed for one complete solar cycle (11 years), trend differences become smaller. However, they still can be seen, since period and amplitude of solar activity can vary.

The trend differences for NIC09 corrections are equal to the NIC-scaled GIM corrections when taking the estimation uncertainties into account. Compared to the unscaled GIM solution and the SGDR GIM solution, the NIC09 trends compare about twice as good to the ALTI solution.

Table 3
Trend Differences Between Global Ionospheric Maps Correction (With Different Scaling) and Dual-Frequency Correction (in mm/year)

	1999–2021	2002–2021
GIM unscaled	0.280 ± 0.014	0.195 ± 0.017
GIM SGDR	–	0.168 ± 0.016
GIM optimal scaled	0.033 ± 0.006	0.045 ± 0.006
GIM NIC scaled	0.123 ± 0.007	0.100 ± 0.009
NIC09	0.127 ± 0.008	0.093 ± 0.009

4. Conclusions

The comparison of different global mean ionospheric delay corrections of satellite altimetry data shows large discrepancies in terms of trends. This study indicates that the GNSS-based GIM product available in the SGDR datasets of the Jason satellites is not optimally adapted to the orbit height. Namely, the effect of plasmaspheric electron content is not removed from the GNSS based datasets. This effect strongly depends on the solar activity and can lead to significant multi-year trend differences that will influence global mean sea level trends. Even over the full period with GIM available

Table 4
Trend Differences Between Model Correction and Dual-Frequency Correction (in mm/year)

	TOPEX	Jason-1	Jason-2	Jason-3
	01/1999–08/2002	01/2002–01/2009	07/2008–09/2016	02/2016–06/2021
GIM unscaled	−1.122 ± 0.116	1.074 ± 0.046	−0.541 ± 0.054	0.477 ± 0.052
GIM SGDR	–	0.985 ± 0.041	−0.519 ± 0.050	0.465 ± 0.051
GIM optimal scaled	−0.533 ± 0.102	0.079 ± 0.028	−0.016 ± 0.018	0.104 ± 0.018
GIM NIC scaled	−0.577 ± 0.101	0.353 ± 0.025	−0.232 ± 0.028	0.329 ± 0.033
NIC09	−0.604 ± 0.132	0.267 ± 0.030	−0.173 ± 0.029	0.291 ± 0.039

(since 1999) that covers more than one solar cycle long-term trend differences in the order of 0.2 mm/year are detectable. When GMSL trends are computed for shorter periods (e.g., single missions) based on SGDR GIM corrections, drift effects can reach up to about 1 mm/year.

The use of a simple scaling factor of 0.881 performs significantly better and reduces the trend difference with respect to dual-frequency altimetry data to less than 0.05 mm/year. Using the constant scaling factor of 0.925 from the NIC09 model as recommended by Scharroo and Smith (2010) results in a trend difference of about 0.1 mm/year.

However, since the relation is not linear and slightly change with time, a better solution might be the application of a precise plasmasheric VTEC model, for example, GCPM (Gallagher et al., 2000), NPSM (Jakowski & Hoque, 2018), or extensions of ionospheric models to the plasmasphere, such as IRI-Plas (Gulyaeva & Titheridge, 2006) or the NeQuick 2 (Nava et al., 2008) that was used for example, in Wielgosz et al. (2021). As long as such information is not part of the altimetry data set, the users are recommended to apply an additional scaling factor of 0.886 on the GIM provided in the GDR data sets.

For GMSL trend estimation, the climatological NIC09 model also provides very good results. The trend differences with respect to dual-frequency altimetry solutions are comparable to NIC-scaled GIM models. Thus, NIC09 corrections should be preferred to (wrongly scaled) GIM corrections. However, this only holds for GMSL applications and might be different for regional applications on shorter spatial and temporal scales.

This study is based on the TOPEX/Jason missions only. However, identical scaling approaches are used for other missions, such as Sentinel-3 and Sentinel-6. Even if for those dual-frequency missions, the GIM corrections are normally not used for GMSL applications, the study results might be of special importance for single-frequency mission that rely on GIM corrections for all applications (e.g., Cryosat-2, SARAL, ERS). When those missions are combined with dual-frequency ones, this will insert large inconsistencies. Moreover, the estimation of coastal sea level trends might be negatively impacted when GIM is used in order to suspend land contamination due to along-track smoothing of the dual-frequency ionospheric corrections.

Data Availability Statement

The altimetry data used within this study is taken from PODAAC (https://podaac.jpl.nasa.gov) and AVISO (https://www.aviso.altimetry.fr). Dual-frequency VTEC data can be found at OpenADB (https://openadb.dgfi.tum.de/en/products/vertical-total-electron-content/). The GIM models were obtained through the online archives of the Crustal Dynamics Data Information System (CDDIS), NASA Goddard Space Flight Center, Greenbelt, MD, USA (https://cddis.nasa.gov/archive/gnss/products/ionex/). NIC09 was downloaded from ftp.star.nesdis.noaa.gov/pub/socd/lsa/rads/nic09.

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