

This manuscript introduces GIFT-BDS, a new regional high-resolution ionospheric dataset over China built upon more than 200 ground GNSS stations and five BeiDou GEO satellites. Taking advantage of the nearly-fixed observation geometry of BDS-GEO, the dataset provides Level-1 slant TEC time series and Level-2 gridded products including VTEC, ROTI, and multi-component Gradient Ionospheric Index (GIX) with $0.25^{\circ} \times 0.25^{\circ}$ spatial resolution and 15-min temporal cadence. The authors comprehensively document network configuration, full processing workflow, quality-control schemes, internal consistency diagnostics, and benchmark comparison against CAS GIM. Representative science cases further demonstrate its capability for investigating Equatorial Ionization Anomaly (EIA), Equatorial Plasma Bubble (EPB), as well as quantifying ionospheric impacts on PPP and network RTK positioning performance. The paper is well-structured; methods are clearly described, validation metrics are properly defined, and example applications are illustrative. Overall, this work is suitable for publication in Earth System Science Data after addressing the following minor points.

Response: We thank the reviewer for the careful review and overall positive assessment of the GIFT-BDS dataset. The comments helped us clarify the scope of the product assessment and the treatment of uncertainty in the STEC and TEC-gradient products.

The manuscript has been revised accordingly. The main changes are summarized as follows:

#1 We revised the scope of the quality assessment for both Level-1 STEC and Level-2 TEC-gradient products, and distinguished short-term stability, internal consistency assessment, and GIM-based morphology and resolution comparison.

#2 We updated the 2026 BeiDou GEO satellite configuration (because of the BeiDou satellite PRN reassignments in April 2026), backfilled the operational GIFT-BDS products, and restored the automated operational update procedure.

#3 We expanded the description of the GIM-assisted receiver DCB estimation and clarified how the associated uncertainties propagate through STEC and VTEC into the TEC-gradient products.

#4 We added a quantitative analysis of the dependence of TEC-gradient estimates

on inter-IPP distance and clarified the spatial scales represented by the Level-2 GIX products.

Detailed point-by-point responses are provided below. For ease of review, all corresponding changes in the revised manuscript are highlighted in red.

Comment 1. It lacks external independent validation. This might be difficult.

Response:

We agree that independent external accuracy validation is not presently available for the GIFT-BDS products. The revised manuscript now states this limitation and separates the different quality measures according to what they actually assess.

For the Level-1 STEC product, a direct absolute comparison with observations from another satellite is not appropriate because STEC is a line-of-sight quantity. Different satellites sample different three-dimensional ionospheric paths, even when their ionospheric pierce points are geographically close. Absolute STEC comparisons are also affected by residual satellite and receiver hardware biases and carrier-to-code leveling errors. The Level-1 product is therefore assessed using detrended STEC residuals within continuous receiver-GEO observation links. This metric characterizes short-term stability and residual variability rather than absolute STEC accuracy.

For the Level-2 TEC-gradient products, direct external validation is limited by the lack of independent two-dimensional TEC-gradient observations with comparable spatial and temporal resolution over China. Existing GIM products are substantially smoother because of their coarser spatial resolution and regularization, and cannot provide a quantitative reference for the amplitudes of the high-resolution gradients resolved by GIFT-BDS. For this reason, the mixed spatiotemporal partial-derivative asymmetry is used only to assess internal consistency. The comparison with the CAS GIM is likewise restricted to large-scale morphology and spatial-resolution differences rather than being interpreted as an independent accuracy validation.

Sections 3.3 and 3.4 have been revised accordingly. The analysis is now described as a stability assessment, the mixed-derivative test as an internal-consistency assessment, and the GIM comparison as a morphology and resolution comparison.

None of these analyses are interpreted as an independent validation of product accuracy. The corresponding revisions are provided below.

Section 3.3.1, Level-1 STEC stability assessment:

“The Level-1 STEC records provide the primary input for the Level-2 VTEC and TEC-gradient products. Direct external validation of absolute STEC is difficult because STEC represents the electron content integrated along a specific receiver-satellite line of sight. Observations from other satellites sample different three-dimensional ionospheric paths, and similar IPP locations do not necessarily imply comparable absolute STEC values. Absolute STEC estimates are also affected by measurement noise, multipath, carrier-to-code leveling errors, and residual satellite and receiver DCB errors. The differential processing used for the Level-2 products largely reduces common bias components, although observation-dependent residuals may still propagate into the derived gradients. Differential STEC within continuous observation arcs has been widely used to assess relative TEC variations and consistency (Hernández-Pajares et al., 2017). Following this approach, each receiver-GEO link is evaluated using detrended STEC residuals. The resulting RMS characterizes the short-term stability and residual variability of Level-1 observations rather than their absolute accuracy.” (Lines 322–331)

Section 3.3.2, Internal consistency of Level-2 products:

“Direct external validation of the Level-2 gradient products is limited by the lack of independent two-dimensional TEC-gradient observations with comparable spatial and temporal resolution over China. Following Li et al. (2025b), the asymmetry of mixed spatiotemporal partial derivatives is used to assess the internal consistency of the derived gradients. This metric evaluates the agreement between two independent derivative paths without requiring an external gradient reference.” (Lines 379–382)

The manuscript further clarifies that this metric should not be interpreted as an absolute gradient error, but as a measure of the internal consistency of the Level-2 gradient products.

Section 3.4, Comparison with GIM-derived gradient estimates:

“A comparison with GIM-derived gradients is used to examine the spatial structures represented by the GIFT-BDS Level-2 products. The CAS GIM provides a global ionospheric representation at a relatively coarse spatial resolution. Its coarse spatial sampling and associated smoothing attenuate localized gradient amplitudes, making it unsuitable as a quantitative reference for the accuracy of the high-resolution GIFT-BDS gradients. The comparison is thus restricted to large-scale spatial structures and differences in spatial resolution.” (Lines 407–412)

“The comparison illustrates the additional regional detail provided by the GIFT-BDS Level-2 gradient products. The GEO-derived products resolve localized TEC-gradient structures and their short-term evolutions at finer spatial scales, whereas the GIM-derived gradients provide the large-scale ionospheric background for comparison.” (Lines 425–427)

Comment 2. The link, Index of /pub/campaign/iono/GIFT-BDS, has no up to date products. It has the same time period as zenodo link. If there is no operational data product available to the users, the significance of the paper is limited.

Response:

We thank the reviewer for pointing out that the operational data directory had not been updated beyond the period covered by the Zenodo release. The interruption of the 2026 operational products was related to the BeiDou GEO satellite PRN reassignment in April 2026. Because GIFT-BDS relies on specific GEO satellites and their near-fixed observation geometry, production could not be continued with the previous processing configuration.

We updated the GEO satellite identification and processing configuration, checked the resulting observation geometry, and reprocessed the affected 2026 data before resuming public data access. The processing methodology, quality-control criteria, product definitions, and gridding strategy remain unchanged. The update concerns only the GEO satellite configuration used for operational processing.

At the time of revision, the 2026 products had been reprocessed and backfilled

through DOY 260, and the automated update procedure had been restored. New products are released with a processing latency of several days.

To avoid ambiguity between the versioned Zenodo release and the regularly updated operational products, we revised the Data availability section as follow:

“The GIFT-BDS dataset used in this paper covers the period from 19 July 2024 to 31 December 2025, corresponding to DOY 201 of 2024 to DOY 365 of 2025. The versioned public release is available at <https://doi.org/10.5281/zenodo.21090695> (Li et al., 2026a). The release contains Level-1 GEO-derived STEC records, Level-2 gridded TEC and TEC-gradient products, quality-control descriptors, and associated metadata.

Operational GIFT-BDS products are available at <https://data.bdsmart.cn/pub/campaign/iono/>. They are generated using the same processing strategy as the versioned release and are updated regularly with a processing latency of several days. These operational products should be regarded as provisional updates until they are included in a subsequent versioned release.”

Comment 3. The authors used the CAS-GIM to estimate the receiver bias. I am not sure i understand correctly or not, this might introduce extra errors in the sTEC and TEC gradient estimation since the GIM is relatively smooth. The authors should emphasize this point.

Response:

We thank the reviewer for raising this important point. We agree that errors in the GIM background can propagate into the receiver DCB estimates, and this contribution was not sufficiently explained in the original manuscript.

We first clarify that two different external products are involved in the bias correction. The daily CAS BSX products are used to correct the satellite code biases, whereas the UPC GIM listed in Table 2 is used as the a priori ionospheric background for estimating receiver DCBs following Montenbruck et al. (2014). The UPC GIM provides the ionospheric path-delay correction used to remove the ionospheric contribution from the dual-frequency code observations during receiver DCB estimation. The coarse GIM cannot fully represent fine-scale regional ionospheric

structures. The systematic component of the resulting modeling residuals is partly absorbed into the receiver DCB estimate. The residual receiver DCB error then propagates into the absolute STEC level. The GIM is not used to reconstruct or spatially smooth the 30-s STEC time series or the Level-2 TEC-gradient field.

The GIM-assisted receiver DCB estimation has been evaluated in previous studies. Receiver DCB estimates generally show consistency at the level of several tenths of a nanosecond (Li et al., 2018; Wang et al., 2016). For the B1I/B3I combination used here, several tenths of a nanosecond correspond to an STEC effect on the order of 1 TECU. Previous TEC calibration and GIX error analyses also indicate that residual link-related TEC biases after calibration are on the order of 1 TECU (Montenbruck et al., 2014; Jakowski et al., 2026). We therefore explicitly retain this bias as an uncertainty term rather than assuming complete DCB removal (Eq. (6)).

$$T_V^i = \frac{T_S^i}{M(\delta^i)} + \frac{\xi^i}{M(\delta^i)} \quad (6)$$

$$\frac{\partial T_V^{(i,j)}}{\partial S^{(i,j)}} \Big|_t = \left(\frac{T_S^i}{M(\delta^i)} - \frac{T_S^j}{M(\delta^j)} \right) \cdot \frac{1}{S^{(i,j)}} + \frac{1}{S^{(i,j)}} \cdot \left(\frac{\xi^i}{M(\delta^i)} - \frac{\xi^j}{M(\delta^j)} \right) \quad (8)$$

The effect of this residual bias on the gradient further depends on the observation geometry. According to Eqs. (6) and (8), the residual bias enters each VTEC observation after mapping. The difference between the mapped residuals of two LOS observations enters the TEC-gradient estimate. Its contribution depends on the mapping factors of the two observations and the inter-IPP distance. Short inter-IPP distances amplify the residual error because the VTEC difference is divided by a smaller distance. Differences in mapping factors introduce additional non-common errors between the two LOS observations.

GIFT-BDS applies two constraints to limit these residual errors. The inter-IPP distance must exceed 50 km, and the mapping-factor difference between the two observations must be smaller than 0.2. These constraints reduce error amplification at short distances and differences in the mapped residual errors between paired observations. Figure 3 further shows a rapid decrease in the P95 gradient as the inter-IPP distance increases within the short-baseline range below approximately 50 km. This

behavior indicates stronger sensitivity to residual observation errors at short inter-IPP distances and supports the adopted 50-km lower threshold. At longer distances, the gradient changes more gradually, while spatial averaging becomes more important.

We have revised the manuscript to clarify the role of the GIM in receiver DCB estimation, state the representative magnitude of the residual TEC bias, describe its propagation into the TEC-gradient estimates, and explain how the pair-selection strategy limits this contribution.

Section 3.1.1, GEO-derived STEC:

“The processing system obtains satellite code biases from the daily CAS BSX bias products provided by the Chinese Academy of Sciences (CAS, Wang et al., 2016, 2026). Level-1 processing estimates receiver DCBs from dual-frequency code observations using the GIM listed in Table 2 as the a priori ionospheric background, following the general GIM-assisted approach (Montenbruck et al., 2014). The estimated receiver DCBs and CAS satellite DCBs are then applied in the carrier-to-code leveling of the STEC observations. Therefore, the released Level-1 STEC records are corrected for both satellite and receiver code biases.

Residual DCB errors remain in both satellite and receiver bias corrections. The external satellite DCB products contain errors from the underlying bias solutions, while the receiver DCB estimates depend on the accuracy of the a priori GIM. Previous studies report receiver DCB consistency at the level of several tenths of a nanosecond (Li et al., 2018; Wang et al., 2016). For the B1I/B3I combination used here, several tenths of a nanosecond correspond to an STEC effect on the order of 1 TECU. Additional receiver DCB errors may arise when regional ionospheric structures are not adequately represented by the relatively coarse GIM. These residual DCB errors mainly affect the absolute STEC level.” (Lines 171–184)

Section 3.2.2, VTEC and temporal derivative estimation at fixed IPPs:

“The VTEC at IPP i is then obtained as:

$$T_V^i = \frac{T_S^i}{M(\delta^i)} + \frac{\xi^i}{M(\delta^i)} \quad (6)$$

where T_S^i is the Level-1 STEC, and $\frac{\xi^i}{M(\delta^i)}$ represents the mapped residual uncertainty in the VTEC estimation. The residual term includes contributions from measurement noise, multipath effects, mapping-function approximation errors, and residual satellite and receiver DCB errors. Previous TEC calibration and GIX error analyses indicate that the residual link-related TEC bias after calibration is typically on the order of 1 TECU (Montenbruck et al., 2014; Jakowski et al., 2026). This residual bias directly affects the absolute VTEC level. Its contribution to the derived TEC gradients depends on the spatial differencing geometry, as discussed in Sect. 3.2.4 (Jakowski and Hoque, 2019; Jakowski et al., 2026).” (Lines 227–236)

Section 3.2.4, Quality control and pair-selection strategy:

“The uncertainty of the spatial gradient estimates originates from the residual errors in the individual VTEC observations at each IPP, including measurement noise, multipath effects, mapping-function approximation errors, and residual satellite and receiver DCB errors. According to Eq. (8), the contribution of residual VTEC errors to the gradient estimate decreases as the inter-IPP distance increases. Specifically, short inter-IPP distances may amplify residual observation errors because the spatial difference is normalized by a smaller separation. Differences in mapping factors between the two line-of-sight observations may introduce additional non-common projection errors. The pair-selection strategy therefore constrains both the inter-IPP distance and the mapping-factor difference.” (Lines 267–274)

Comment 4. In the inter-IPP pair-selection, different distance means smooth the gradient in different scale. When the threshold has a wide range, this is also an error source.

Response:

We thank the reviewer for this insightful comment. We agree that the inter-IPP distance defines the spatial scale of the finite-difference TEC-gradient estimate and that gradients derived over different distances are not directly equivalent. Shorter baselines retain greater sensitivity to localized TEC variations but also amplify residual

observation errors, whereas longer baselines increasingly average smaller-scale ionospheric structures.

To quantify this dependence, we added an additional sensitivity analysis using the Level-1 GIFT-BDS observations sampled at 15-min intervals from 05:20 to 08:20 UT on 21 September 2024, during the daytime EIA development period. The inter-IPP pairs were reconstructed using the same mapping-function constraint adopted in the Level-2 processing and grouped into 50-km distance bins. A total of 861,247 valid pairs were analyzed. We additionally included pairs with distances below the 50-km lower limit used in the operational Level-2 processing to characterize the behavior at short baselines.

The results show a clear dependence of the finite-difference gradient on inter-IPP distance. The absolute VTEC difference increases with distance, indicating that longer baselines sample TEC variations over broader spatial regions. In contrast, the gradient magnitude decreases with increasing distance. The P95 gradient decreases particularly rapidly at short baselines, reflecting the combined effects of residual-error amplification and localized ionospheric variability. At longer baselines, the median gradient decreases more gradually and the distribution becomes narrower, consistent with increasing spatial averaging of smaller-scale TEC structures.

The influence of the upper distance threshold was further assessed by increasing the maximum inter-IPP distance from 500 to 1000 km. The mean gradient magnitude over all valid pairs decreases from 0.0513 to 0.0451 TECU/km, corresponding to a reduction of approximately 12.2%. This difference quantifies the sensitivity of the derived gradients to the adopted upper distance threshold and is consistent with increased spatial averaging at longer baselines. The adopted 50–1000 km range represents a compromise between limiting error amplification at short baselines and avoiding excessive spatial averaging at long baselines. The released Level-2 GIX should consequently be considered as a finite-difference TEC gradient product derived over a specified range of spatial scales, rather than as an infinitesimal gradient at a single spatial scale. Because the Level-1 products retain the original STEC observations and IPP geometry, users can reconstruct gradients using alternative baseline ranges for

specific scientific objectives.

We have revised Sect. 3.2.4 accordingly and added a new analysis in Fig. 3 to explicitly characterize the dependence of the finite-difference gradient estimates on inter-IPP distance. The corresponding revisions are provided below.

Section 3.2.4, Quality control and pair-selection strategy:

“The uncertainty of the spatial gradient estimates originates from the residual errors in the individual VTEC observations at each IPP, including measurement noise, multipath effects, mapping-function approximation errors, and residual satellite and receiver DCB errors. According to Eq. (8), the contribution of residual VTEC errors to the gradient estimate decreases as the inter-IPP distance increases. Specifically, short inter-IPP distances may amplify residual observation errors because the spatial difference is normalized by a smaller separation. Differences in mapping factors between the two line-of-sight observations may introduce additional non-common projection errors. The pair-selection strategy therefore constrains both the inter-IPP distance and the mapping-factor difference.

In the Level-2 processing, only selected inter-IPP pairs are retained. Three constraints are applied. First, the inter-IPP distance must exceed 50 km to limit error amplification at short baselines. Second, it must be smaller than 1000 km to limit spatial averaging of smaller-scale TEC structures at long baselines. Third, the difference in mapping-function values between the two IPPs must be smaller than 0.2 (Jakowski and Hoque, 2019). These criteria account for both the error propagation in the TEC-gradient estimate and the spatial sampling characteristics of BeiDou GEO fixed-geometry observations.” (Lines 267–281)

Section 3.2.4, added analysis of distance dependence:

“The inter-IPP distance range determines the spatial scale of the TEC-gradient estimates. Figure 3 illustrates this dependence using Level-1 GEO observations grouped by inter-IPP distance. The absolute VTEC difference increases steadily with distance, whereas the corresponding gradient magnitude decreases (Fig. 3a, b). The increasing VTEC difference indicates that longer baselines sample TEC variations over broader spatial

regions. At short baselines, the P95 gradient decreases rapidly with increasing distance, reflecting the combined effects of greater sensitivity to residual observation errors and localized ionospheric variability. At larger separations, the median gradient decreases more gradually and the gradient distribution becomes narrower, consistent with increasing spatial averaging of smaller-scale TEC structures. The influence of the upper distance threshold was further examined by increasing the maximum inter-IPP distance from 500 to 1000 km. The mean gradient magnitude over all retained pairs decreases from 0.0513 to 0.0451 TECU · km⁻¹, corresponding to a reduction of approximately 12.2%. This difference quantifies the sensitivity of the derived gradient magnitude to the adopted upper distance threshold and is consistent with increased spatial averaging at longer baselines. The adopted 50–1000 km range represents a compromise between limiting error amplification at short baselines and avoiding excessive spatial averaging at long baselines. The Level-1 STEC observations and IPP geometry are also provided, allowing users to derive gradients over alternative baseline ranges when required.”

(Lines 286–299)

Figure 3 was added to quantify this dependence:

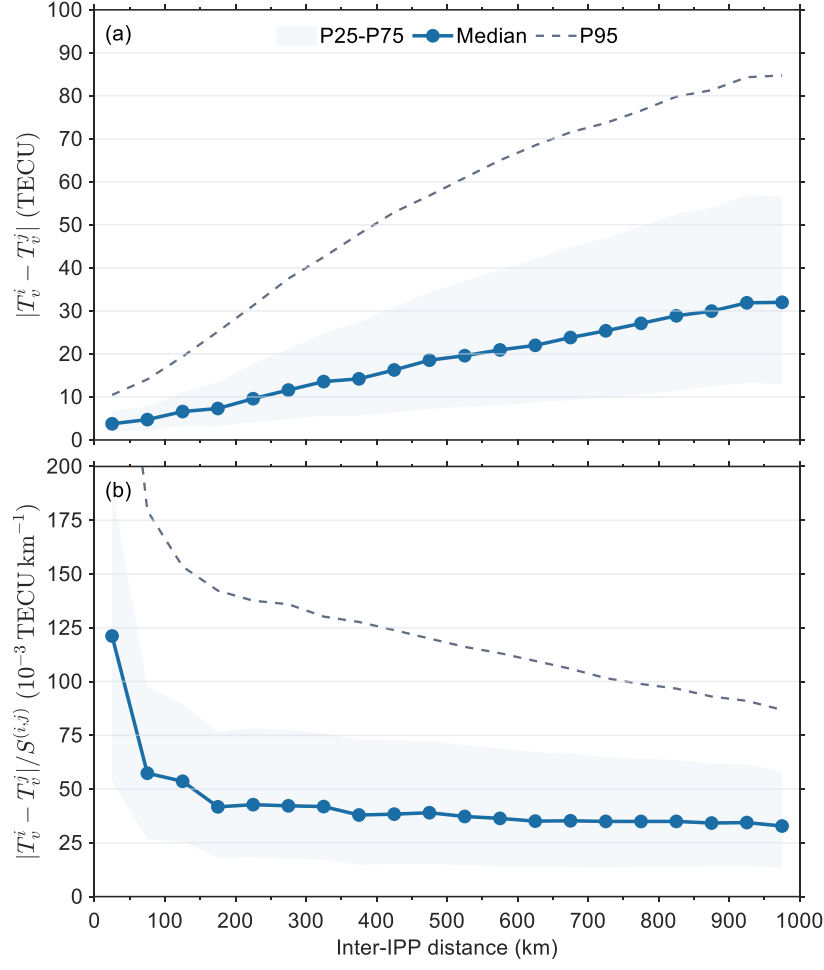


Figure 3. Dependence of pairwise VTEC differences and TEC-gradient estimates on inter-IPP distance. (a) Absolute VTEC difference, $|T_v^i - T_v^j|$. (b) VTEC gradient, $|T_v^i - T_v^j|/S^{(i,j)}$, where $S^{(i,j)}$ denotes the inter-IPP distance. BDS GEO Level-1 data were sampled at 15-min intervals from 05:20 to 08:20 UT on 21 September 2024. A total of 861,247 valid pairs satisfying $\Delta M < 0.2$ were grouped into 50-km distance bins according to inter-IPP distance. Inter-IPP distances below the 50-km lower limit were included to characterize the short-baseline behavior. Solid lines indicate the medians, shaded regions denote the P25–P75 intervals, and dashed lines indicate the P95 values.