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GIFT-BDS: A high-resolution TEC and Gradient Ionospheric Index dataset over China derived from BeiDou GEO fixed-geometry observations

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Abstract. High-resolution ionospheric total electron content (TEC) gradient observations are well-suited for characterizing ionospheric spatial structure and for assessing ionospheric effects on Global Navigation Satellite System (GNSS) positioning applications. Existing global ionospheric products provide valuable information on large-scale ionospheric conditions, but their spatial and temporal sampling is generally not sufficient to resolve fine-scale TEC gradient structures over China. We present GIFT-BDS (Gradient Ionospheric index from Fixed-geometry TEC observations using BDS GEO satellites), a high-resolution regional ionospheric dataset derived from a dense ground-based GNSS network and BeiDou geostationary Earth orbit (GEO) fixed-geometry observations. The network consists of more than 200 ground-based GNSS receivers and five BeiDou GEO satellites, providing stable receiver-satellite geometries and repeated sampling of nearly fixed ionospheric pierce points. The released dataset contains two product levels. Level-1 provides 30 s GEO-derived slant TEC (STEC) time series for individual receiver-satellite links. Level-2 provides gridded vertical TEC (VTEC), rate of TEC index (ROTI), Gradient Ionospheric Index (GIX), and directional TEC gradient components. The TEC-gradient products are provided on a 0.25° × 0.25° grid with a temporal resolution of 15 min. The dataset is assessed using STEC stability statistics, internal consistency diagnostics, and comparison with Global Ionospheric Map (GIM) derived gradients. Selected examples illustrate the use of GIFT-BDS for studies of daytime Equatorial Ionization Anomaly (EIA) morphology, nighttime Equatorial Plasma Bubble (EPB) evolution, and ionospheric effects on Precise Point Positioning (PPP) and Real-Time Kinematic (RTK) positioning performance. The dataset is available at https://doi.org/10.5281/zenodo.21090695 (Li et al.,

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2026a), with daily updates provided at https://data.bdsmart.cn/pub/campaign/iono/. GIFT-BDS extends the currently available ionospheric data resources over China by providing continuous high-resolution observations of TEC and TEC gradients, enabling investigations of ionospheric dynamics, space-weather effects, and GNSS positioning error characterization.

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1 Introduction

High-resolution ionospheric observations are required to describe regional electron-density structures and to assess their impact on trans-ionospheric radio signals. The ionosphere affects Global Navigation Satellite System (GNSS) signals through propagation delay caused by spatially variable total electron content (TEC), making it one of the main error sources for positioning, navigation and timing (PNT) applications. Beyond its practical relevance for GNSS, ionospheric variability provides information on geospace processes driven by solar-terrestrial forcing, geomagnetic activity, and neutral-atmosphere dynamics (Buonsanto, 1999; Francis, 1974; Hedin, 1987; Sheng et al., 2025). Spatially dense and temporally continuous regional observations are therefore needed to characterize ionospheric structures and associated TEC gradients, particularly in regions where low- and mid-latitude processes coexist.

The Chinese sector spans low- and mid-latitude ionospheric regions and exhibits variability over a wide range of spatial and temporal scales. Daytime Equatorial Ionization Anomaly (EIA) development and nighttime Equatorial Plasma Bubble (EPB) activity are two representative manifestations of low-latitude ionospheric variability in this sector (Balan et al., 2018; Li et al., 2021a). These phenomena reflect both the background electrodynamic evolution of the low-latitude ionosphere and the development of plasma instabilities, with clear local-time, seasonal and regional dependences (Abdu, 2001; Chen et al., 2016; Li et al., 2021a). Geomagnetic storms may further produce strong regional responses through the coupled effects of solar-wind forcing, geomagnetic activity, and thermosphere–ionosphere dynamics (Chen et al., 2025; Zhang et al., 2024). Atmospheric waves generated by earthquakes and volcanic eruptions can also disturb the ionosphere over broad areas (Astafyeva, 2019; Li et al., 2025a; Zhai et al., 2025). Resolving these structures and their associated TEC gradients requires observations with sufficient spatial sampling and temporal continuity, which are also relevant for assessing ionospheric effects on GNSS-based applications over China (Yang et al., 2021; Yuan et al., 2019).

GNSS observations provide continuous measurements of path-integrated electron density along satellite-receiver lines of sight, and ground-based receiver networks have become an important basis for ionospheric monitoring. Global Ionospheric Maps (GIMs) are among the most widely used public GNSS-based ionospheric products and provide valuable information on large-scale ionospheric background conditions and storm-time responses at global and continental scales (Astafyeva et al., 2015; Chen et al., 2017; Cherniak et al., 2025; Li et al., 2021b). Their spatial and temporal sampling, however, is often not adequate for resolving fine-scale regional TEC gradient structures (Hu et al., 2024; Liu et al., 2026; Savastano et al., 2019). High-resolution regional products therefore require dense and continuously operated GNSS receiver networks. At the global scale, the International GNSS Service (IGS) provides a widely used network of permanent GNSS stations and openly available ionospheric products (Hernández-Pajares et al., 2009; Liu et al., 2021). At the regional scale, dense GNSS infrastructures, including NOAA CORS, GEONET, EUREF, and Australian GNSS networks, provide important observational bases for regional ionospheric monitoring (Kenyeres and Bruyninx, 2004; Snay and Soler, 2008; Takamatsu et al., 2023; Woodgate et al., 2017). For the China region, GIFT-BDS uses a dedicated ground-based GNSS receiver network comprising more than 200 stations and fixed-geometry observations from BeiDou geostationary Earth orbit (GEO) satellites. In contrast to conventional medium Earth orbit (MEO) GNSS observations, which involve moving line-of-sight (LOS) geometry, BeiDou GEO observations provide nearly fixed receiver-satellite geometry over China. This property enables repeated sampling of nearly fixed ionospheric pierce points and supports temporally consistent regional TEC gradient estimation (Li et al., 2023; Wang et al., 2020).

The GIFT-BDS dataset is based on a fixed-geometry ionospheric observation network comprising ground-based GNSS receivers and BeiDou GEO satellites. The near-stationary GEO geometry provides continuous observations over nearly fixed ionospheric pierce points (IPPs), while pairs of IPPs define geometry-invariant inter-IPP vectors on the ionospheric shell (Li et al., 2025b). Each inter-IPP vector is used as a sensing element for estimating VTEC differences mapped to the ionospheric shell over a known distance. This configuration increases the spatial sampling density and redundancy of regional gradient observations without relying on moving IPP tracks (Jakowski and Hoque, 2019). Spatial TEC gradients are derived from the network of inter-IPP vectors, whereas temporal TEC variations are estimated from the time series at nearly fixed IPPs. The same observation geometry therefore supports the generation of both Level-1 GEO-derived slant TEC (STEC) records and Level-2 gridded regional TEC-gradient products.

GEO-derived STEC records and TEC-gradient products are useful for studies of multi-scale ionospheric variability and for analyses of ionospheric effects on GNSS positioning. The nearly fixed LOS geometry supports time-continuous comparisons at nearly fixed IPPs and reduces sampling

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differences caused by moving satellite geometry. GEO-based observations have been used, for example, to detect traveling ionospheric disturbances (TIDs) and to estimate the altitude and zonal drift velocity of ionospheric irregularities (Huang et al., 2025; Rao et al., 2025; Zhong et al., 2023). TEC gradients describe horizontal spatial changes in TEC and provide diagnostics of regional ionospheric structure. The Gradient Ionospheric Index (GIX), derived from TEC spatial gradients, is included in the dataset as a quantitative indicator of gradient intensity (Jakowski and Hoque, 2019; Nykiel et al., 2024). Such gradient information can support studies of Equatorial Ionization Anomaly (EIA) evolution, Equatorial Plasma Bubble (EPB) development, and Large-scale Traveling Ionospheric Disturbances (LSTIDs) propagation (Fu et al., 2025a; Li et al., 2025b), as well as the analysis of Precise Point Positioning (PPP) and Real-Time Kinematic (RTK) performance under disturbed ionospheric conditions (Fu et al., 2025a; Nykiel et al., 2024). These applications motivate the release of a documented and reusable regional dataset rather than isolated event-based products.

This paper describes GIFT-BDS (Gradient Ionospheric Index from Fixed-geometry TEC observations using BeiDou GEO satellites), a high-resolution regional ionospheric TEC and Gradient Ionospheric Index dataset over China. The focus is on dataset construction, product definition, quality control, technical assessment, and example uses. The following sections first describe the ground and space segments of the fixed-geometry observation network. We then present the processing workflow, including GEO-derived STEC generation, TEC gradient estimation, grid mapping, and product standardization. The dataset is assessed using STEC stability statistics, internal consistency diagnostics of the gradient products, and comparison with GIM-derived gradients. Selected examples illustrate representative uses of the dataset for ionospheric process studies and GNSS positioning-related analyses. Finally, data access, usage information, and the daily update procedure are provided.

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2 Observation network

The GIFT-BDS dataset is generated from a fixed-geometry ionospheric observation network that combines a dense ground-based GNSS receiver network with BeiDou GEO satellites. The ground segment provides continuous multi-GNSS measurements over China, whereas the GEO satellites provide near-stationary receiver-satellite viewing geometries and repeated sampling of nearly fixed ionospheric pierce points.

2.1 China real-time multi-GNSS station network

The ground segment of GIFT-BDS is the China real-time multi-GNSS station network, which comprises more than 200 continuously operating GNSS stations over China. Each station is equipped with a Septentrio PolaRx5 receiver supporting GPS, GLONASS, Galileo, and BeiDou observations. The stations provide 1 Hz RTCM real-time data streams and 30 s RINEX observation files to the data center. The station network was completed in mid-2024 and has been continuously operated since then. Figure 1 shows the geographical distribution of the receivers within the study region of 15°N–50°N and 95°E–135°E. The stations are mainly distributed over the low- and mid-latitude regions of China, with relatively dense and homogeneous coverage south of 35°N. In this southern part of the network, the median nearest-station spacing is approximately 100 km, as shown in Fig. 1b.

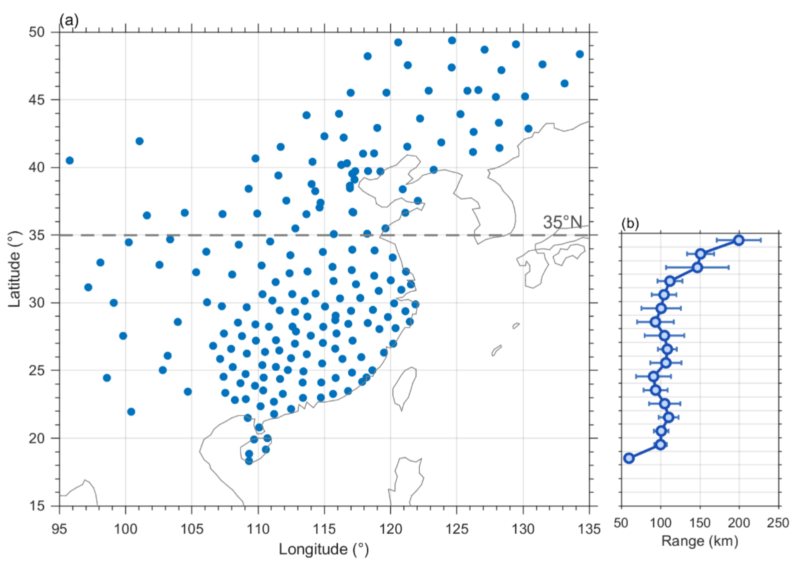

Figure 1. Ground segment of the GIFT-BDS observation network. (a) Geographical distribution of the China real-

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time multi-GNSS station network over the study region (15°N–50°N, 95°E–135°E). (b) Median nearest-station spacing within 1° latitude bins south of 35°N. The horizontal dashed line in (a) denotes 35°N.

2.2 BeiDou GEO satellites

The space segment of the GIFT-BDS observation network consists of five GEO satellites from the BeiDou Navigation Satellite System (BDS). Table 1 lists the PRN identifier, satellite name, nominal longitude, launch date, and orbital inclination of each BeiDou GEO satellite used in the processing. The five GEO satellites are located at different longitudes and therefore provide multiple fixed-viewing geometries over the China region. Unlike MEO GNSS satellites, BeiDou GEO satellites provide near-stationary receiver-satellite geometry. Each valid receiver-GEO link defines a line of sight and an associated IPP on the assumed ionospheric shell. These IPPs vary only slowly with time, enabling repeated sampling of nearly the same ionospheric regions.

Table 1. BeiDou GEO satellites used in the space segment of the GIFT-BDS observation network.

PRN	Satellite	Longitude	Launch Date	Inclination (°)
C01	BDS2 GEO8	144.5°E	2019-05-17	0.4001
C02	BDS2 GEO6	84.0°E	2012-10-25	1.4764
C03	BDS2 GEO7	110.5°E	2016-06-12	1.5196
C04	BDS2 GEO4	160.0°E	2010-10-31	0.8047
C05	BDS2 GEO5	59.0°E	2012-02-24	1.8963

2.3 Input data and auxiliary products

Based on the observation network described in Sects. 2.1 and 2.2, the GIFT-BDS dataset generation uses archived station observation files together with several auxiliary products. The daily RINEX observation files provide the primary ground-based input. These files are archived at an internal data center with a sampling interval of 30 s. The station coordinate file provides receiver positions for geometric calculations. Broadcast ephemerides supply satellite orbit information for the BeiDou GEO satellites. Satellite code bias products are used for satellite DCB corrections, and IONEX products provide a global ionospheric background used in receiver bias estimation. The detailed processing steps are described in Sect. 3. The combined information is summarized in Table 2.

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Table 2. Essential input data and auxiliary products used for GIFT-BDS dataset generation.

Data	Institution	URL
Daily RINEX observation files	China real-time multi-GNSS station network	–
Station coordinate file	Network coordinate solution	–
Multi-GNSS broadcast ephemeris	IGS	ftp://igs.ign.fr/pub/igs/data/yyyy/ddd/BRDC00IGS_R_yyyyddd0000_01D_MN.rnx.gz
Satellite code bias product	CAS	https://data.bdsmart.cn/pub/product/bias/yyyy/CAS0MGXRAP_yyyyddd0000_01D_01D_DCB.BSX.gz
IONEX product	UPC	https://data.bdsmart.cn/pub/product/iono/ionex/yyyy/ddd/uqrgddd0.yyi.Z

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3 Data processing and product generation

The GIFT-BDS dataset is organized into two product levels. Level-1 contains 30 s GEO-derived STEC time series for individual receiver-satellite links, together with Rate Of TEC Index (ROTI), LOS geometry and IPP information. These observation-level records form the basis for the higher-level gridded products. Level-2 provides gridded VTEC, ROTI and TEC-gradient variables derived from Level-1 products. The spatial gradient fields are provided on a 0.25° × 0.25° grid to describe regional ionospheric variability over China at a finer spatial scale. Figure 2 shows the two-stage processing workflow used to generate the released GIFT-BDS dataset from raw BeiDou GEO observations. The Level-1 processing uses raw GEO measurements and auxiliary GNSS products to estimate DCB-corrected STEC time series and the associated LOS geometry for each receiver-satellite link. The resulting STEC and geometry records are then used in the Level-2 processing, where regional TEC, ROTI and TEC-gradient quantities are derived and mapped onto regular grids. Details of the individual processing steps are given in the following subsections.

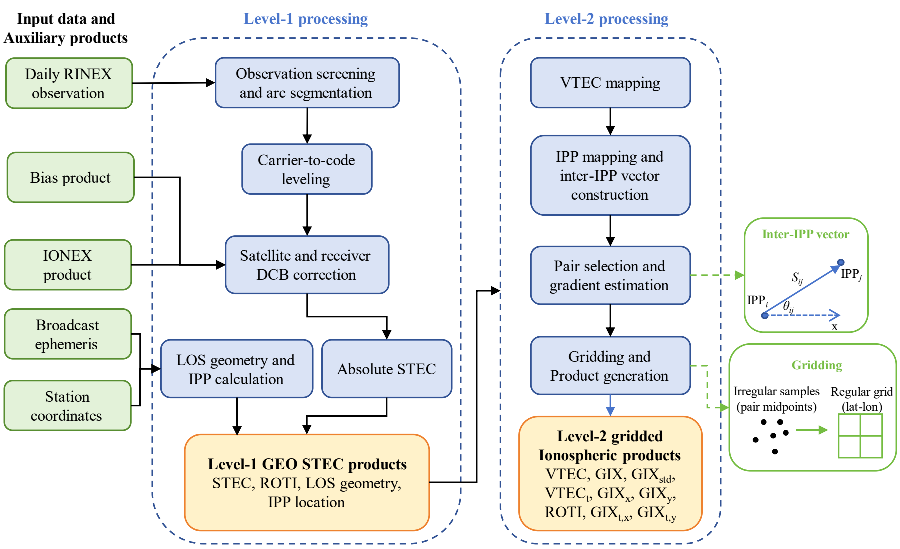

Figure 2. Two-stage processing workflow used to generate the GIFT-BDS Level-1 and Level-2 ionospheric products.

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3.1 Level-1 dataset generation

3.1.1 GEO-derived STEC

For each GEO satellite-receiver link, the GEO-derived STEC time series is generated from dual-frequency carrier-phase observations using the B1I/B3I geometry-free combination at a sampling interval of 30 s. The B1I and B3I signals correspond to carrier frequencies of 1561.098 and 1268.52 MHz, respectively (Li et al., 2026b). Observations with elevation angles below 20° are excluded to reduce multipath effects and low-elevation geometry-related errors. The carrier-phase geometry-free combination can be converted to STEC as:

$$T_S = \frac{{f_1}^2 {f_2}^2}{40.3\times10^{16}({f_1}^2 - {f_2}^2)}[(\lambda_1 L_1 - \lambda_2 L_2) - (\lambda_1 N_1 - \lambda_2 N_2) + (d_1 - d_2)] \tag{1}$$

where T_S denotes the STEC in TECU (1 TECU = 10^{16} electrons/m^2), L_1 and L_2 are the carrier-phase measurements in cycles at two frequencies f_1 and f_2, respectively, λ_1 and λ_2 are the corresponding wavelengths, N_1 and N_2 are the integer ambiguities, and d_1 and d_2 are the frequency-dependent hardware delays. The ambiguity-related term remains constant within a continuous carrier-phase arc and is absorbed into an arc-dependent leveling offset.

Level-1 processing is performed independently for each receiver-satellite link. After applying the elevation mask, cycle slips and data gaps are detected from the geometry-free phase combination, and the observations are segmented into continuous arcs. Within each arc, the precise but ambiguous carrier-phase STEC is aligned with the code-derived STEC by carrier-to-code leveling (CCL; Mannucci et al., 1998). This procedure removes the arc-dependent ambiguity offset while preserving the high precision of the carrier-phase observations. 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 for the regional stations. This estimation uses dual-frequency code observations, known satellite code biases, and a GIM background ionospheric constraint (Montenbruck et al., 2014). Then, Level-1 processing applies the estimated receiver DCBs and the satellite code bias corrections to the carrier-to-code leveled STEC records. The released Level-1 STEC records are therefore corrected for both satellite and receiver code biases.

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3.1.2 Quality control

Quality control is implemented at the epoch, arc, and LOS levels. At the epoch and arc levels, elevation screening, cycle-slip detection, data-gap identification, and continuous-arc segmentation are applied to define valid carrier-phase arcs for each receiver-satellite link (Kim et al., 2014). Carrier-to-code leveling and DCB corrections are then applied to these valid arcs to generate absolute STEC time series. To avoid retaining receiver-satellite links with persistently unstable behavior, the overall stability of each LOS STEC record is further checked using a detrended STEC residual. The residual is computed using a 5 min moving window (Ma et al., 2022):

$$STEC_{\mathrm{res}}(t) = STEC(t) - \overline{STEC}_{5\ \mathrm{min}}(t) \tag{2}$$

where $\overline{STEC}_{5\ \mathrm{min}}(t)$ denotes the moving-average STEC within the 5 min window centered at epoch t. The residual series $STEC_{\mathrm{res}}(t)$ is used as a LOS-level stability indicator. A receiver-satellite LOS is excluded if the mean absolute residual during ionospheric quiet periods (ROTI<0.3 TECU/min) exceeds 0.15 TECU. This criterion is used to remove links with persistently unstable residual behavior, which may be caused by receiver-related problems or unstable observations. The retained LOS STEC records are used to form the released Level-1 product and provide the observational basis for the Level-2 products.

3.1.3 Released Level-1 products

The Level-1 products are released as time series for individual receiver-GEO satellite links. Each time series corresponds to one valid LOS at a 30 s sampling interval and contains the GEO-derived STEC, the corresponding ROTI, and the associated elevation angle and IPP information. These variables provide the direct observational basis for the Level-2 gridded products. The main variables released in the Level-1 products are summarized in Table 3.

Table 3. Summary of Level-1 variables released in the GIFT-BDS dataset.

Variable	Description	Unit
STEC	GEO-derived slant TEC along the receiver-satellite LOS	TECU
ROTI	Rate of TEC index derived from the STEC time series	TECU/min
Elevation angle	Satellite elevation angle at the receiver	degree
IPP latitude	Latitude of the IPP on the ionospheric shell at 400 km	degree
IPP longitude	Longitude of the IPP on the ionospheric shell at 400 km	degree
LOS ID	Identifier of the receiver-satellite LOS	–

3.2 Level-2 dataset generation

The Level-2 products are generated from the quality-controlled Level-1 STEC products. This product level includes gridded VTEC, ROTI, temporal TEC gradients at fixed IPPs, and horizontal TEC-gradient quantities from inter-IPP vectors. The following subsections describe the processing steps used to derive these variables.

3.2.1 GEO-derived ROTI

The LOS-level ROTI is first computed from the Level-1 STEC series and then mapped onto the Level-2 grid. The ROTI describes short-term fluctuations in the rate of TEC change (ROT) and characterizes ionospheric irregularity activity (Li et al., 2026b; Zhang et al., 2025). In GIFT-BDS, ROTI is computed for each valid receiver-satellite link over a 5 min moving window as (Pi et al., 1997):

$$I_{\mathrm{ROTI}}^{i} = \sqrt{\left\langle \left(I_{\mathrm{ROT}}^{i}\right)^{2} \right\rangle - \left\langle I_{\mathrm{ROT}}^{i} \right\rangle^{2}} \tag{3}$$

where I_{ROTI}^{i} denotes the ROTI value at IPP i, and $\langle\cdot\rangle$ denotes averaging over the 5 min window. The corresponding I_{ROT}^{i} is defined as:

$$I_{\mathrm{ROT}}^{i} = \frac{\Delta T_{\mathrm{S}}^{i}}{\Delta t} = \frac{T_{\mathrm{S}}^{i}(t_2) - T_{\mathrm{S}}^{i}(t_1)}{t_2 - t_1} \tag{4}$$

where $T_{\mathrm{S}}^{i}(t_1)$ and $T_{\mathrm{S}}^{i}(t_2)$ are the STEC values at two epochs, and $\Delta t = 0.5\ min\ (30\ s)$.

3.2.2 VTEC and temporal derivative estimation at fixed IPPs

STEC at each receiver-satellite link is mapped to VTEC using the elevation-dependent mapping function. A single-layer ionospheric shell model is adopted with a fixed shell height of 400 km (Klobuchar, 1987; Zhong et al., 2016a). The mapping function $M(\delta)$ is written as:

$$M(\delta) = \frac{1}{\sqrt{1 - \left(\frac{R_{\mathrm{e}} \cos\delta}{R_{\mathrm{e}} + h}\right)^{2}}} \tag{5}$$

where R_e is the Earth's radius, h is the ionospheric shell height, and δ is the satellite elevation angle. The VTEC at IPP i is then obtained as:

$$T_{\mathrm{V}}^{i} = \frac{T_{\mathrm{S}}^{i}}{M(\delta^{i})} + \frac{\xi}{M(\delta^{i})} \tag{6}$$

where T_{S}^{i} is the Level-1 STEC, and $\frac{\xi}{M(\delta^{i})}$ denotes the mapped residual error caused by measurement noise, multipath, and mapping-function approximation. This residual term affects the absolute VTEC estimate, but its influence is partly reduced in the differential quantities used for TEC gradient estimation

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(Jakowski and Hoque, 2019; Li et al., 2014).

The temporal derivative of VTEC at IPP i is derived from the STEC rate of change. Because the receiver-GEO LOS geometry varies slowly over short time intervals, the mapping function can be treated as locally stable for the 30 s ROT calculation (Zhong et al., 2016b; Li et al., 2023). The VTEC temporal derivative is therefore approximated as:

$$\frac{\partial T_{\mathrm{V}}^{i}}{\partial t} = \frac{1}{M(\delta^{i})}\frac{\Delta T_{\mathrm{S}}^{i}}{\Delta t} = \frac{1}{M(\delta^{i})} I_{\mathrm{ROT}}^{i} \quad (7)$$

where I_{ROT}^{i} is the STEC rate of change defined in Eq. (4).

3.2.3 Spatial gradient estimation from inter-IPP vectors

Spatial-gradient products are derived from pairs of simultaneous IPP observations. For two IPPs, i and j, an inter-IPP vector is constructed on the ionospheric thin shell. Its magnitude $S^{(i,j)}$ is the great-circle distance between the two IPPs, and its azimuth angle $\theta^{(i,j)}$ is measured clockwise from north. Due to the near-stationary GEO observation geometry, both $S^{(i,j)}$ and $\theta^{(i,j)}$ vary only slowly with time. The TEC spatial gradient along the inter-IPP vector is estimated from the VTEC difference between the two IPPs as:

$$\frac{\partial T_{\mathrm{V}}^{(i,j)}}{\partial S^{(i,j)}}\Big|_{t} = \left(\frac{T_{\mathrm{S}}^{i}}{M(\delta^{i})} - \frac{T_{\mathrm{S}}^{j}}{M(\delta^{j})}\right)\cdot\frac{1}{S^{(i,j)}} + \frac{1}{S^{(i,j)}}\cdot\left(\frac{\xi_{i}}{M(\delta^{i})} - \frac{\xi_{j}}{M(\delta^{j})}\right) \quad (8)$$

The magnitude of the spatial TEC gradient along the inter-IPP vector is defined as:

$$\nabla T_{\mathrm{V}}^{(i,j)}(t) = \left|\frac{\partial T_{\mathrm{V}}^{(i,j)}}{\partial S^{(i,j)}}\Big|_{t}\right| \quad (9)$$

and is used as the GIX. The corresponding zonal (x) and meridional (y) components are given by:

$$\frac{\partial T_{\mathrm{V}}^{(i,j)}}{\partial x}\Big|_{t} = \nabla T_{\mathrm{V}}^{(i,j)}(t)\sin\theta^{(i,j)} \quad (10)$$

$$\frac{\partial T_{\mathrm{V}}^{(i,j)}}{\partial y}\Big|_{t} = \nabla T_{\mathrm{V}}^{(i,j)}(t)\cos\theta^{(i,j)} \quad (11)$$

where positive x and y denote the eastward and northward directions, respectively.

The spatial variation of the temporal VTEC gradient is derived from the difference in temporal derivatives between the two IPPs:

$$\frac{\partial^{2} T_{\mathrm{V}}^{(i,j)}}{\partial x\,\partial t} = \left|\frac{\partial T_{\mathrm{V}}^{i}}{\partial t} - \frac{\partial T_{\mathrm{V}}^{j}}{\partial t}\right|\cdot\frac{\sin\theta^{(i,j)}}{S^{(i,j)}} \quad (12)$$

$$\frac{\partial^{2} T_{\mathrm{V}}^{(i,j)}}{\partial y\,\partial t} = \left|\frac{\partial T_{\mathrm{V}}^{i}}{\partial t} - \frac{\partial T_{\mathrm{V}}^{j}}{\partial t}\right|\cdot\frac{\cos\theta^{(i,j)}}{S^{(i,j)}} \quad (13)$$

The sign convention follows the direction used to define the inter-IPP vector. In practice, each inter-IPP gradient estimate is assigned to the midpoint of the great-circle arc connecting IPPs i and j. This midpoint is used as the representative location of the gradient sample in the subsequent gridding procedure.

3.2.4 Quality control and pair-selection strategy

The uncertainty of the spatial gradient estimates is mainly affected by residual observation errors, mapping-function approximations, residual bias errors, and local multipath effects. This influence is amplified for very short inter-IPP distances, whereas excessively long vectors may smooth regional structures and reduce sensitivity to smaller-scale ionospheric variability. A pair-selection strategy is therefore applied to balance residual-error control and spatial representativeness.

In the Level-2 processing, only selected inter-IPP pairs are retained. Three constraints are applied. First, the inter-IPP distance $S^{(i,j)}$ must exceed 50 km to avoid amplification of residual errors at short baselines. Second, $S^{(i,j)}$ must be smaller than 1000 km to limit over-smoothing of large-scale structures and preserve regional sensitivity. Third, the difference in mapping-function values between the two IPPs, $\Delta M = |M(\delta^j) - M(\delta^i)|$, must be smaller than 0.2. These criteria are chosen for the BeiDou GEO fixed-geometry observation configuration and follow the general considerations of Jakowski and Hoque (2019).

The pair selection is applied epoch by epoch. The retained inter-IPP vectors form the basis of the spatial-gradient products. Because the BeiDou GEO viewing geometry changes only slowly, the valid pair geometry is generally stable in time, except during data gaps, station outages, and quality-control exclusions. This temporal stability supports the generation of temporally continuous regional TEC-gradient products.

3.2.5 Gridding and released Level-2 products

The Level-2 products are released as gridded regional ionospheric products. All Level-2 products have a temporal resolution of 15 min. The released Level-2 dataset includes the following variables: VTEC, $VTEC_t$, ROTI, GIX, GIX_{std}, GIX_x, GIX_y, $GIX_{t,x}$, and $GIX_{t,y}$. Their spatial resolutions, units, and source quantities are summarized in Table 4. The IPP-based variables, including VTEC, ROTI, and the temporal derivative $\frac{\partial T_V}{\partial t}$, are mapped onto a 1° × 1° grid. The inter-IPP-based variables, including GIX, GIX_x, GIX_y, $GIX_{t,x}$, and $GIX_{t,y}$, are mapped onto a 0.25° × 0.25° grid. The value in each grid cell is calculated as the arithmetic mean of all valid samples within that cell.

A grid cell is retained only when at least two valid samples are available. This criterion reduces the

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influence of isolated observations and improves the robustness of the gridded products. In addition, the within-cell standard deviation of the contributing spatial-gradient samples is calculated as

$$\sigma(\nabla T_{\mathrm{V}}) = \sqrt{\langle (\nabla T_{\mathrm{V}})^2 \rangle - \langle \nabla T_{\mathrm{V}} \rangle^2} \tag{14}$$

where $\langle \cdot \rangle$ denotes the arithmetic mean over all valid samples within the grid cell. This quantity is released as $\mathrm{GIX_{std}}$ and provides an auxiliary measure of the sub-grid variability and internal consistency of the gradient estimates.

Table 4. Summary of Level-2 gridded variables released in the GIFT-BDS dataset.

Variable	Description	Grid spacing	Unit	Source quantity
VTEC	Vertical total electron content	1° × 1°	TECU	T_V
$\mathrm{VTEC_t}$	Time derivative of VTEC	1° × 1°	TECU/min	$\frac{\partial T_V}{\partial t}$
ROTI	Rate of TEC index	1° × 1°	TECU/min	I_{ROTI}
GIX	Magnitude of horizontal TEC spatial gradient	0.25° × 0.25°	10^{-3} TECU/km	∇T_{V}
$\mathrm{GIX_{std}}$	Standard deviation of GIX	0.25° × 0.25°	10^{-3} TECU/km	$\sigma(\nabla T_{\mathrm{V}})$
$\mathrm{GIX_x}$	Zonal component of horizontal TEC spatial gradient	0.25° × 0.25°	10^{-3} TECU/km	$\frac{\partial T_{\mathrm{V}}}{\partial x}$
$\mathrm{GIX_y}$	Meridional component of horizontal TEC spatial gradient	0.25° × 0.25°	10^{-3} TECU/km	$\frac{\partial T_{\mathrm{V}}}{\partial y}$
$\mathrm{GIX_{t,x}}$	Zonal component of the spatial gradient of the TEC temporal derivative	0.25° × 0.25°	10^{-3} TECU/min/km	$\frac{\partial^2 T_{\mathrm{V}}}{\partial x\, \partial t}$
$\mathrm{GIX_{t,y}}$	Meridional component of the spatial gradient of the TEC temporal derivative	0.25° × 0.25°	10^{-3} TECU/min/km	$\frac{\partial^2 T_{\mathrm{V}}}{\partial y\, \partial t}$

3.3 Product validation and uncertainty assessment

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. Because the Level-2 products are derived mainly from temporal and spatial differences, they are less sensitive to constant systematic biases and slowly varying residual errors than absolute TEC estimates. Nevertheless, the short-term stability of the GEO-derived STEC records affects the quality of the Level-2 gradient products.

Following the Level-1 quality control procedures described in Sect. 3.1.2, the stability of the STEC records is assessed using the detrended STEC residuals defined in Eq. (2). This metric quantifies the

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short-term variability of STEC observations and is sensitive to both residual observation noise and increased ionospheric variability (Ma et al., 2022). Figure 3 shows an example of the Level-1 GIFT-BDS GEO STEC product, the corresponding ROTI, and the absolute detrended STEC residual. The STEC record in Fig. 3a shows the temporal evolution of the LOS ionospheric delay after Level-1 processing. During the disturbed interval, enhanced residuals are accompanied by increased ROTI values, indicating that the residual increase is related to short-term ionospheric variability. During most of the day, the absolute detrended residual remains small, indicating stable short-term STEC behavior under relatively quiet conditions.

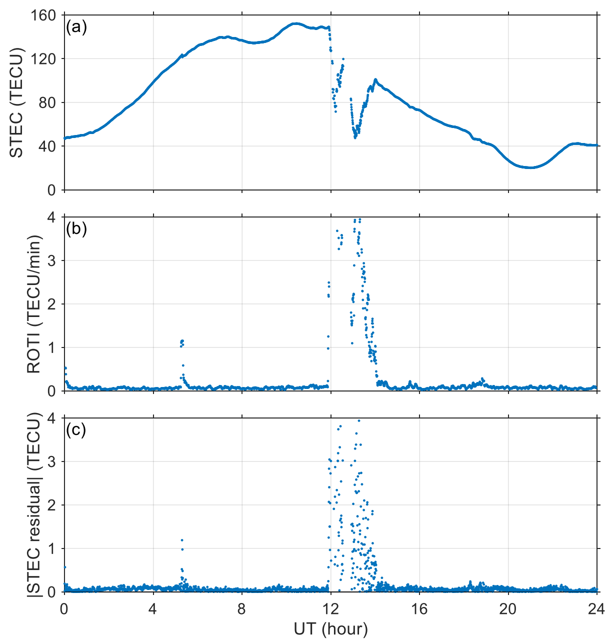

Figure 3. Example of the Level-1 GIFT-BDS GEO STEC products and the absolute residual of detrended STEC. The example corresponds to the BDS GEO satellite C01 on 21 September 2024. The IPP is located at 23.13°N and 120.92°E. (a) STEC record in the Level-1 product. (b) ROTI derived from the STEC. (c) Absolute residual of detrended STEC.

Figure 4 shows the daily median RMS of all valid LOS STEC residuals over the full data period, together with the corresponding interquartile range (IQR) and the daily number of valid IPPs. The RMS remains below 0.1 TECU for most of the record, with a mean value of about 0.06 TECU. Increased RMS values occur mainly during the equinox periods, when ionospheric irregularities are more frequent in the low-latitude region. The daily number of valid IPPs remains relatively stable, typically ranging between

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800 and 950. These results demonstrate stable Level-1 STEC availability and short-term precision over most of the data period, while retaining sensitivity to periods of enhanced ionospheric variability. Station maintenance activities and data transmission interruptions may prevent valid GNSS observation files from being received at the data center. As a result, no processable observation files were available for 26 of the 531 days covered by the released dataset.

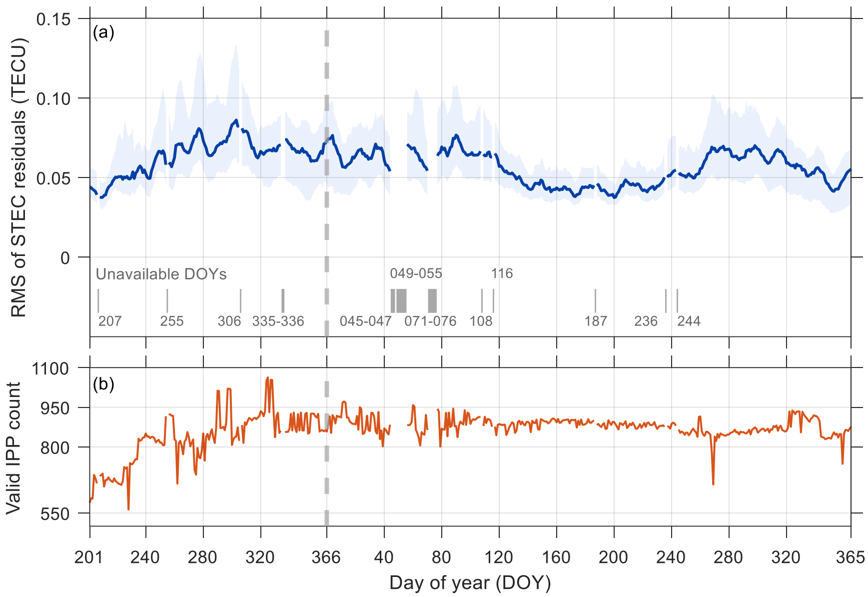

Figure 4. Daily Level-1 STEC stability statistics for the GIFT-BDS dataset over the full period. (a) Daily RMS statistics of detrended line-of-sight STEC residuals. The blue curve denotes the 7-day moving mean of the daily median RMS, and the light-blue shading represents the interquartile range (IQR; 25th–75th percentiles) of the daily RMS values. Gray vertical bars and labels indicate DOYs for which no processable observation files were available. (b) Daily number of valid IPPs used in the Level-1 product generation. The vertical dashed line marks the boundary between 2024 and 2025.

3.3.2 System-level consistency of Level-2 products

The internal consistency of the Level-2 gradient products depends on the stability of the GEO observation geometry. Although GEO satellites remain nearly stationary relative to the ground, small orbital variations introduce minor changes in IPP geometry, and may affect the derived gradient estimates (Li et al., 2023).

Figure 5 presents an example of the Level-2 GIFT-BDS products at a representative epoch. The products include all variables listed in Table 4. The quantitative system-level consistency assessment is

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based on the relationship between the temporal and spatial derivatives of the TEC field. Specifically, the spatial variation of the local VTEC temporal change ($\partial(\partial T_V/\partial t)/\partial S$) should be compatible with the temporal variation of the horizontal VTEC gradient ($\partial(\partial T_V/\partial S)/\partial t$) under an internally consistent gridded TEC field. This relationship is expected to hold more clearly when residual errors are low and the GEO observation geometry is temporally stable. In this case, the spatial variation of the TEC temporal change and the temporal variation of the TEC spatial gradient provide two complementary descriptions of the same evolving TEC distribution.

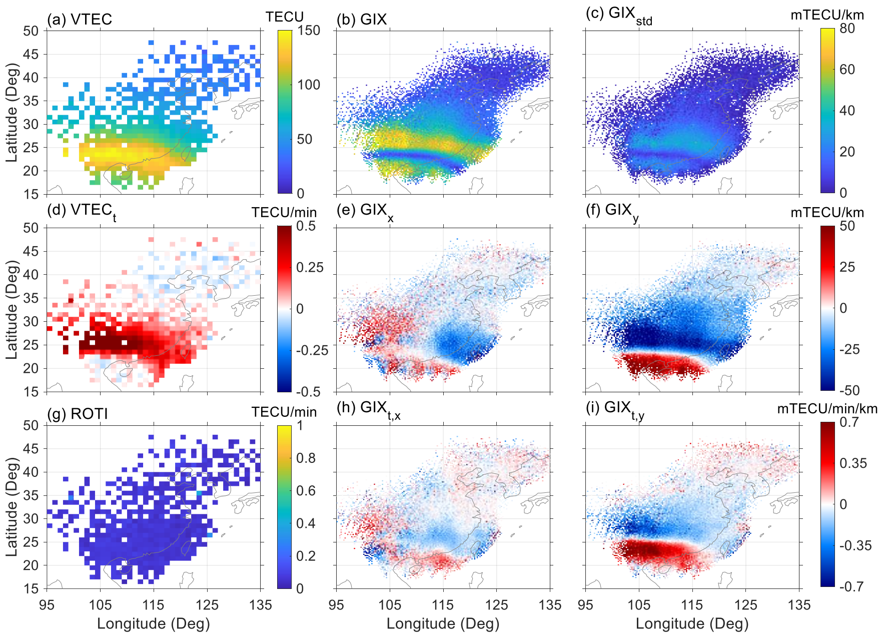

Figure 5. Example GIFT-BDS TEC gradient products at 13:40 LT (115°E) on 21 September 2024. All panels display grid-mean values. Panels b, c, e, f, h and i use a 0.25° × 0.25° grid, while panels a, d and g use a 1° × 1° grid. The positive x and y directions denote eastward and northward, respectively.

Following Li et al. (2025b), the asymmetry of mixed spatiotemporal partial derivatives is used as an internal consistency metric for the Level-2 products. This metric does not require an external reference product, and is therefore useful for assessing a GEO-based regional gradient dataset for which independent gradient observations are not generally available. The asymmetry metric is defined as:

$$Asymmetry = \sqrt{\left(\frac{\partial^2 T_V}{\partial t\,\partial x} - \frac{\partial^2 T_V}{\partial x\,\partial t}\right)^2 + \left(\frac{\partial^2 T_V}{\partial t\,\partial y} - \frac{\partial^2 T_V}{\partial y\,\partial t}\right)^2} \tag{15}$$

where the terms represent the differences between the two orders of mixed partial derivatives in the zonal and meridional directions, respectively. For an ideal, smooth TEC distribution on the ionospheric shell,

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the asymmetry should be close to zero. In practice, non-zero values may result from residual measurement noise, small variations in GEO observation geometry, mapping and gridding effects, and genuine ionospheric spatiotemporal variability. The asymmetry metric is therefore not interpreted as an absolute error estimate, but as a system-level diagnostic of the internal consistency of the Level-2 gradient products.

Figure 6 summarizes the daily internal consistency statistics of the Level-2 gradient products. The daily median mixed-partial-derivative asymmetry remains close to 0.06×10^{-3} TECU min^{-1} km^{-1} for most of the record, with no significant long-term trend. The interquartile range is also generally stable throughout the period, indicating that the combined effects of geometry-related variability, residual observation errors, and gridding noise on the Level-2 gradient products are limited and temporally consistent. The long-term behavior of this metric supports the internal-consistency assessment of the GIFT-BDS Level-2 gridded gradient products.

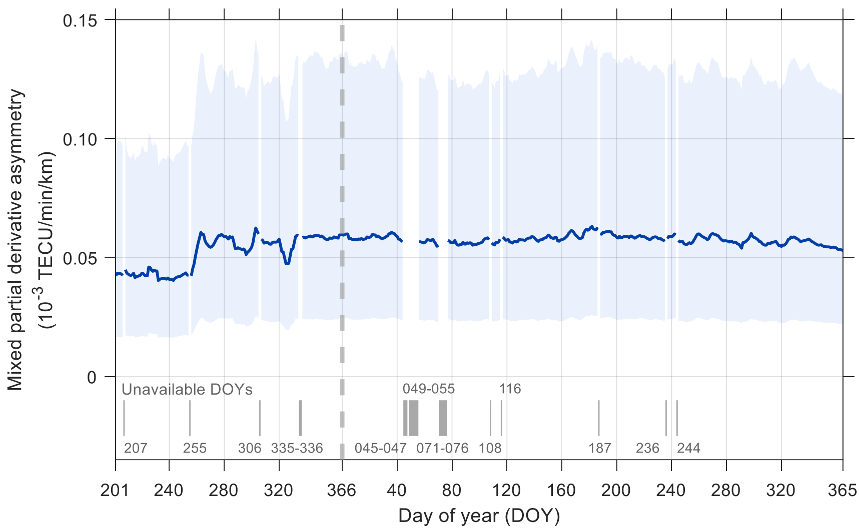

Figure 6. Daily internal-consistency statistics of the GIFT-BDS Level-2 gradient products over the full data period. The blue curve shows the 7-day moving mean of the daily median mixed-partial-derivative asymmetry, and the blue shading denotes the interquartile range (IQR; P25–P75). Gray bars and labels mark DOYs without valid observations. The vertical dashed line indicates the boundary between 2024 and 2025.

3.4 Comparison with GIM-derived gradient estimates

A qualitative comparison with GIM-derived gradients illustrates the spatial structures resolved by the GIFT-BDS Level-2 products. Note that the two products have different design objectives and spatial resolutions. The CAS GIM provides a global ionospheric representation on a relatively coarse grid, whereas GIFT-BDS is designed to describe regional TEC gradients over China using BeiDou GEO observations. The comparison is designed as a resolution and morphology check rather than as an independent accuracy validation.

Figure 7 compares the temporal evolution of VTEC and spatial gradient quantities along the 115°E meridian between 20°N and 30°N during 5–7 April 2025. Panels (a, c, e, g) show CAS GIM-derived results, while panels (b, d, f, h) show the corresponding GIFT-BDS products. The CAS GIM has a spatial resolution of 2.5° in latitude and 5° in longitude, whereas the GIFT-BDS TEC-gradient products are provided on a 0.25° × 0.25° grid. Both products reproduce the broad diurnal evolution of VTEC over the selected latitude range, including the daytime enhancement and nighttime decay. The GIM-derived results are, however, smoother in space and time, as expected from the coarser grid spacing. Their corresponding gradient structures are weaker and broader, with limited representation of localized gradient features. In contrast, the GIFT-BDS products show sharper and more localized gradient enhancements in GIX, together with meridional and zonal gradient structures in GIX_y and GIX_x. The difference is especially evident near the low-latitude crest region, where GIFT-BDS captures narrow and rapidly evolving meridional gradient features that are largely smoothed in the GIM-derived results.

The comparison illustrates the additional regional detail provided by the GIFT-BDS Level-2 gradient products. The higher-resolution GEO-derived results are better suited for describing localized TEC-gradient structures and their short-term evolution, whereas GIM-derived gradients provide a useful large-scale background reference. The results therefore support the intended use of GIFT-BDS for regional ionospheric gradient monitoring and for applications requiring detailed characterization of ionospheric spatiotemporal variability.

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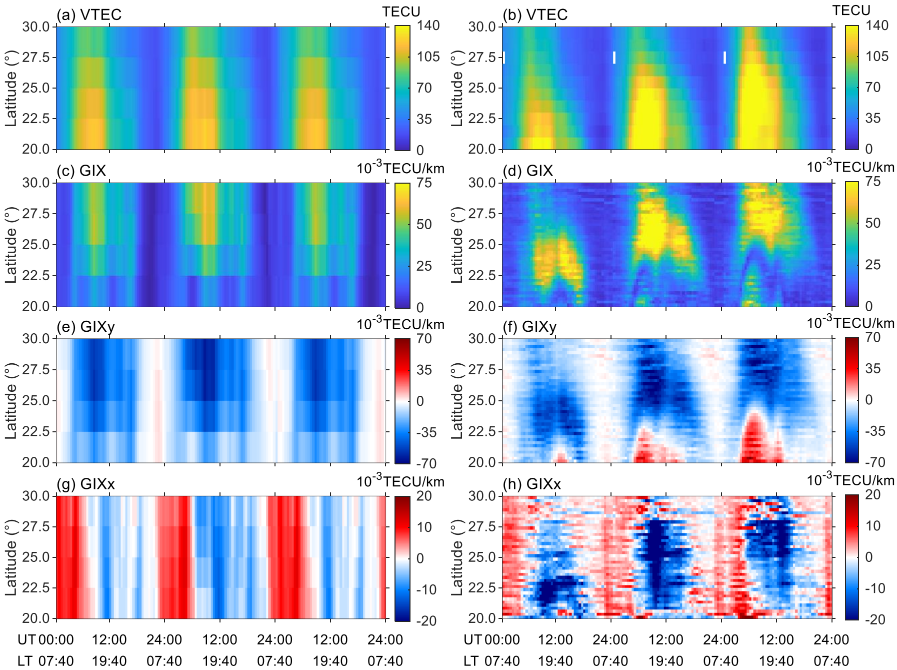

Figure 7. Latitude-time variations of ionospheric TEC and its spatial gradients along the 115°E meridian from 5 to 7 April 2025. The left panels are derived from the CAS GIM, and the right panels are derived from the GIFT-BDS dataset. Panels (a, b) show VTEC, panels (c, d) show GIX, panels (e, f) show GIX_y, and panels (g, h) show GIX_x over 20°N–30°N. Time is labeled in UT, with the corresponding local time at 115°E shown below. Positive GIX_x and GIX_y denote eastward and northward TEC gradient components, respectively. The CAS GIM has a nominal grid spacing of 5°×2.5°, whereas the GIFT-BDS TEC-gradient products are provided on a 0.25°×0.25° grid.

4 Example applications

This section provides two examples to illustrate possible uses of the released products. The first example uses GIX and its directional components to describe event-scale and seasonal TEC gradient structures associated with daytime Equatorial Ionization Anomaly (EIA) development and nighttime Equatorial Plasma Bubble (EPB) activity. The second example compares GIFT-BDS-based GIX indicators with PPP and network RTK (NRTK) positioning performance during disturbed ionospheric conditions.

4.1 Example use for event-scale and seasonal TEC-gradient characterization

EIA development and EPB activity are representative low-latitude ionospheric processes over China and its surrounding regions. EIA occurs during daytime and is characterized by a trough in electron density near the magnetic equator and two anomaly crests at low magnetic latitudes. It is formed by the fountain effect, which lifts plasma upward and redistributes it along geomagnetic field lines (Chen et al., 2023; Nigussie et al., 2022). EPBs mainly occur at night and appear as depleted plasma density structures that originate in the equatorial ionosphere and may extend to low latitudes. They are often aligned nearly north-south and drift zonally, producing pronounced spatial gradients and irregular perturbations (Li et al., 2021a; Song et al., 2025). Because both phenomena exhibit clear spatial patterns and temporal evolution, they provide suitable examples for illustrating the use of GIFT-BDS in describing regional TEC gradient structures.

Figure 8 shows GIX and its directional components for a daytime EIA-related structure and a nighttime EPB-related structure on 21 September 2024, together with their evolution along selected meridional and zonal sections. In panel (a), enhanced GIX values appear on both flanks of the daytime EIA crest at low latitudes, indicating enhanced horizontal TEC gradients associated with the anomaly structure. Panel (b) shows the corresponding meridional TEC gradient pattern. The near-zero transition zone marks the approximate crest location, while the opposite signs on the two sides indicate rapid TEC decay away from the crest. In panel (c), nighttime EPB-related structures appear as narrow, nearly meridional bands of enhanced GIX. Panel (d) shows the associated zonal TEC gradient component, with enhanced GIX_x values along the edges of the depletion structures. Along 115°E, panel (e) shows the daytime enhancement of GIX around the EIA crest region, while panel (f) illustrates the associated meridional gradient pattern through the sign reversal of GIX_y and the displacement of the near-zero transition zone. Along 23.5°N, panel (g) shows the zonal evolution of EPB-related GIX_x enhancements

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in longitude-time space. These examples illustrate how GIFT-BDS can be used to follow regional TEC-gradient structures under daytime and nighttime ionospheric conditions.

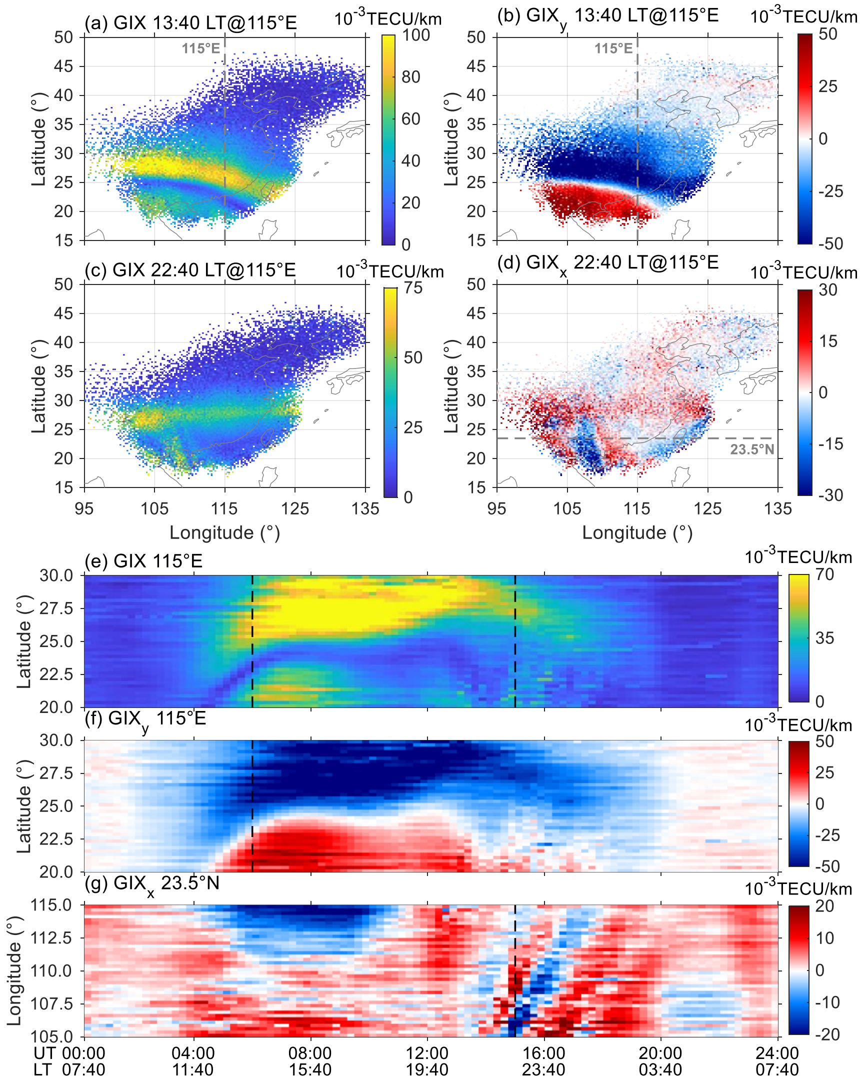

Figure 8. Example GIFT-BDS TEC gradient products on 21 September 2024. Panels (a, b) show GIX and its meridional component GIX_y at 13:40 LT, and panels (c, d) show GIX and its zonal component GIX_x at 22:40 LT over the region 15°N–50°N, 95°E–135°E. The dashed line in panels (a, b) marks the 115°E meridian used for the latitude-time sections in panels (e, f), and the dashed line in (d) marks the 23.5°N parallel used for the latitude-time section in panel (g). Panels (e, f) present latitude-time variations of GIX and GIX_y along 115°E over 20°N–30°N, and panel (g) presents a longitude-time variation of GIX_x along 23.5°N over 105°E–115°E. The vertical dashed lines in (e-g) indicate 13:40 and 22:40 LT, corresponding to the snapshots in (a, b) and (c, d), respectively.

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Figure 9 extends the event-scale example to a longer timescale and illustrates the seasonal variability of daytime EIA-related gradient structures. To emphasize the latitudinal organization of the anomaly, GIX and GIX_y are first averaged over 100°E-120°E and then averaged within a fixed local time window of 13:40-17:40 LT for each day. This averaging reduces short-term longitudinal variability and provides a consistent daytime view of day-to-day and seasonal changes. In panel (a), enhanced GIX values are mainly around the EIA crest region. The intensity and latitudinal extent of these gradients show clear seasonal modulation, with stronger and broader structures during the equinox seasons and weaker signatures around the June solstice. Panel (b) shows the corresponding latitude-DOY distribution of GIX_y, which represents the meridional TEC gradient pattern. Positive values south of the crest region and negative values to the north indicate opposite meridional TEC gradient directions on the two sides of the EIA crest. The near-zero transition region marks the approximate crest location. Together with the event-scale example in Fig. 8, these results illustrate the use of GIFT-BDS for describing TEC-gradient morphology from event to seasonal timescales.

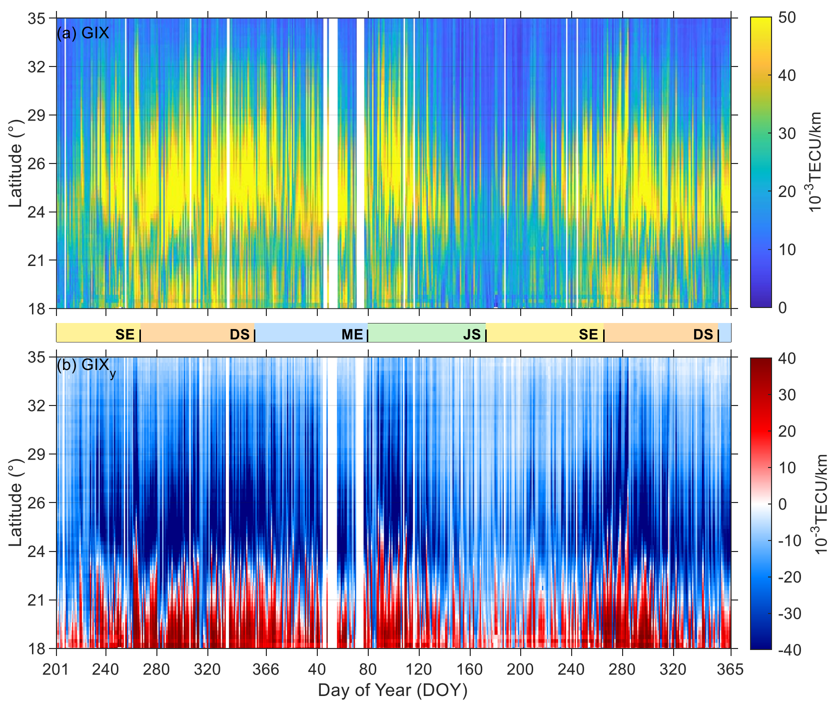

Figure 9. Seasonal variability of daytime GIFT-BDS TEC gradient products from mid-2024 to the end of 2025. Panels (a) and (b) show latitude-DOY variations of longitude-averaged GIX and its meridional component GIX_y, respectively, over 18°N–35°N and 100°E–120°E. For each day, the values are first averaged over 100°E–120°E and

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then averaged within the local-time window of 13:40–17:40 LT referenced to 115°E. White gaps indicate days or latitude bins without valid gridded products. The colored bar below panel (a) indicates the seasonal partition used in the analysis: SE, September equinox; DS, December solstice; ME, March equinox; JS, June solstice.

4.2 Example use for GNSS positioning-related analysis

GNSS positioning performance can be notably affected by ionospheric disturbances, particularly under conditions of rapid spatial and temporal variations in electron density. Such effects are typically more pronounced during disturbed ionospheric periods, when ionospheric irregularities such as EPBs and sharp TEC gradients occur more frequently. GIX quantifies the magnitude of horizontal TEC spatial gradients and can therefore be used as a diagnostic variable for comparing regional ionospheric structure with GNSS positioning performance. Previous studies have reported associations between enhanced GIX and degraded PPP performance during geomagnetic storms (Fu et al., 2025b; Nykiel et al., 2024). In this section, GIFT-BDS is used to illustrate how regional TEC gradient products can be compared with PPP and NRTK positioning metrics.

Figure 10 shows the temporal evolution of TEC gradient activity and PPP/NRTK positioning performance over 15°N–25°N and 100°E–120°E during a geomagnetically disturbed period. The ionospheric conditions are characterized using two GIFT-BDS variables: GIX, which quantifies horizontal TEC spatial gradient intensity, and ROTI, which describes short-term TEC temporal variability. In this case, enhanced GIX and ROTI structures are observed during the disturbed interval, with an apparent eastward evolution in panels (d) and (e). Panels (a) and (b) show the horizontal and vertical RMS of PPP positioning errors for 48 stations in the selected region. In both panels, the station-mean and P95 RMS values increase during the interval of enhanced TEC gradient activity. Panel (c) compares the mean horizontal error of NRTK solutions in Hong Kong with the collocated GIX time series at 23°N, 113°E. The enhanced and rapidly varying GIX values are consistent with the passage of EPB-related gradient structures over the region. Increased NRTK errors occur during intervals of enhanced GIX, suggesting that the local TEC gradient activity contributed to the observed positioning degradation. This example indicates that the GIFT-BDS gradient products provide useful context for interpreting GNSS positioning performance under disturbed ionospheric conditions.

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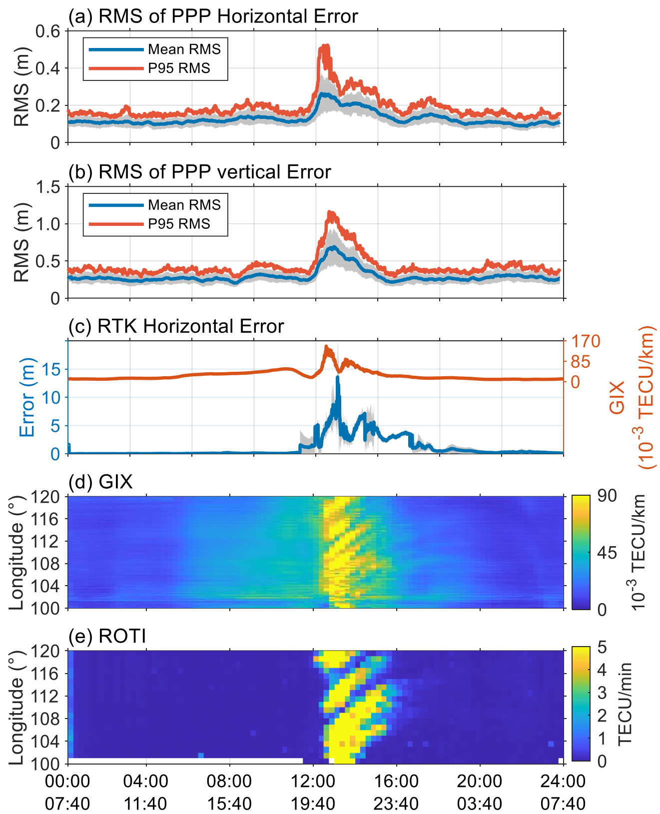

Figure 10. Example use of GIFT-BDS for comparing TEC gradient activity with GNSS positioning performance during a geomagnetically disturbed period. Panels (a) and (b) show the horizontal and vertical RMS of PPP positioning errors, respectively, computed from 48 stations within 15°N–25°N and 100°E–120°E. The blue curves denote the station-mean RMS, the orange curves denote the 95th percentile (P95) of station-wise RMS, and gray shaded envelopes indicate ±1 standard deviation about the mean. Panel (c) shows the mean horizontal error of network RTK solutions from 12 stations in Hong Kong, with an average baseline length of about 20 km, together with the collocated GIX time series at 23°N, 113°E. The gray envelope indicates ±1 standard deviation across the RTK stations. Panels (d) and (e) show the latitude-averaged GIX and ROTI, respectively, over 15°N–25°N and 100°E–120°E. The time axis is labeled in UT, with the corresponding LT at 115°E shown below.

Figure 11 presents a statistical analysis of NRTK horizontal positioning errors and collocated GIX values over the Hong Kong network. Note that TEC-gradient structures over low-latitude China are produced by different ionospheric processes, and enhanced GIX values may occur during both daytime EIA development and nighttime EPB activity. Since daytime EIA conditions are generally associated with smoother electron density variations and lower ROTI, this analysis is restricted to nighttime conditions during the equinox-to-solstice interval, when enhanced GIX values are more likely associated

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with EPB-related structures. Panel (a) shows the relationship between the median NRTK horizontal positioning error and GIX. Large-error samples in the 2–15 m range tend to occur at higher GIX values, with a correlation coefficient of 0.752 for this subset. In contrast, smaller-error samples below 2 m show weaker dependence on GIX, indicating that other error sources may contribute substantially under moderate-error conditions. Panel (b) shows the occurrence probabilities of the two error ranges as a function of GIX. The probability of large NRTK errors increases with GIX, whereas the moderate-error range does not show the same monotonic behavior. These results illustrate how GIFT-BDS can be used to examine statistical associations between regional TEC gradient activity and NRTK positioning degradation.

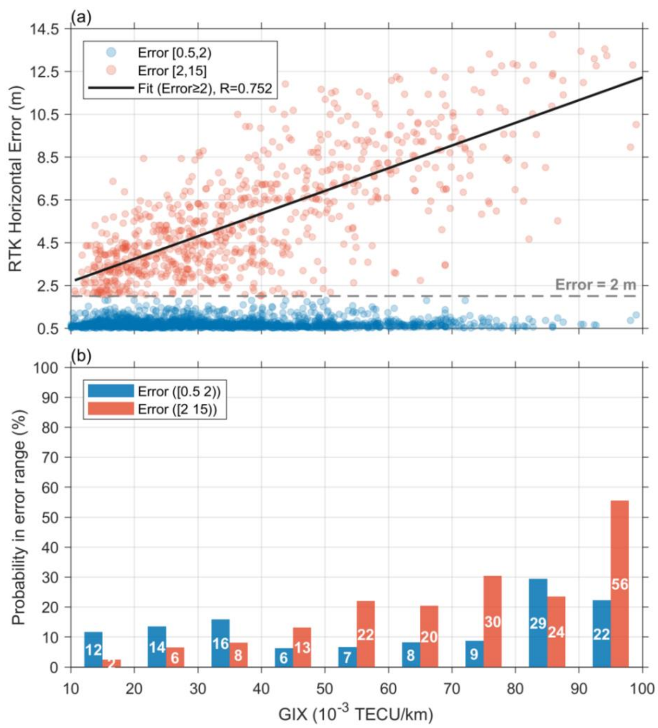

Figure 11. Example use of GIFT-BDS for relating collocated GIX to NRTK horizontal positioning errors in Hong Kong (23°N, 113°E) during the equinox-to-solstice interval from 10 August to 29 October 2024. The analysis uses a 12-station network RTK configuration with a mean baseline length of about 20 km. GNSS solutions are computed at 30 s intervals and summarized at a 15 min sampling cadence. For each 15 min interval, the median horizontal positioning error across the RTK stations is compared with the collocated GIX value. Panel (a) shows the epoch-wise median horizontal error as a function of GIX, separated into two error ranges, 0.5–2 m (blue) and 2–15 m (orange). The solid black line shows a regression fit to the 2–15 m samples, and the dashed gray line marks the 2 m threshold used here to indicate severe positioning degradation. Panel (b) shows the occurrence probability of the two

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error ranges as a function of GIX, obtained by binning the GIX values. Numbers within the bars denote the corresponding percentages.

5 Data availability

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. Daily updated GIFT-BDS products are available at https://data.bdsmart.cn/pub/campaign/iono/. These daily products follow the same processing strategy as the archived release, but should be regarded as operational updates until they are included in a subsequent versioned release.

6 Conclusion

This paper presents GIFT-BDS, a continuously updated regional ionospheric TEC and GIX dataset over China. The dataset is generated from a fixed-geometry observation network combining more than 200 ground-based GNSS receivers and five BeiDou GEO satellites. The near-stationary receiver-satellite geometry provides repeated sampling of nearly fixed ionospheric pierce points and supports the estimation of regional TEC-gradient quantities. The released products are organized into two levels. Level-1 provides GEO-derived STEC time series for individual receiver-satellite links, while Level-2 provides gridded TEC, ROTI and GIX products. The TEC gradient products are provided on a 0.25° × 0.25° grid with a temporal resolution of 15 min.

The quality and consistency assessments support the reliability and usability of the released dataset. The Level-1 STEC records show short-term stability at the sub-TECU level, as assessed from detrended STEC residuals. The Level-2 gradient products show temporally stable internal consistency under the BeiDou GEO observation geometry, based on the mixed-partial-derivative asymmetry diagnostic. Comparison with GIM-derived gradients further illustrates the added regional detail and temporal continuity provided by GIFT-BDS. The example applications show how the dataset can be used to describe EIA-related gradient morphology, EPB-related gradient structures, seasonal TEC gradient variability, and ionospheric conditions relevant to PPP and NRTK performance analyses.

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GIFT-BDS provides a new regional data resource for ionospheric process studies, space-weather monitoring, and GNSS application analyses over China. The archived release used in this paper is complemented by daily updated products. Future versions will extend the temporal coverage, improve product completeness, and further refine the quality-control procedures and metadata information to support long-term use of the dataset.

Author contributions

NW and JZ contributed to the conceptualization; ZL, JZ, NW, YH, YY, XW and AL were involved in the methodology; ZL and NW assisted in the formal analysis and investigation; ZL and JZ contributed to writing—original draft preparation; ZL, JZ, NW, YH, XW, NJ, and MH helped in writing—review and editing; JZ, NW, YH and XW acquired the funding; NW, JZ, ZsL, YH and XW contributed to the resources; JZ, NW, YH, AL, XW and ZsL contributed to the supervision. All authors have read and agreed to the final version of the manuscript.

Competing interests

The contact author has declared that none of the authors has any competing interests.

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