

Article

Sporadic-E Occurrence, Intensity, and PyIRI foEs Assessment Using Four Years of Ganzi Digisonde Observations over the Eastern Tibetan Plateau

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Abstract

The sporadic-E (Es) layer is a recurrent feature of the mid-latitude E region, yet the eastern Tibetan Plateau remains poorly sampled by routine ionosonde observations. We analyze 28,771 automatically scaled top-of-hour Digisonde soundings recorded at Ganzi (31.17° N, 100.44° E) from September 2015 to August 2019 during the declining phase of solar cycle 24. We examined monthly and local solar time (LST) variations in Es occurrence, foEs, and hpEs and evaluated the PyIRI foEs specification. Es occurs in 53.1% of interpretable soundings, with a summer-daytime maximum and a late-autumn minimum (about 77% in June and 37% in November). The layers are comparatively weak, with a median foEs of 3.35 MHz and only 2.1% of soundings exceeding 7 MHz. Adjusted daytime Es occurrence and mean foEs differ among the F10.7 quintiles, but neither varies monotonically across the groups. The global Kp tests are not significant for either outcome, while the Dst groups differ only in adjusted mean foEs. For Es-present soundings, PyIRI gives a small overall bias of −0.17 MHz, but the month–LST decomposition reveals summer-daytime overestimation of 1–1.5 MHz and a weaker winter underestimation. Leave-one-analysis-year-out validation reduces the pooled RMSE from 1.44 to 1.39 MHz, with improvement in three of the four held-out years.

Keywords: sporadic E; ionosonde; Tibetan Plateau; foEs; IRI; E-region climatology



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1. Introduction

Sporadic-E (Es) layers are thin, dense concentrations of metallic ions in the lower ionosphere, typically occurring at altitudes of about 90–130 km [1,2]. Although historically termed sporadic, mid-latitude Es is in fact a recurrent feature of the E region with a well-organized seasonal and diurnal climatology. Es can support unexpected over-the-horizon high-frequency propagation, obscure the overlying F region in vertical soundings, and serve as a tracer of neutral dynamics in the lower thermosphere. A reliable description of Es behavior is therefore relevant to radio-propagation applications and atmosphere–ionosphere coupling studies.

Mid-latitude Es is generally attributed to wind-shear convergence of meteoric metallic ions [3,4]. Its climatology often shows a summer-daytime maximum at middle latitudes [5,6]. Previous studies also emphasize the roles of tidal wind dynamics and electric fields in Es formation [7,8]. A radio-occultation case study further linked inclined Es-layer structure to internal gravity waves [9]. Long-term ionosonde records remain

one of the principal sources for Es occurrence and intensity statistics, and station-level climatologies continue to provide valuable regional constraints [10,11].

In the East Asian sector, Es has been characterized at a number of ionosonde stations spanning low to middle latitudes [6,10,12]. The eastern margin of the Tibetan Plateau, however, remains sparsely represented in routine ionosonde studies. A particularly relevant precedent is the Zhangye (39.21° N, 100.54° E) ionosonde on the northeastern edge of the plateau, where Wang et al. [11] contrasted plateau and plain-region Es characteristics. Nevertheless, a multi-year Es climatology for the eastern Tibetan Plateau has not been reported, and the occurrence, intensity, and virtual-height characteristics of Es in this sector remain poorly constrained by observations. The Ganzi station provides a multi-year ionosonde record for this region.

The International Reference Ionosphere (IRI) is the most widely used empirical model of the ionosphere [13]. The standard IRI releases do not include an Es representation. PyIRI, a Python implementation of the IRI framework [14], provides an empirical foEs specification based on the global ionosonde-derived maps of Leftin et al. [15]. Ingestion of an Es description into the IRI itself has been proposed [16]. Alternative empirical foEs models based on GNSS radio-occultation observations have recently been developed [17,18]. PyIRI has recently been assessed against ionosonde observations for the E region proper [19]. Its foEs specification has not been evaluated against independent station data. Because the underlying foEs maps are fitted to globally distributed ionosonde data, sparsely sampled regions such as the eastern Tibetan Plateau provide a stringent independent test.

In this study, we use four years of automatically scaled Digisonde observations at Ganzi (31.17° N, 100.44° E) to characterize the occurrence rate, intensity, and virtual height of Es layers during 2015–2019. We further examine their diurnal–seasonal structure and relationships with solar-flux and geomagnetic conditions. Finally, we evaluate PyIRI foEs values against ground-based observations for soundings in which Es is observed.

2. Data

2.1. Site and Instrument

The observations were made at Ganzi, located at 31.17° N, 100.44° E on the eastern margin of the Tibetan Plateau, near the transition from low to middle latitudes (Figure 1). The station operates a DPS-4S Digisonde, which records vertical-incidence ionograms at a 15 min cadence. Because this study focuses on the month–LST climatology over a four-year interval, the ionogram recorded at the top of each hour was selected to provide a regular hourly sampling scheme. The resulting dataset covers 1 September 2015 to 31 August 2019. The Es parameters are the unedited ARTIST autoscaling output in SAO Explorer, one algorithm applied to every ionogram with no inter-operator differences. The F-region parameters, used only in the data screening of Section 2.2, were scaled manually by a single experienced operator.

2.2. Scaled Es Parameters and Sounding Record

Three Es parameters are produced by the autoscaling at Ganzi—foEs, fminEs, and hpEs. foEs is a measure of the peak electron density of the layer. fminEs is the minimum reflection frequency from the Es trace. hpEs is the virtual height of the trace's leading edge and reflects group retardation. The scaled characteristic set at Ganzi does not include the blanketing frequency fbEs, and the intensity statistics in this study are therefore based on foEs.

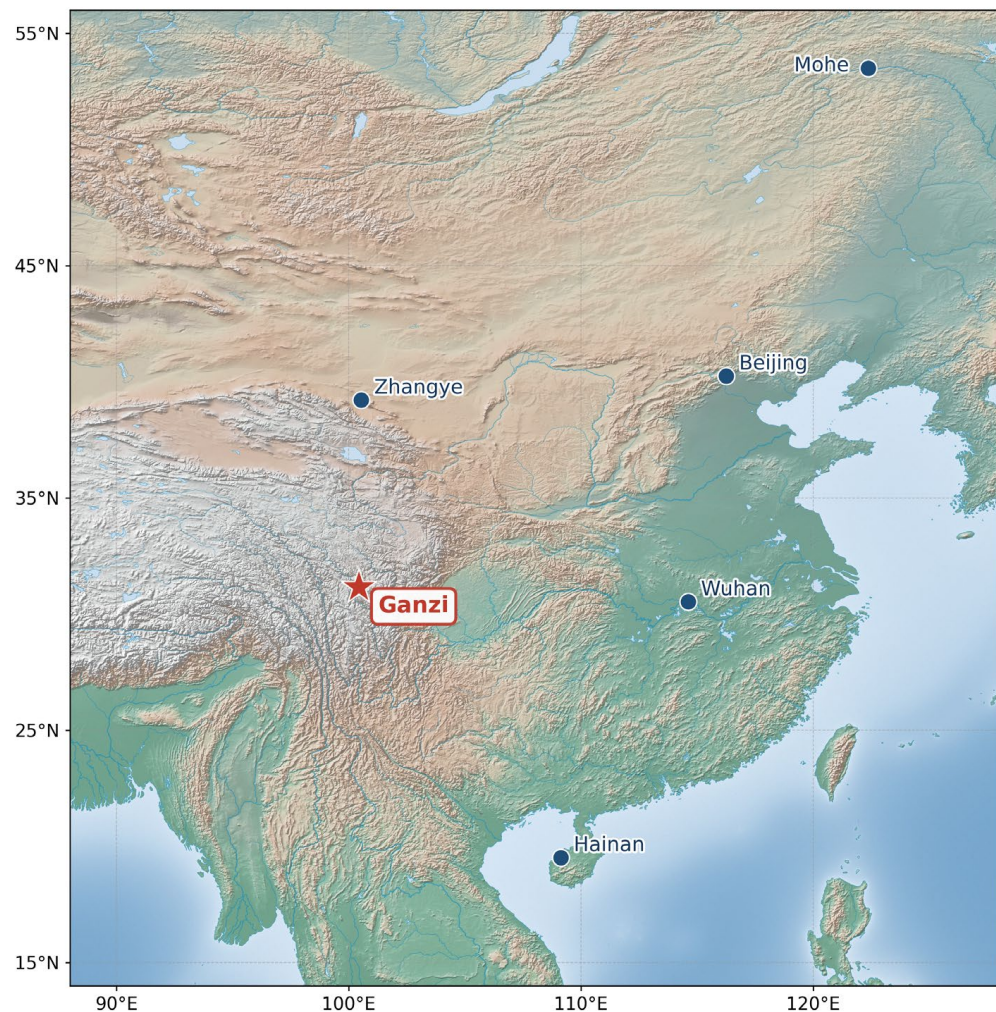


Figure 1. Location of the Ganzi DPS-4S Digisonde station (31.17° N, 100.44° E, red star) on the eastern margin of the Tibetan Plateau. Blue circles mark the comparison stations discussed in Section 5.2 (Zhangye, Beijing, Mohe, Wuhan, Hainan). Shaded-relief basemap from Natural Earth.

The window contains 28,771 top-of-hour soundings, 82% of the nominal hourly total, with the gaps scattered across the four years. Of these, 28,742 (99.9%) are interpretable (at least one of f_{min} , f_oF_2 , or f_oE_s scaled). Scaled f_oE_s was available in 15,250 of the interpretable soundings, with h_pE_s and $f_{min}E_s$ also scaled.

2.3. Time Conventions and Auxiliary Indices

Times are reported in three frames. The raw instrument records are timestamped in Beijing time (BJT = UT + 8 h). Coordinated Universal Time (UT) is used for matching with solar-flux and geomagnetic indices. For the diurnal description of E_s , we adopt local solar time (LST), defined from the station longitude as $LST = UT + 6.70 \text{ h} = BJT - 1.30 \text{ h}$. Calendar months are assigned from the BJT date.

Solar and geomagnetic conditions are represented by the solar radio flux F10.7 (daily), the planetary index K_p (3-hourly), and the ring-current index Dst (hourly), all obtained from the OMNI database and matched to each sounding by time. Over the four-year analysis interval, F10.7 ranged from 65 to 186 sfu (median 75), reflecting the declining phase of solar cycle 24. K_p ranged from 0.0 to 8.3 (median 1.7), and Dst ranged from −176 to +60 nT (median −9). Figure 2 shows the time series of daily F10.7, 3-hourly K_p , and hourly Dst over the analysis window.

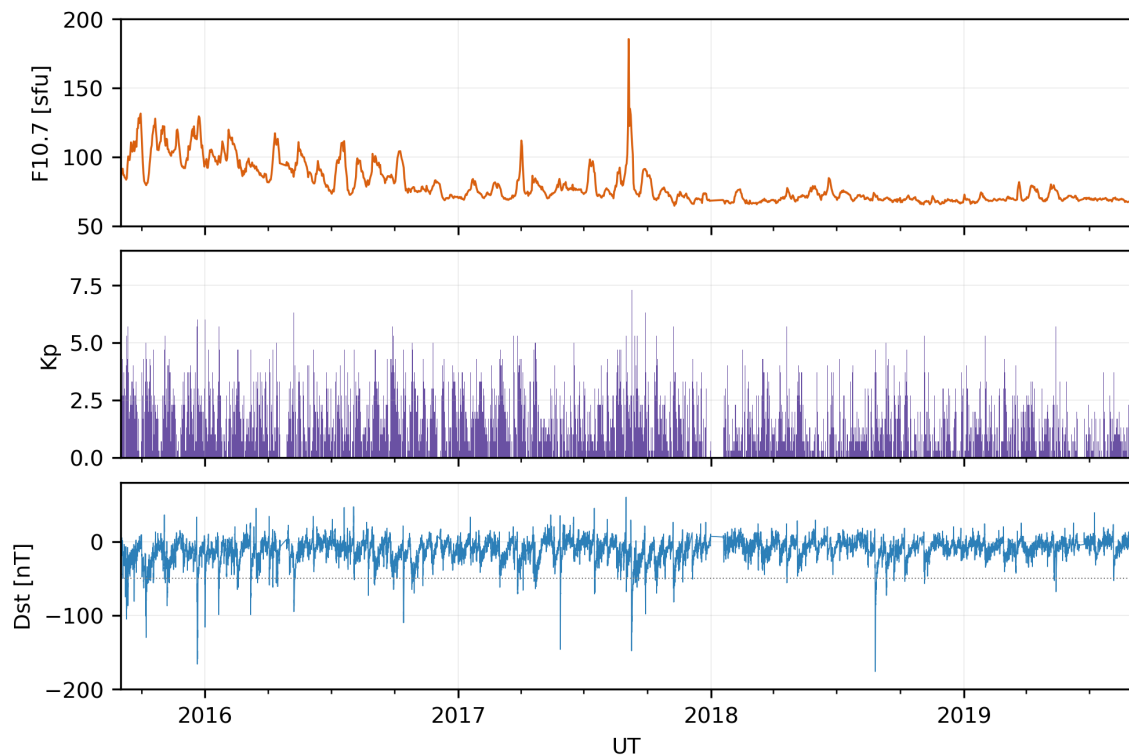


Figure 2. Solar and geomagnetic indices over the four-year analysis window, 1 September 2015 to 31 August 2019. Panels from top to bottom: daily F10.7 [sfu], 3-hourly Kp, and hourly Dst [nT].

3. Methods

3.1. Es Occurrence Definitions, Quality Control, and Binning

The Es occurrence rate is the fraction of interpretable soundings in which foEs was scaled. Interpretable soundings without scaled foEs are counted as Es-absent. Threshold occurrence rates are calculated as the fractions of interpretable soundings with foEs ≥ 3 , 5, and 7 MHz. Es intensity is reported as the foEs distribution over Es-present soundings.

Climatological quantities are binned by calendar month or season and by LST hour, with two-hour LST bins for the hpEs and fminEs medians. For each diagnostic, bins with fewer than 20 samples of the relevant denominator are left blank. The denominator is interpretable soundings for occurrence, Es-present soundings for hpEs and fminEs, and model–observation pairs for the model comparison. Apparent morning descent rates of hpEs are computed between the seasonal-median maximum over the bin centers 03–09 LST and the subsequent minimum up to 15 LST.

For the interannual comparison, the record was divided into four complete September-to-August analysis years. Annual and June Es occurrence rates, median foEs, F10.7, Kp, Dst, and data coverage are summarized in Figure S1 and Table S1.

3.2. Solar-Flux and Geomagnetic Analyses

3.2.1. Solar-Flux Analyses

Within the daytime window (LST 06–20), daily F10.7 values were divided into five quintiles based on unique UT dates. This categorical treatment accommodates the sparsely sampled upper F10.7 range. Es occurrence was analyzed by logistic regression using all interpretable soundings. foEs was analyzed by ordinary least-squares regression using Es-present soundings. The models included F10.7 quintile, calendar month, LST hour, and September-to-August analysis year as categorical predictors. Standard errors were clustered

by UT date to account for dependence among hourly soundings from the same day. Adjusted marginal estimates, 95% confidence intervals, and global Wald tests were calculated.

3.2.2. Geomagnetic Analysis

Kp was grouped as $Kp < 3$, $3 \leq Kp < 5$, and $Kp \geq 5$. Dst was grouped as $Dst > -20$ nT, -50 nT $< Dst \leq -20$ nT, and $Dst \leq -50$ nT. Kp and Dst were analyzed separately using the same logistic and OLS framework. Each model included F10.7 quintile, calendar month, LST hour, and analysis year as categorical predictors. Standard errors were clustered by UT date. Adjusted marginal estimates, 95% confidence intervals, and global Wald tests were calculated.

3.3. PyIRI Configuration and Conditional Comparison Framework

The model foEs was computed for the Ganzi location and observation times with PyIRI version 0.1.6 [14], which provides foEs from the ionosonde-derived maps of Leftin et al. [15], using the CCIR coefficient option and the observed daily F10.7 as solar input. For every sounding with Es present, the observed foEs is paired with the PyIRI foEs at the same UT hour. Soundings without Es are excluded from the pairing, and no zero foEs is assigned. The mean bias error (MBE), root-mean-square error (RMSE), and mean absolute error (MAE) therefore quantify PyIRI foEs errors conditional on observed Es occurrence. They do not assess the ability of PyIRI to represent Es occurrence or absence. All differences were calculated as model minus observed. The seasonal structure of the bias is characterized by the model-minus-observed median foEs in each month–LST bin.

3.4. Bin-Wise Regional Correction and Validation

A bin-wise correction was first derived and evaluated using a chronological training–validation split. The four-year window was split by UT date into a three-year training period, 1 September 2015 to 31 August 2018, and a held-out validation year, 1 September 2018 to 31 August 2019. A chronological split was used to test whether a correction derived from the first three years could be applied to a later, unseen year. A random split would mix observations from all four years between the training and validation sets and would not provide the same test of temporal transferability.

During training, the correction for each month $\times$ LST-hour bin was defined as the median observed-minus-PyIRI foEs difference. Bins with fewer than 20 training pairs were left uncorrected. After training, the correction map was fixed. Each validation sample was matched to the correction from the same month $\times$ LST-hour bin. No validation observations were used to derive the correction. The corrected foEs was calculated by adding the corresponding bin correction to the PyIRI value. Corrected and uncorrected values were evaluated on the same held-out Es-present pairs using MBE, RMSE, and MAE.

Temporal consistency was further evaluated using four-fold leave-one-analysis-year-out validation. Each September-to-August analysis year was held out in turn, and the correction was recomputed from the remaining three years using the same binning and minimum sample requirement. Metrics were calculated separately for each held-out year and for the pooled out-of-fold predictions.

4. Results

4.1. Es Occurrence Climatology

Across the four-year window, Es was present in 53.1% of the interpretable soundings. The occurrence rate depends strongly on the adopted definition. The rates for foEs ≥ 3 , 5, and 7 MHz are 37.3%, 7.0%, and 2.1%, respectively (Figure 3a). Monthly Es occurrence ranges from about 77% in June to about 37% in November (Figure 3b).

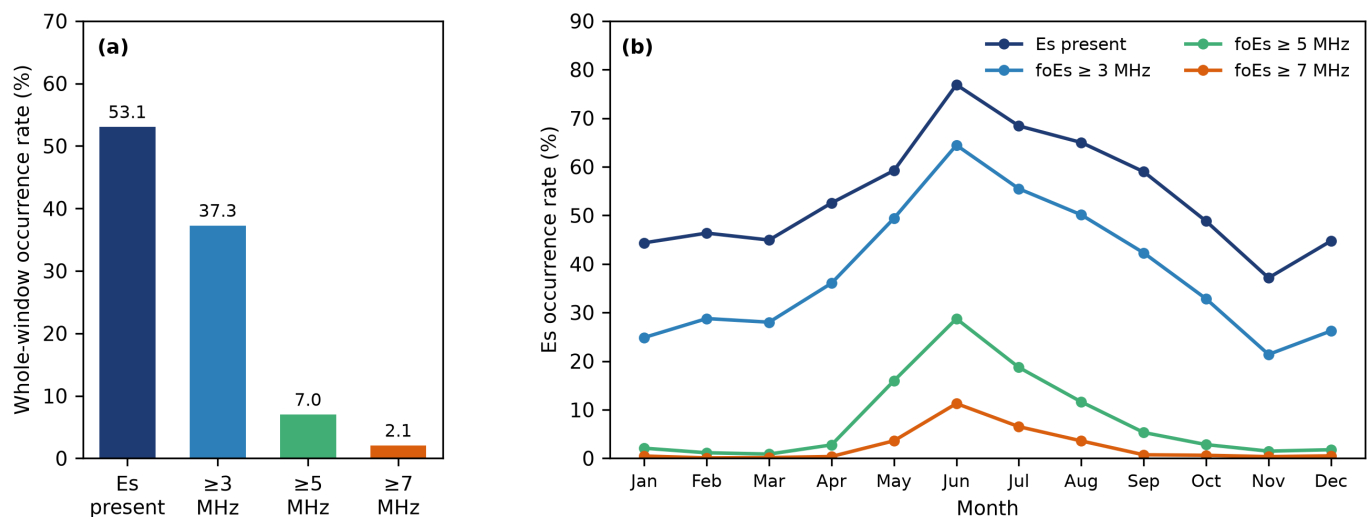


Figure 3. Es occurrence at Ganzi. (a) Four-year rates for Es-present soundings and foEs thresholds of 3, 5, and 7 MHz. (b) Corresponding monthly rates.

The month–LST distribution of Es occurrence (Figure 4) displays the organized pattern characteristic of the mid-latitude E region. Es is predominantly a daytime phenomenon, with high occurrence between approximately 07 and 17 LST and much lower occurrence at night. Monthly mean occurrence peaks in June and July, when the high-occurrence interval is widest. The highest single-bin occurrence rates occur in spring and early autumn mornings, near 99% in March (LST 10), 96–98% in April (LST 8–10), and about 95% in September (LST 8). Summer peaks are slightly lower but spread over a broader daytime interval. In winter the occurrence is more strongly confined to the daytime sector. Daytime values in December, January, and February remain comparable to the equinox months, while nighttime occurrence is markedly lower than in the other seasons.

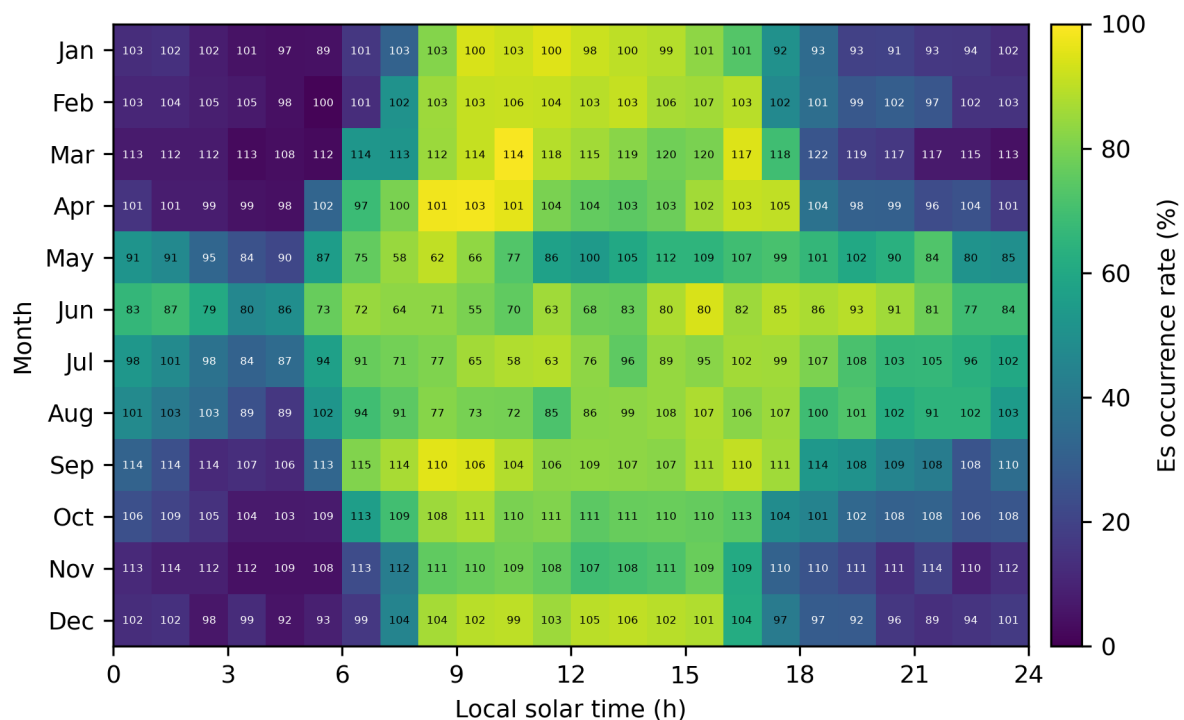


Figure 4. Month–LST distribution of Es occurrence. Color indicates occurrence rate (%) and cell labels give the number of interpretable soundings.

4.2. foEs Intensity Distribution and Climatology

The foEs distribution (Figure 5a) is sharply peaked near 3 MHz. The median is 3.35 MHz, half of the Es-present soundings fall between 2.85 and 4.30 MHz, and only 5% exceed 6.35 MHz. The monthly distribution (Figure 5b) shows a clear seasonal modulation of intensity. Median foEs (Figure 5b, black curve) is highest in summer (4.50 MHz in June) and lowest in late autumn and winter (about 3.0 MHz). The distribution is narrowly concentrated near 3 MHz in winter and broadens substantially in summer, with appreciable fractions reaching 5–8 MHz. The months with more Es are also the months with stronger Es. The monthly median foEs values are summarized in Table 1.

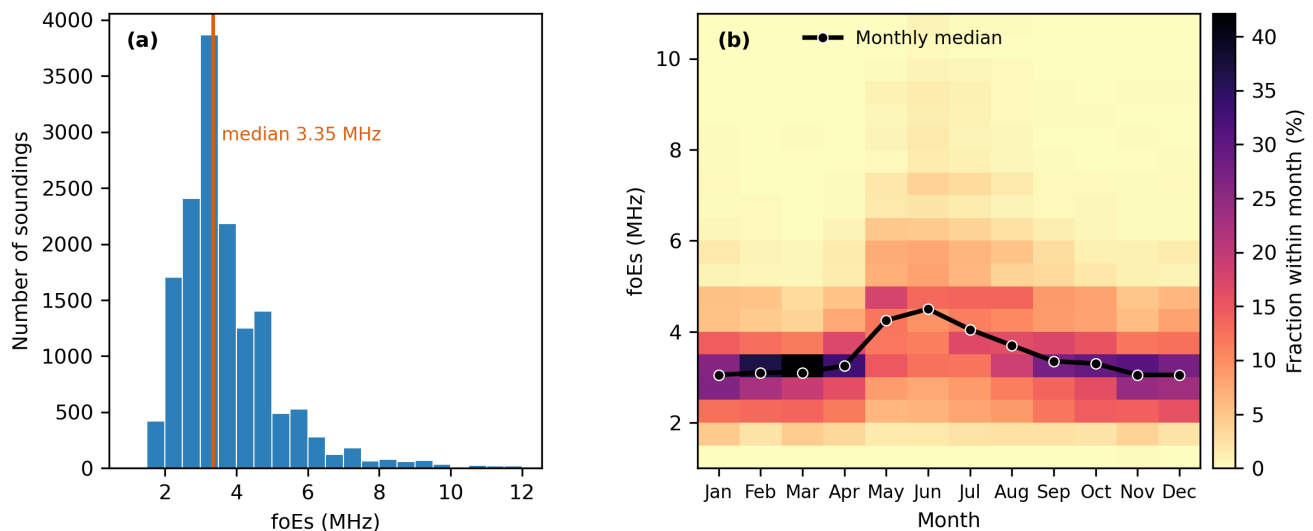


Figure 5. foEs climatology for Es-present soundings. (a) Overall distribution with the median marked by the vertical line. (b) Monthly normalized distributions with monthly medians shown by the black curve.

Table 1. Monthly median foEs at Ganzi.

Month	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Median foEs (MHz)	3.05	3.10	3.10	3.25	4.25	4.50	4.05	3.70	3.35	3.30	3.05	3.05

Note: Median foEs was calculated using Es-present soundings.

4.3. Virtual Height and Lower-Edge Frequency

The Es virtual height hpEs (Figure 6a) shows a pronounced morning peak near LST 5–7 (reaching about 119 km in spring), a midday minimum of about 100–104 km, and a weaker afternoon rebound near LST 15–17. Between the morning maximum and the midday minimum, the seasonal-median hpEs decreases at an apparent rate of 1.2–2.2 km/h, fastest in spring. Outside the morning peak, nighttime and evening values generally remain near 102–105 km. The minimum reflection frequency fminEs (Figure 6b) is lowest through the daytime hours, near 1.5–2.0 MHz. Pronounced dawn peaks occur near LST 5–7, reaching about 3.0 MHz in summer and 2.65 MHz in winter. Nighttime values rise to 1.7–2.8 MHz, highest in spring. The seasonal peak occurrence rates and apparent hpEs descent rates are summarized in Table 2.

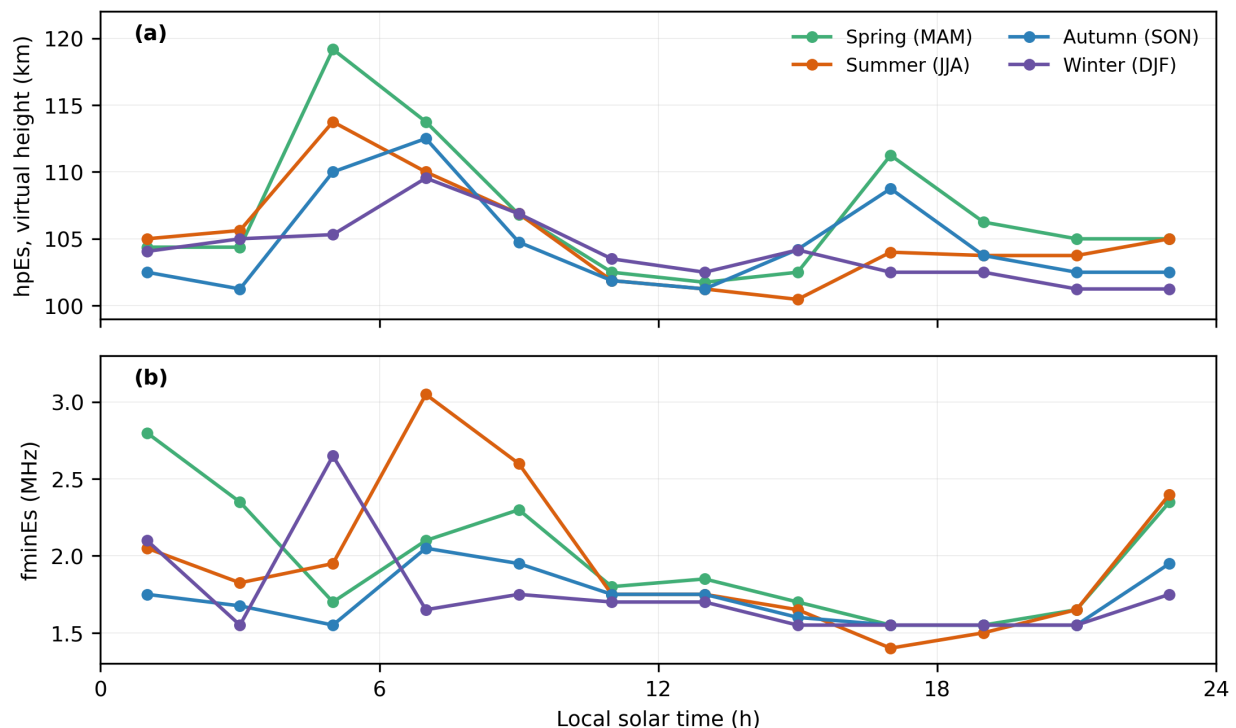


Figure 6. Seasonal medians of (a) hpEs and (b) fminEs in two-hour LST bins for Es-present soundings.

Table 2. Seasonal peak Es occurrence and apparent hpEs descent at Ganzi.

Season	Peak Occurrence (%)	Apparent Descent Rate (km h^{-1})
Spring (MAM)	99.1	2.18
Summer (JJA)	93.8	1.33
Autumn (SON)	95.5	1.88
Winter (DJF)	95.0	1.17

Note: Peak occurrence is the maximum month–LST value within each season. Apparent hpEs descent rates are calculated from the seasonal-median maximum between 03 and 09 LST to the subsequent minimum up to 15 LST. The rates describe apparent changes in virtual height.

4.4. Solar-Flux and Geomagnetic Comparison

Figure 7 shows the adjusted daytime estimates across the five F10.7 quintiles. Adjusted Es occurrence ranges from 66.9% to 74.8%, and adjusted mean foEs ranges from 3.63 to 3.85 MHz. The global Wald tests indicate differences among the F10.7 quintiles for Es occurrence ($p = 0.002$) and foEs ($p = 0.023$). However, neither outcome varies monotonically across the five groups. The results therefore do not indicate a continuous F10.7 dependence over the observed range.

Figure 8 shows the corresponding adjusted estimates for the Kp and Dst groups. Across the three Kp groups, adjusted Es occurrence ranges from 69.7% to 72.3%, and adjusted mean foEs ranges from 3.71 to 3.82 MHz. The global Kp differences are not significant for Es occurrence ($p = 0.082$) or foEs ($p = 0.327$). Across the three Dst groups, adjusted Es occurrence ranges from 67.3% to 71.7%, with no significant global difference ($p = 0.151$). Adjusted mean foEs increases from 3.70 MHz for $\text{Dst} > -20$ nT to 3.96 MHz for $\text{Dst} \leq -50$ nT, and the global difference is significant ($p = 0.021$). The foEs difference between these two groups is 0.264 MHz, with a 95% confidence interval of 0.043 to 0.486 MHz. This result is mainly associated with the $\text{Dst} \leq -50$ nT group, which also has the widest confidence interval. The adjusted values and global Wald test results are summarized in Table S2.

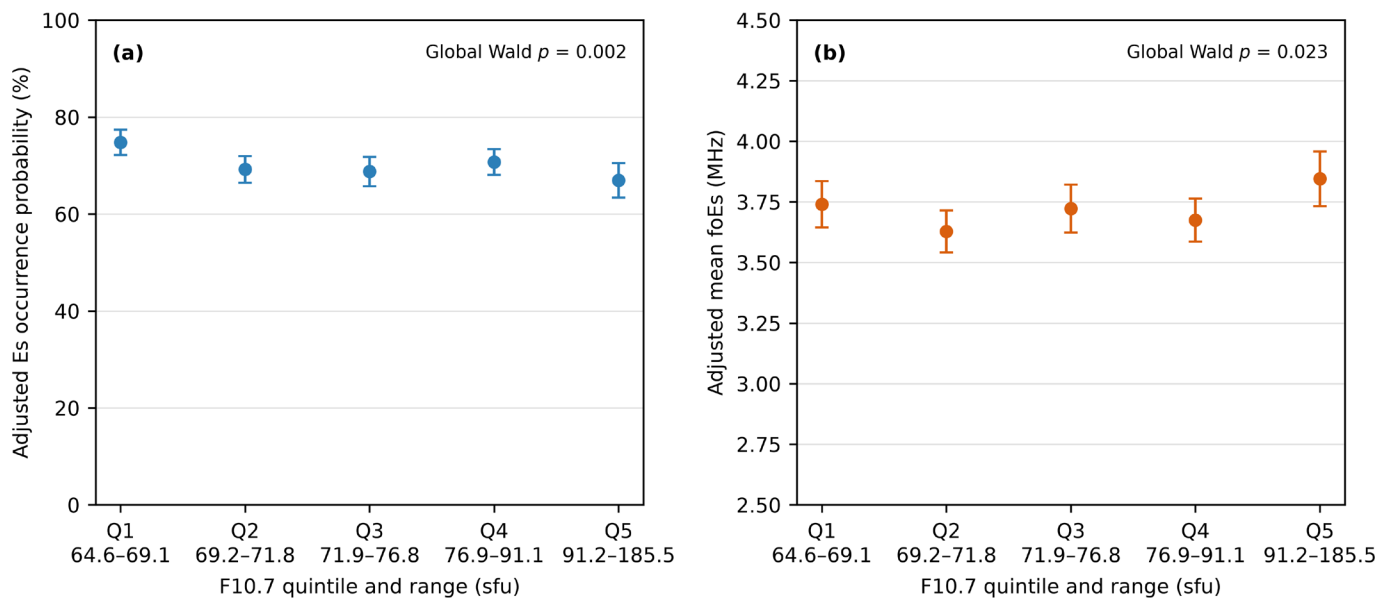


Figure 7. Adjusted (a) Es occurrence probability and (b) mean foEs across the five F10.7 quintiles during LST 06–20. Error bars show 95% confidence intervals.

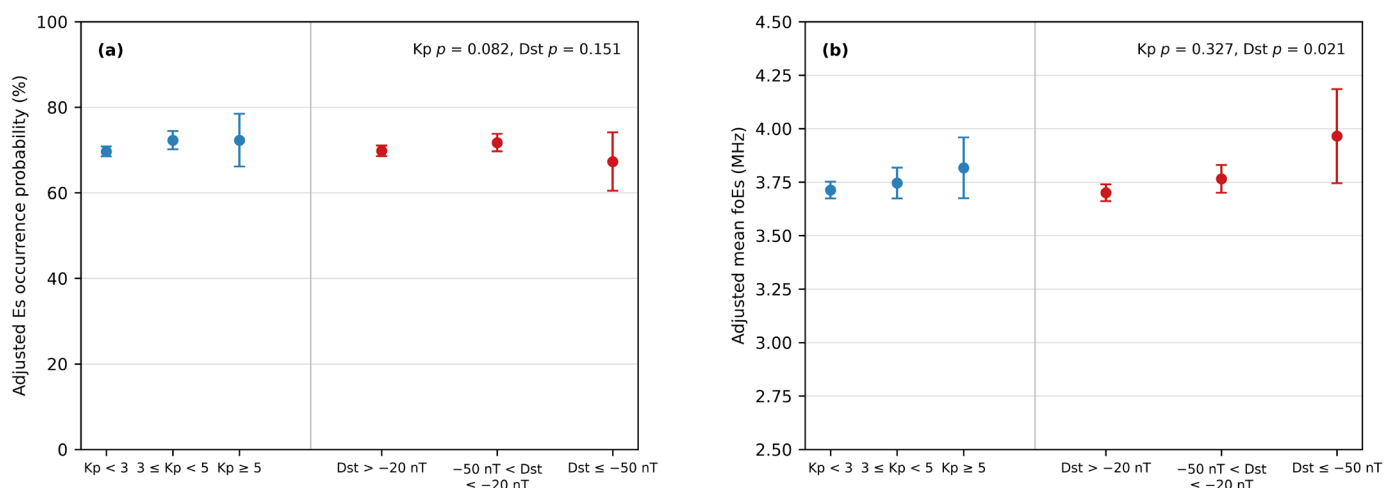


Figure 8. Adjusted (a) Es occurrence probability and (b) mean foEs across the Kp and Dst groups defined in Section 3.2. Error bars show 95% confidence intervals.

4.5. PyIRI foEs Assessment

Across the 15,250 Es-present soundings (Figure 9a), PyIRI has a small overall foEs bias (MBE = -0.17 MHz) and moderate scatter (RMSE = 1.44 MHz, MAE = 1.00 MHz). Individual pairs remain widely scattered around the 1:1 line, indicating that positive and negative errors partly offset in the MBE. In Figure 9b, each colored cell gives the median PyIRI-minus-observed foEs for one month–LST bin. Positive values indicate overestimation and negative values indicate underestimation. White bins contain fewer than 20 Es-present pairs. The matrix shows that the near-zero overall bias conceals a systematic seasonal structure. The model overestimates foEs by roughly 1–1.5 MHz during the daytime sectors of late spring and summer, and underestimates it in winter, typically by about 0.5 MHz. The winter underestimate exceeds 1 MHz in the late-afternoon sector.

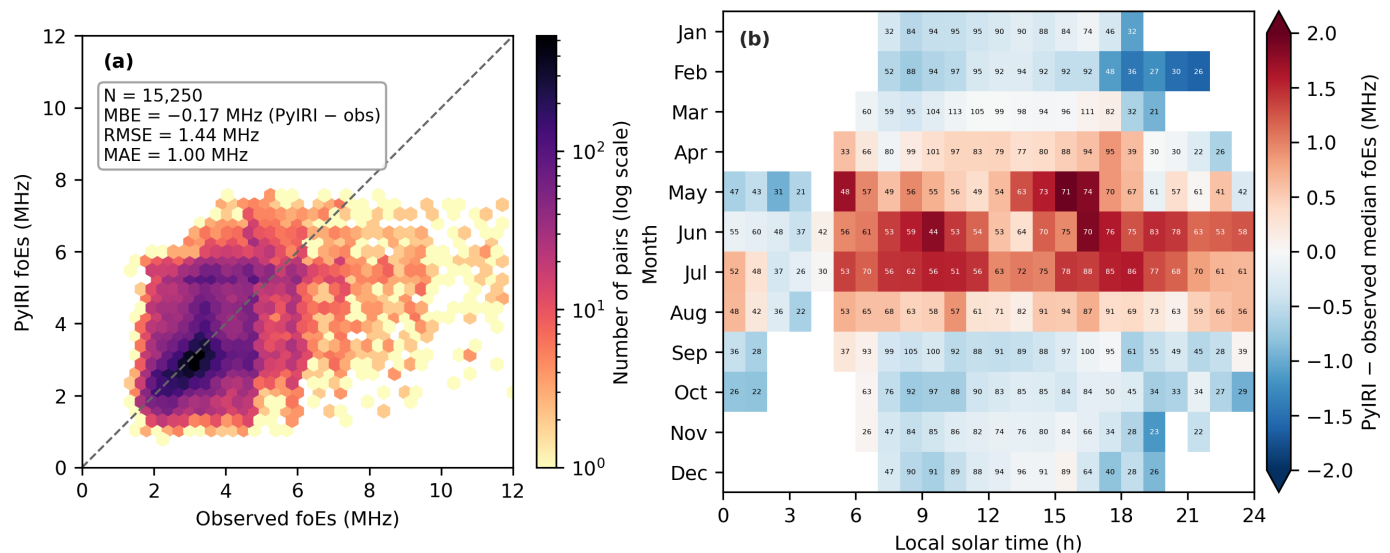


Figure 9. Conditional PyIRI foEs assessment for Es-present soundings. (a) Observed versus modeled foEs with the 1:1 line shown as dashed. (b) Median PyIRI-minus-observed foEs by month and LST. Cell labels give the number of model-observation pairs.

4.6. Bin-Wise Regional Correction

For the chronological split holding out 2018–2019, the three training years yield corrections in 216 of the 288 month–LST bins (Figure 10a). The correction map reproduces the bias structure of Figure 9b with the opposite sign. It subtracts up to 1.9 MHz in the early-summer daytime sector and adds up to 1.7 MHz in the winter late-afternoon sector.

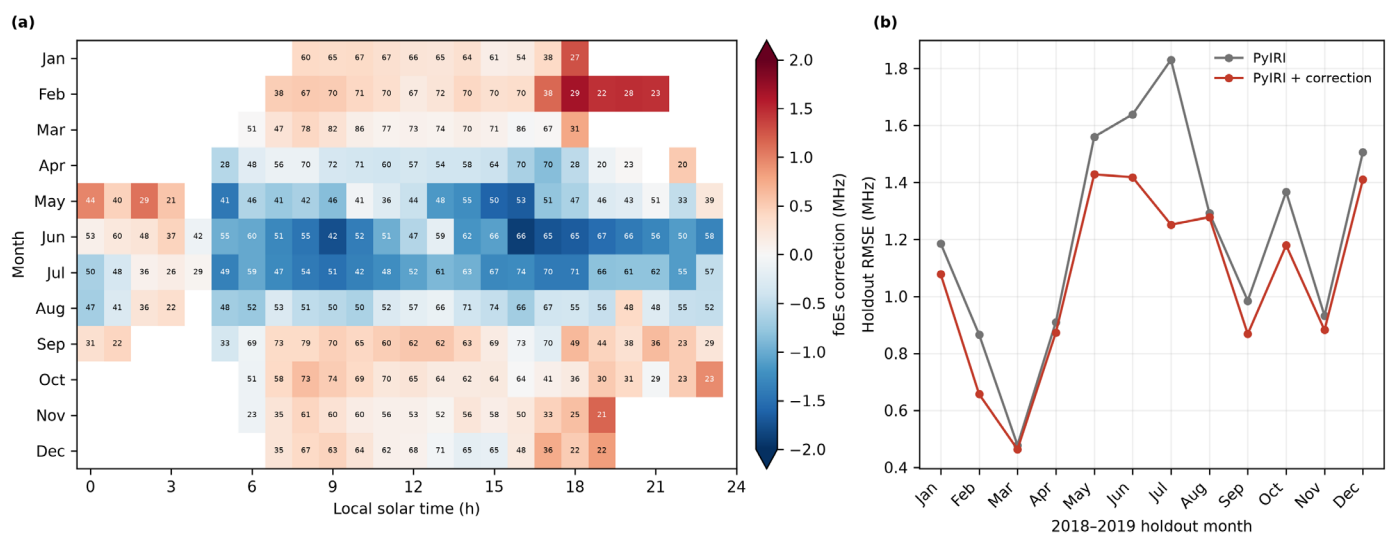


Figure 10. Month–LST correction and chronological holdout validation. (a) Median observed-minus-PyIRI foEs correction derived from September 2015 to August 2018, with training-pair counts. (b) Monthly RMSE before and after correction in the 2018–2019 holdout.

Applied to the Es-present pairs in the 2018–2019 chronological holdout, the correction reduces the RMSE from 1.21 to 1.07 MHz and the MAE from 0.86 to 0.71 MHz. Figure 10b compares the monthly RMSE of the same held-out pairs before and after correction. The RMSE decreases in all twelve months, although the magnitude of the reduction varies. The largest reduction occurs in July. From April to August, the correction map applies predominantly negative daytime adjustments to the spring–summer PyIRI overestimation identified in Figure 9b.

Leave-one-analysis-year-out validation shows that RMSE decreases by 4.8–11.5% in three folds and increases by 2.5% in 2016–2017 (Figure 11 and Table S3). The increase is concentrated in June–August, where the negative corrections derived from the other three years overadjust the smaller summer bias in 2016–2017. MAE decreases in all four folds. Across the pooled out-of-fold predictions, RMSE decreases from 1.44 to 1.39 MHz, and MAE decreases from 1.00 to 0.88 MHz. The pooled MBE changes from -0.17 to -0.35 MHz.

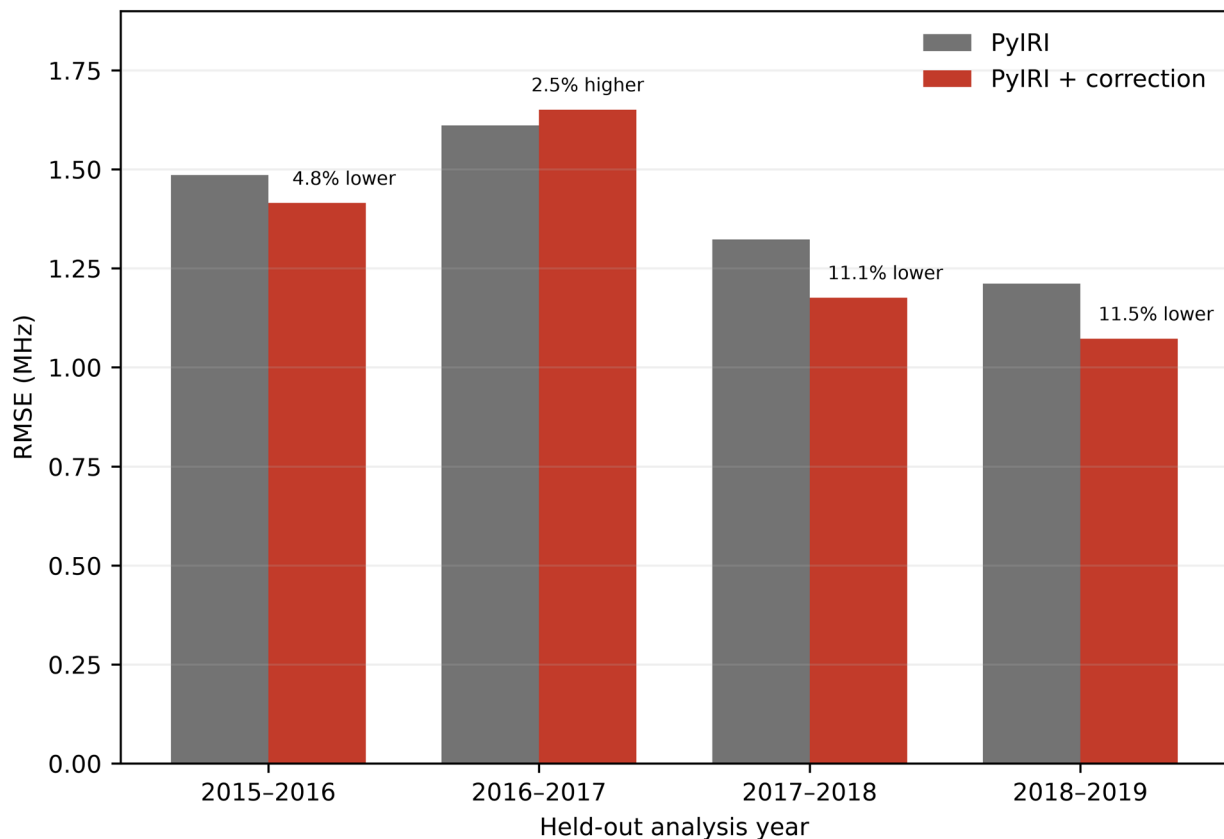


Figure 11. RMSE before and after bin-wise correction in the four leave-one-analysis-year-out validation folds. Percent labels show the relative RMSE change after correction.

5. Discussion

5.1. Es Climatology and the Wind-Shear Framework

The Es climatology at Ganzi shows the summer-daytime maximum commonly observed at middle latitudes. In the wind-shear mechanism, vertical neutral-wind shears act through ion-neutral collisions in the geomagnetic field to converge long-lived metallic ions into thin layers [3,4]. The seasonal organization of these shears by atmospheric tides provides a framework for interpreting this pattern [5,6]. Within the generalized wind-shear framework, background electric fields may further modify vertical ion drift and convergence [2]. Although occurrence and intensity share broadly similar seasonal behavior, they are not interchangeable quantities. Their differences may reflect the combined influence of layer formation efficiency and the available metallic-ion reservoir, but these factors cannot be separated from the present dataset. The diurnal hpEs pattern resembles the downward phase progression reported for tidal E-region structures [2,3]. However, hpEs is a virtual height affected by group retardation. The apparent rate of 1.2–2.2 km/h therefore does not measure the physical downward velocity of the layer. Without co-located neutral-wind measurements, the tidal wind-shear interpretation cannot be tested directly at Ganzi.

5.2. Comparison with Other Chinese-Sector Stations

Placed against published ionosonde results from the Chinese sector (station locations in Figure 1), the Ganzi climatology shares the summer-daytime maximum in Es occurrence and intensity reported across the mid-latitude chain stations Mohe (53.50° N, 122.37° E), Beijing (40.25° N, 116.25° E), and Wuhan (30.53° N, 114.61° E) [6,10,12]. At the low-latitude reference station Hainan (19.52° N, 109.13° E), Es behavior belongs to a different regime with higher occurrence at low layer altitudes [12]. The Ganzi layers appear comparatively weak in the present dataset, as indicated by the median foEs of 3.35 MHz and an occurrence rate of only 2.1% for foEs $\geq$ 7 MHz. Because the published studies use different occurrence definitions and intensity metrics, the comparison remains qualitative [5].

Zhangye (39.21° N, 100.54° E) is the closest comparison because it lies at nearly the same longitude as Ganzi and on the northeastern edge of the Tibetan Plateau. The Zhangye–Beijing study reported broadly similar diurnal and seasonal patterns but identified a winter maximum in daily mean foEs at Zhangye [11]. The pooled Ganzi climatology does not show a comparable maximum. Zhangye is 8.04° farther north, and the two studies cover different observation periods. The Ganzi record extends from September 2015 to August 2019, while the Zhangye study used observations from 2018. Differences in latitude, observing period, ionosonde system, scaling procedure, and data coverage may contribute to the contrasting seasonal patterns.

Plateau orography, elevated surface heating, deep convection, and tropospheric upward motion can provide source conditions for gravity waves. Using coordinated OH airglow, meteor-radar wind, and satellite observations, Li et al. [20] reported gravity-wave momentum fluxes of $11.6 \pm 5.2 \text{ m}^2 \text{ s}^{-2}$ in winter and $7.5 \pm 3.1 \text{ m}^2 \text{ s}^{-2}$ in summer over the southeastern Tibetan Plateau. More recently, Liu et al. [21] found that daytime gravity waves and Es were both frequent over the eastern Tibetan Plateau in summer. Nearly 60% of the Es events in their regional statistics coincided with locally strong gravity-wave activity. These observations provide quantitative regional context for a possible role of gravity waves in Es variability. During upward propagation, gravity-wave filtering, dissipation, and momentum deposition may modify the amplitude and phase of thermal tides. The resulting changes in E-region wind shear may shift, strengthen, or weaken the convergence levels at which metallic ions accumulate. However, the larger winter gravity-wave momentum flux reported by Li et al. [20] does not by itself imply a winter foEs maximum. The Es seasonal pattern also depends on latitude-dependent tidal wind shear and metallic-ion availability. Their combined effects may help explain why the winter maximum reported at Zhangye is absent at Ganzi.

5.3. Regional Performance of the PyIRI foEs Specification

The structured seasonal bias of the PyIRI foEs specification, with summer overestimation and winter underestimation, is the central result of conditional foEs-intensity assessment. One possible explanation is that the underlying Leftin et al. maps [15], compiled from the 1960s ionosonde network, are under-constrained in this sector. The fitted maps would then capture the annual-mean level better than the amplitude of the seasonal cycle. A regional adjustment should therefore target the seasonal amplitude. The bin-wise correction of Section 4.6 lowers the pooled out-of-fold RMSE and MAE. RMSE does not improve in every held-out year, and the pooled MBE becomes more negative. The correction therefore captures part of the repeatable seasonal structure but is not uniformly effective across years. The procedure itself needs only paired soundings and model values and can be applied at other stations in under-sampled sectors. The reported error statistics and correction results therefore describe PyIRI foEs intensity conditional on observed Es occurrence.

5.4. Interpretation Limits and Temporal Coverage

Because the Es parameters were autoscaled, the absolute occurrence rates and the magnitude of the PyIRI bias carry an additional scaling uncertainty. For foEs, a year-long comparison at Mohe found ARTIST scaling to agree with manual scaling at a correlation of 0.98, with misidentification rates of 2% or less [6]. A recent assessment of PyIRI and E-PROBED E-region predictions against Digisonde observations found that automatically scaled layer heights differ systematically from manually scaled ones [19]. For the corresponding virtual-height parameter h'Es, Enell et al. [22] reported a manual-minus-automatic difference of -6.0 ± 8.3 km, with a median of -3.7 km, based on 507 paired values. These Autoscala results from a high-latitude station provide an approximate reference for uncertainty in the ARTIST-derived hpEs at Ganzi.

The location of Ganzi on the eastern Tibetan Plateau provides regional context, but without co-located neutral-wind, temperature, gravity-wave, or metallic-ion measurements, the present dataset does not allow a physical attribution of the observed Es behavior to plateau-related forcing. Multi-instrument follow-up campaigns combining ionosonde, meteor radar, and metallic-ion observations would be required to test plateau-forcing hypotheses.

Figure S1 and Table S1 show pronounced interannual variability in June. The June occurrence rates were 83.9%, 92.3%, 67.5%, and 39.1% across the four analysis years. The corresponding median foEs values were 4.25, 5.05, 4.15, and 4.75 MHz. Neither the annual occurrence rates nor the June differences showed a consistent correspondence with annual F10.7, Kp, or Dst. Internal atmospheric variability and differences in data coverage may also contribute.

The four-year analysis interval lies entirely within the declining phase of solar cycle 24. Median F10.7 declined from 96.3 to 69.1 sfu during this period. Solar activity and time therefore covary in the present record. Long-term Es archives at other mid-latitude stations indicate that Es occurrence and intensity can vary across the solar cycle [23]. The present results characterize this declining phase. A longer record spanning a complete solar cycle is needed.

6. Conclusions

We have presented a four-year climatology of the Es layer at Ganzi on the eastern margin of the Tibetan Plateau. The study covers the declining phase of solar cycle 24 and uses 28,771 automatically scaled top-of-hour Digisonde soundings. We also evaluated the PyIRI empirical foEs specification for Es-present soundings. The main findings are as follows.

First, Es occurs in 53.1% of interpretable soundings, with a pronounced summer-daytime maximum and a late-autumn minimum. Monthly occurrence is about 77% in June and 37% in November. The occurrence rate is strongly definition-dependent, falling to 2.1% for foEs ≥ 7 MHz.

Second, Es intensity is generally modest, with a median foEs of 3.35 MHz. The seasonal-median hpEs shows an apparent descent of 1.2–2.2 km/h from its morning maximum to a midday minimum. Because hpEs is a virtual height, this rate does not represent the physical downward velocity of the layer.

Third, adjusted daytime Es occurrence and foEs vary nonmonotonically among the F10.7 quintiles. The global Kp differences are not significant for either outcome. The Dst groups do not differ significantly in Es occurrence, while a higher adjusted mean foEs is found for Dst ≤ -50 nT than for Dst > -20 nT. June occurrence varied from 39.1% to 92.3% across the four analysis years, without a consistent relationship with annual F10.7, Kp, or

Dst. Because the record covers only the declining phase of solar cycle 24, a longer dataset is needed to assess the full solar-cycle response.

Fourth, PyIRI gives an overall bias of -0.17 MHz for the Es-present samples. This near-zero average conceals a structured seasonal error. The model overestimates foEs by about 1–1.5 MHz in the late-spring and summer daytime sectors and underestimates it in winter by typically about 0.5 MHz. Leave-one-analysis-year-out validation reduces the pooled RMSE from 1.44 to 1.39 MHz and the pooled MAE from 1.00 to 0.88 MHz. RMSE improves in three of the four held-out years. These results characterize PyIRI foEs intensity for Es-present soundings.

The results provide a multi-year observational constraint on Es behavior over a sparsely sampled sector of the eastern Tibetan Plateau, together with an independent station-level test of the PyIRI foEs specification. They further indicate that a regional adjustment of the empirical foEs maps in this sector should focus on the seasonal bias.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/atmos17090877/s1>, Figure S1: Interannual climatology of Es at Ganzi for four September-to-August analysis years. Months are arranged chronologically from September to August. Panel (a) shows the monthly Es occurrence rate and the number of interpretable soundings. Panel (b) shows the monthly median foEs for Es-present soundings. Table S1: Annual data coverage, Es occurrence, median foEs, solar activity, geomagnetic activity, and June-specific Es statistics. Each analysis year extends from September to the following August. Table S2: Adjusted Es occurrence and foEs across F10.7, Kp, and Dst categories during LST 06–20. Table S3: Leave-one-analysis-year-out validation of the month–LST bin-wise foEs correction.

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Abbreviations

Abbreviation	Definition
ARTIST	Automatic Real-Time Ionogram Scaler with True Height
BJT	Beijing Time
CCIR	International Radio Consultative Committee
DPS-4S	Digisonde Portable Sounder 4S

Dst	Disturbance Storm Time Index
E-PROBED	E-Region Prompt Radio Occultation Based Electron Density
Es	Sporadic E
F10.7	10.7 cm Solar Radio Flux
fbEs	Blanketing Frequency of the Es Layer
fmin	Minimum Frequency of Ionogram Echoes
fminEs	Minimum Reflection Frequency from the Es Trace
foEs	Critical Frequency of the Es Layer
foF2	Critical Frequency of the F2 Layer
GNSS	Global Navigation Satellite System
hpEs	Virtual Height of the Es Trace's Leading Edge
IRI	International Reference Ionosphere
Kp	Planetary Geomagnetic Activity Index
LST	Local Solar Time
MAE	Mean Absolute Error
MAM, JJA, SON, DJF	March–May, June–August, September–November, and December–February
MBE	Mean Bias Error
NASA	National Aeronautics and Space Administration
OH	Hydroxyl
OLS	Ordinary Least Squares
OMNI	Multisource Space-Physics Data Set
OMNIWeb	Web Interface for the OMNI Data Set
PyIRI	Python Implementation of IRI
RMSE	Root-Mean-Square Error
SAO	Standard Archiving Output
sfu	Solar Flux Unit
UT	Coordinated Universal Time

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