



1 Tracking Ionospheric Changes during Solar Eclipses: Concepción

2 Historical Data

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9 **Abstract.** Solar eclipses offer a unique natural experiment to probe ionospheric responses to sudden reductions in solar
10 radiation. This study examines the Concepción (36.79°S, 73.03°W/Chillán (36.64°S, 71.99°W) ionosphere during 16
11 selected eclipses, out of 21 identified events between 1958 and 2024, using a historical ionogram dataset spanning several
12 decades. Critical frequencies (foE, foF1, foF2) and virtual heights (h'E, h'F1, h'F2/F) were extracted from digitized and
13 scaled ionograms to quantify eclipse-induced perturbations. Diurnal variations show typical dips in the E- and F1-layer
14 critical frequencies, while F2-layer responses are more complex and variable. Regression analysis was performed
15 exclusively on critical frequencies, revealing a nearly linear decrease of foE with increasing solar obscuration, whereas
16 virtual heights exhibited inconsistent behavior due to neutral winds, plasma transport, and other dynamical processes.
17 High-cadence observations, available for select events, provided further insight into short-term ionospheric variability. Only
18 the 2 July 2019 and 14 December 2020 eclipse responses were previously published. The study highlights the rescue and
19 standardization of historical ionograms, many originally on fragile or hazardous 35 mm film, emphasizing the scientific
20 value of long-term datasets. Predictions for the 06 February 2027 eclipse indicate an expected foE decrease of ~0.7 MHz at
21 Chillán, offering a timely opportunity to validate the regression models and assess predictive skill across solar cycle
22 conditions.

23 1 Introduction

24 Solar eclipses offer unique opportunities to understand how the ionosphere reacts when solar radiation is interrupted during
25 daylight conditions. A "small night" generated by a total solar eclipse produces disturbances in the ionosphere, both directly
26 by the suppression of incident radiation or induced by chemical and transport processes. As solar radiation decreases, the
27 electron concentration of the ionospheric layers E and F1, which mainly depend on the production and loss terms, decrease
28 considerably or even disappear throughout the eclipse. Other layers, such as the F2 layer, for which the electron



concentration depends significantly on plasma transport by neutral winds and electrodynamics, react with delays and are difficult to predict (Le et al., 2009; Hoque et al., 2016; Zhang et al., 2024). Furthermore, the ionosphere's response depends on regional conditions and external factors such as space weather and lower atmospheric coupling. Additionally, changes in the virtual and real heights of ionospheric layers, such as h'F1, h'F2/F, and hmF2, have been frequently reported, generally showing an upward motion followed by a post-maximum descent as the ionosphere recovers (Le et al., 2008; Chuo, 2013 ; Zhang et al., 2024).

Historically, from 1920 onward, studies of solar eclipses have progressively revealed how reduced solar radiation affects the ionosphere (Ratcliffe, 1956). Early radio observations established solar radiation as the main ionization source and highlighted layer-specific density and plasma transport effects. From 1960–2015, hundreds of studies based on observations with instruments such as VLF receivers, GNSS arrays, ionosondes, riometers, incoherent scatter radars and Doppler systems have determined eclipse-induced variations in TEC, foF2, hmF2, electron temperature, and ion velocities, etc. These studies have consistently shown that during eclipses there are delayed responses, latitude-dependent effects, and evidence of acoustic gravity waves (AGW) and traveling ionospheric disturbances. Major events like the 2017 Great American Eclipse provided unprecedented high-resolution data, allowing detailed modeling and confirmation of earlier findings, while recent studies emphasize the role of geomagnetic activity and AGW generation in modulating post-eclipse ionospheric dynamics. A detailed review of these studies is compiled in Appendix A of Bravo et al. (2020).

Early days determination of ionospheric responses during solar eclipses was made mainly from ionosonde (vertically incidence HF radar) observations. There are long time series of these observations, allowing the study of ionospheric long-term trends. Early works are, for example, those of Smith and King, 1981; Bremer, 1992; Ortiz de Adler et al., 1997; Jarvis et al., 1998; Foppiano et al., 1999. Later work has been reviewed by Lastovicka et al. (2017, and references within) and recent progress reported by Lastovicka (2023). One of these long-term series also offers a unique dataset to analyze both short-term eclipse-induced ionospheric variations and broader temporal trends in the South American sector (Bravo et al., 2020).

The purpose of this work is to characterize the response of the Concepción (36.79°S, 73.03°W) ionosphere under solar eclipse conditions over several solar cycles, so that its response can be associated with parameters such as the amount of darkness, season, time of day, etc., in order to predict the response for future eclipses.

2 Methodology

2.1 Eclipse Event Selection and Station Characteristics

A comprehensive search was conducted to identify all solar eclipse events whose trajectory passed over the ionospheric observation stations in central Chile during the period 1957–2024.



Ionospheric characteristics during these events were selected from the long series of ionosonde records (ionogram) of ionospheric station j3o: Concepción (36.79°S, 73.03°W). The Concepción ionosonde was a C4 type (1-25 MHz range) and associated antennae (crossed deltas), installed in 1957 at the Universidad de Concepción, Andalien campus, by personnel from the National Bureau of Standards (NBS, USA) for the International Geophysical Year (Ramírez, 1963). Later, the ionosonde was moved to the nearby Bellavista campus (less than 2 km), the sweep range modified (0.25-20 MHz) and the antennae improved to make better use of the quiet electromagnetic environment (adjustable folded dipole 0.25 to 3 MHz and log-periodic 3 to 20 MHz). Maintenance difficulties of the antennae lead to a change during 1975 (cross deltas again). The C4 ionosonde operated till 1994 with a transmitted power of approximately 1–5 kW, and employed simple pulse transmissions without signal coding. Ionograms were recorded on 35 mm film. The interpretation and scaling required optical projection on a screen and visual determination of parameters using a manual overlay. The j3o station resumed operation in 1999. An IPS 42 type ionosonde (1- 22 MHz) was installed using the existing antennae. Recording was changed from photographic to digital and routine observations were made until 2012, when it was relocated approximately 100 km northeast to Chillán (36.64°S, 71.99°W), renamed as j3p, as part of an instrumentation modernization program (Ovalle et al., 2017). For a short time interval a Canadian Advanced Digital Ionosonde (CADI) was also used. The ionosondes were operated by dedicated academics, supported by electronic engineers and technicians (Muzzioli, 1977; Bravo et al., 2011), providing continuous and high-quality measurements of ionospheric parameters (critical frequencies, virtual heights, etc.). The ionosonde and antennae changes do not preclude standard accuracy of critical frequencies and virtual heights since these parameters are not very system gain sensitive. Both locations share similar geomagnetic latitude characteristics, enabling the construction of a long-term ionospheric database representative of the mid-latitude South American sector.

From the initial catalog of eclipse events identified, we selected those with solar obscuration exceeding 15% as observed from the station coordinates (21 events). This threshold was established to ensure detectable ionospheric perturbations while maintaining sufficient statistical samples for comparative analysis. The selected events span various phases of the solar cycle and include eclipses with obscuration levels ranging from partial to near-totality, providing a diverse dataset for investigating the relationship between eclipse magnitude and ionospheric response.

2.2 Historical Ionogram Database

The ionospheric observations analyzed in this study comprise a unique historical archive of vertical incidence ionograms recorded between 1958 and 2024. The sounding cadence varied throughout the operational period, with temporal resolutions of 1 hour, 30 minutes, 15 minutes, 5 minutes and 1 minute, depending on the scientific objectives and operational constraints of each campaign period. Higher-cadence observations (1–5 minute intervals) were typically implemented during special events, including eclipse campaigns and geomagnetic storm monitoring periods.



The archival records consist primarily of 35 mm photographic film containing ionogram traces acquired by the C4 ionosonde (1957–1994, the IPS-42 system delivered digital ionograms during an intermediate period (1999–2012), the CADI for a few days only, and the IPS 42 after that. A substantial portion of this historical dataset had not been previously interpreted and scaled or had undergone only partial manual scaling, representing a significant untapped scientific resource for long-term ionospheric studies.

2.3 Data Processing Pipeline

2.3.1 Digitization: SOCIO Software

Ionograms preserved on celluloid film were digitized using an Epson Perfection V600 Photo scanner at 1200 dpi resolution to ensure adequate capture of trace details and frequency-height grid specifications. The digitized images required geometric correction due to perspective distortion, film degradation, and variations in original recording formats across different ionosonde systems.

To address these challenges, we developed the Software de Corrección de Ionogramas (SoCio), a MATLAB-based tool specifically designed for the geometric correction and standardization of historical ionogram imagery. SoCio performs automated detection of the frequency-height grid structure, applies perspective correction algorithms to compensate for scanning distortions, and standardizes image dimensions according to the specific ionosonde system (C4, IPS-42, or CADI) that generated each record. The software includes modules for handling common film deterioration artifacts, including opaque regions, physical damage, and inconsistent image density. This preprocessing step was essential for ensuring accurate subsequent parameter extraction, as uncorrected geometric distortions can introduce systematic errors in frequency and height measurements.

2.3.2 Scaling: DISS Software Enhancement

Following geometric correction, ionospheric parameters were extracted using the Digitized Ionogram Scaling Software (DISS v. 3.0), previously employed in eclipse observation campaigns (Bravo et al., 2020). For the present study, DISS capabilities were substantially enhanced to accommodate the diversity and technical challenges of the historical dataset. Key improvements included: (1) implementation of interactive trace digitization tools enabling manual extraction of frequency-virtual height coordinates from user-drawn traces on the ionogram display, (2) development of selectable region-of-interest functionality to isolate specific ionospheric layers for detailed analysis, (3) incorporation of adjustable frequency and height calibration parameters to fine-tune the pixel-to-physical-unit conversion for each ionogram variant, and (4) integration of quality control modules to identify and flag problematic traces requiring manual review.

These enhancements enabled DISS to handle the heterogeneous characteristics of multi-decade ionosonde observations, including variations in frequency sweep ranges (typically 1–20 MHz with system-dependent upper limits), height display



scales (100–500 km, later extended to 1000 km for topside observations), and trace characteristics influenced by film aging and storage conditions.

2.3.3 Parameter Extraction

From each scaled ionogram, we extracted the following standard ionospheric parameters: critical frequencies of the E, F1, and F2 layers (f_oE , f_oF1 , f_oF2) and their corresponding virtual heights ($h'E$, $h'F1$, $h'F2/F$).

2.4 Statistical Analysis and Eclipse Response Quantification

Eclipse-induced ionospheric perturbations were quantified by calculating both absolute and percentage deviations of critical frequencies relative to reference day median values at corresponding local times. Absolute deviations were computed as:

$$\Delta f_oL = f_oL_{eclipse} - f_oL_{reference}$$

where L represents the ionospheric layer (E, F1, F2). Percentage deviations were calculated as:

$$\% \Delta f_oL = \frac{f_oL_{eclipse} - f_oL_{reference}}{f_oL_{reference}} \times 100$$

Reference day values were obtained from monthly median parameters of each eclipse event, selecting the median value across multiple reference days to minimize day-to-day ionospheric variability. When multiple measurements were available during the eclipse period (depending on the operational cadence: 1, 5, 15, 30, or 60 minutes), we selected the observation closest to the time of maximum obscuration for regression analysis.

Linear regression analysis was performed using NumPy's polyfit function (NumPy v1.24.0) to investigate the functional relationship between solar obscuration percentage (independent variable, x) and ionospheric parameter deviations (dependent variable, y). The regression model adopted was:

$$y = mx + b$$

where m represents the sensitivity of the ionospheric parameter to eclipse magnitude (slope) and b the intercept. The goodness of fit was assessed using the coefficient of determination (r^2), computed as:

$$r^2 = 1 - \frac{\sum_{i=1}^n (y_i - \hat{y}_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$



where y_i are observed values, $\hat{y}_i$ are predicted values from the regression line, and $\bar{y}$ is the mean of observed values. r^2 quantifies the proportion of variance in ionospheric response explained by solar obscuration, with values ranging from 0 (no explanatory power) to 1 (perfect prediction).

From the initial catalog of 21 eclipse events identified over the period 1957–2024 (see Table 1), we selected events exhibiting clear ionospheric signatures and sufficient data coverage during the eclipse period. Both absolute (MHz) and percentage (%) deviations were analyzed to assess whether normalization by baseline values improved the linearity of the eclipse response. The heterogeneous nature of the dataset—comprising observations from three different ionosonde systems (C4, IPS-42, CADI) with varying temporal resolutions—introduces additional variability that may affect correlation strength, particularly for parameters sensitive to instrumental characteristics.

Table 1: Timing of selected solar eclipses over Concepción/Chillán (Maximum darkness >15%) from 1958 to 2030, including start, maximum, and end times, according to Eclipse Calculator 2.0 (Masana, 2012).

#	Date (DD-MM-YYYY)	Start time in Concepción (hh:mm UT)	Maximum time in Concepción (hh:mm UT)	End time in Concepción (hh:mm UT)	Maximum darkness in Concepción/ Chillán (%)	Ionospheric Station: j3o, Concepción; j3p, Chillán	Eclipse-time sampling interval
1	12-10-1958	21:32	22:31	23:01	95	j3o: C4, cross deltas, 1-25 MHz	5 min film
2	25-01-1963	11:02	12:04	13:14	73	j3o: C4, cross deltas, 1-25 MHz	1 hour film
3	12-11-1966	12:46	13:51	15:00	49	j3o: C4, folded dipole + logperiodic, 0.25-20 MHz	5 min film
4	11-09-1969	21:03	21:53	22:35	20	j3o: C4, folded dipole + logperiodic, 0.25-20 MHz	30 min film
5	04-01-1973	13:14	14:50	16:39	78	j3o: C4, folded dipole + logperiodic, 0.25-20 MHz	5 min film
6	03-11-1975	11:22	12:06	12:52	19	j3o	Instrument failure
7	22-08-1979	16:35	18:04	19:27	31	j3o: C4, cross deltas, 0.25-20 MHz	30 min film
8	10-08-1980	19:47	20:51	21:49	27	j3o: C4, cross deltas, 0.25-20 MHz	No data
9	04-02-1981	22:25	23:18	23:56	43	j3o: C4, cross deltas, 0.25-20 MHz	1 hour film
10	12-11-1985	12:36	13:20	14:06	17	j3o: C4, cross deltas, 0.25-20 MHz	1 hour film
11	29-03-1987	11:07	11:07	12:01	58	j3o: C4, cross deltas,	1 hour

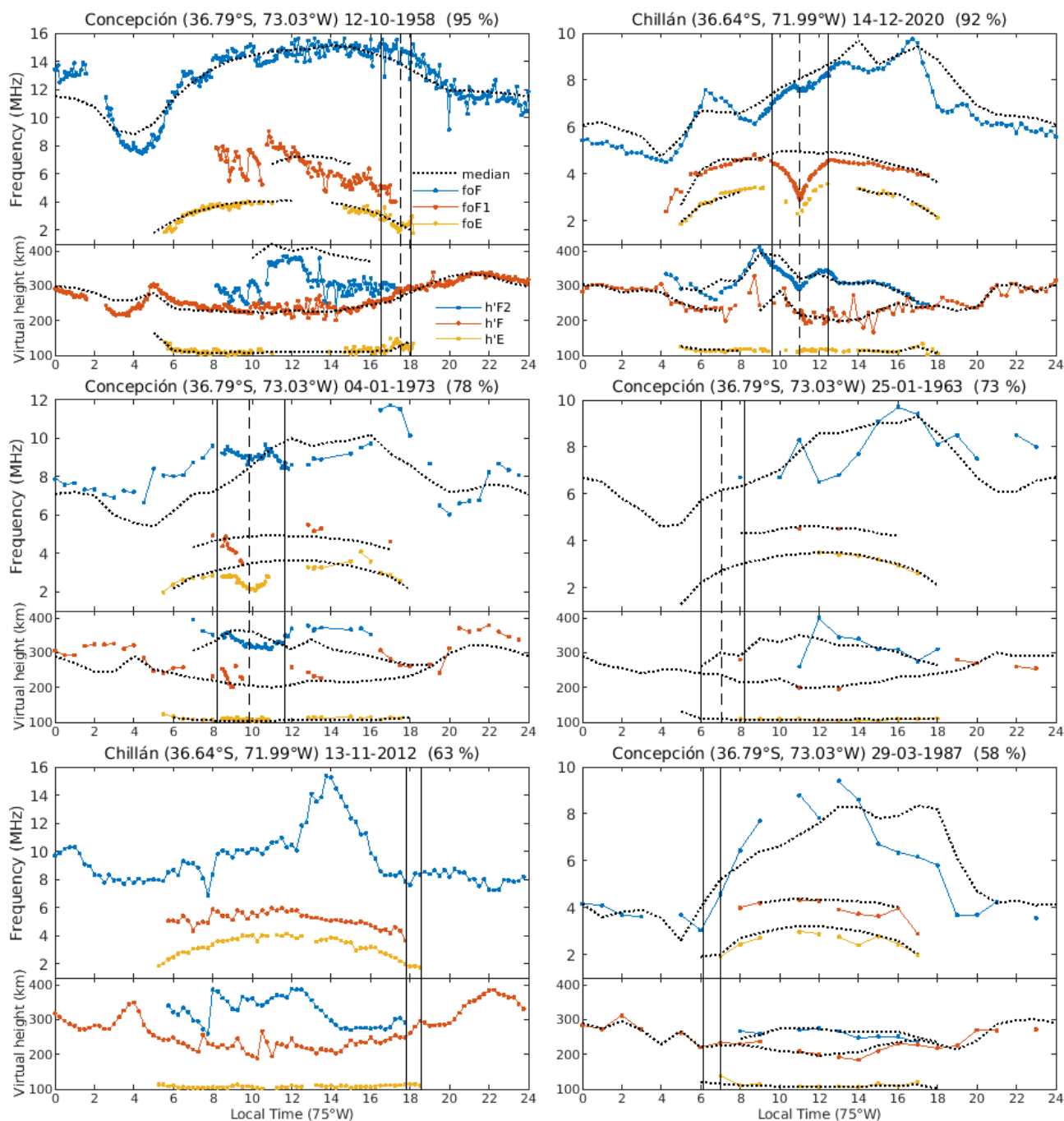


						0.25-20 MHz	film
12	26-01-1990	19:30	20:28	21:22	23	j3o: C4, cross deltas, 0.25-20 MHz	1 hour film
13	03-11-1994	11:49	12:45	13:46	45	j3o: C4, cross deltas, 0.25-20 MHz	1 hour film
14	11-09-2007	11:03	11:46	12:55	49	j3o: IPS 42, cross deltas, 1-22 MHz	15 min digital
15	11-07-2010	19:54	20:58	21:47	62	j3o: IPS 42, cross deltas, 1-22 MHz	No data
16	13-11-2012	22:48	23:34	23:34	63	j3p: IPS 42, cross deltas, 1-22 MHz	15 min digital
17	26-02-2017	12:18	13:30	14:51	67	j3p	Instrument failure
18	02-07-2019	19:16	20:31	21:38	81	j3p	Instrument failure
19	14-12-2020	14:36	16:00	17:28	92	j3p: IPS 42, cross deltas, 1-22 MHz	1 min digital
20	30-04-2022	20:21	21:30	22:03	34	j3p: IPS 42, cross deltas, 1-22 MHz	15 min digital
21	02-10-2024	18:56	20:24	21:42	55	j3p: IPS 42, cross deltas, 1-22 MHz	15 min digital
22	06-02-2027	13:21	14:56	16:39	70	j3p: IPS 42, cross deltas, 1-22 MHz	-

Using the established regression relationships, we computed predicted ionospheric responses for the upcoming 06 February 2027 solar eclipse, during which Chillán is expected to experience approximately 70% solar obscuration (last row of Table 1). These predictions are indicated by orange star markers in all regression plots, providing quantitative forecasts to support observation campaign planning.

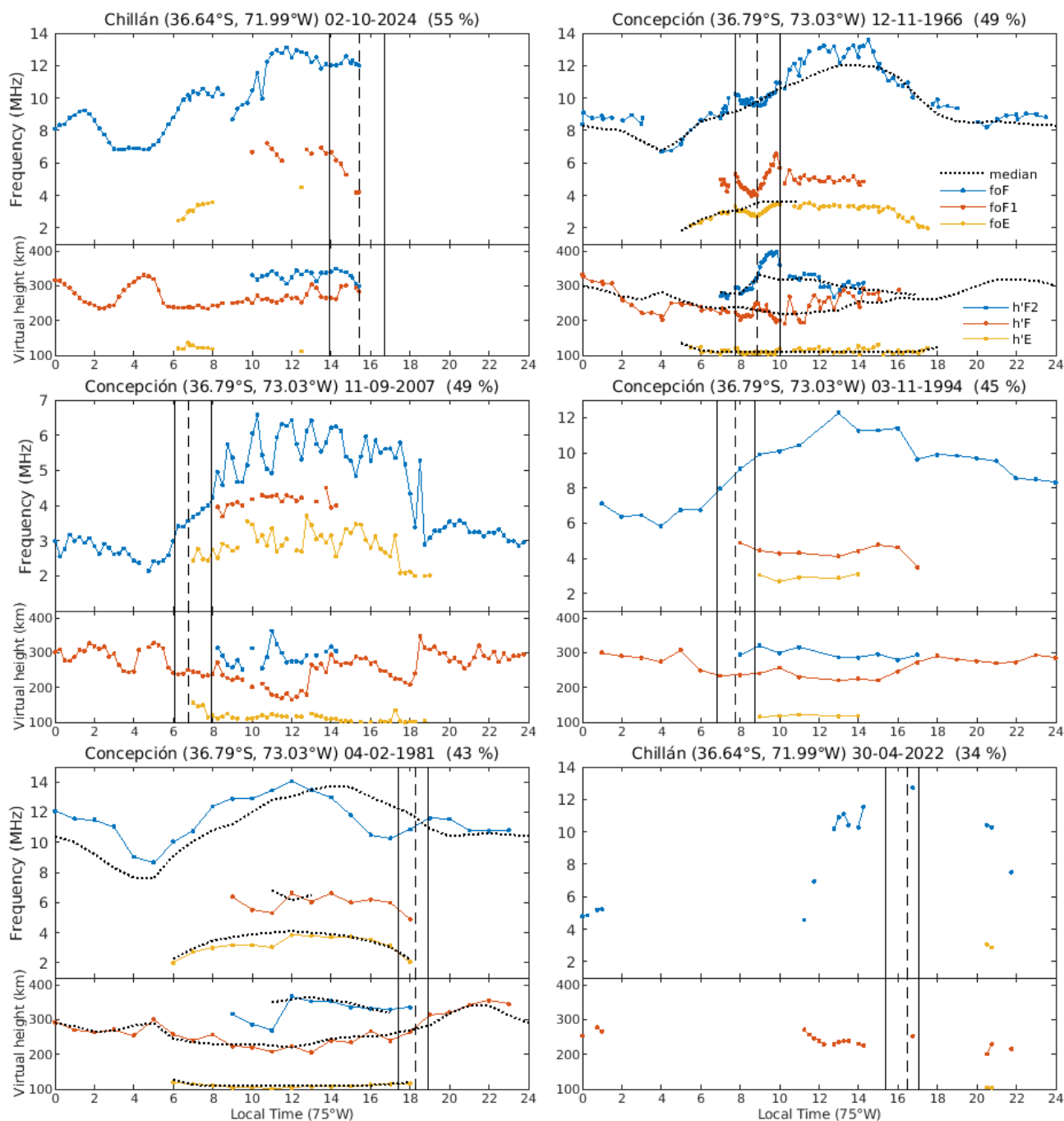
3 Results and Discussion

The diurnal variations of critical frequencies and virtual heights observed during the days in which the 16 selected eclipses occur are shown in Figures 1 to 3. Diurnal variations of monthly mean values are also shown as reference. As already indicated, observed values are given at different time intervals as appropriate to the available ionograms for the different eclipses. The diurnal variations are arranged according to the darkness level, regardless of the time-of-day, month, year or solar activity epoch.



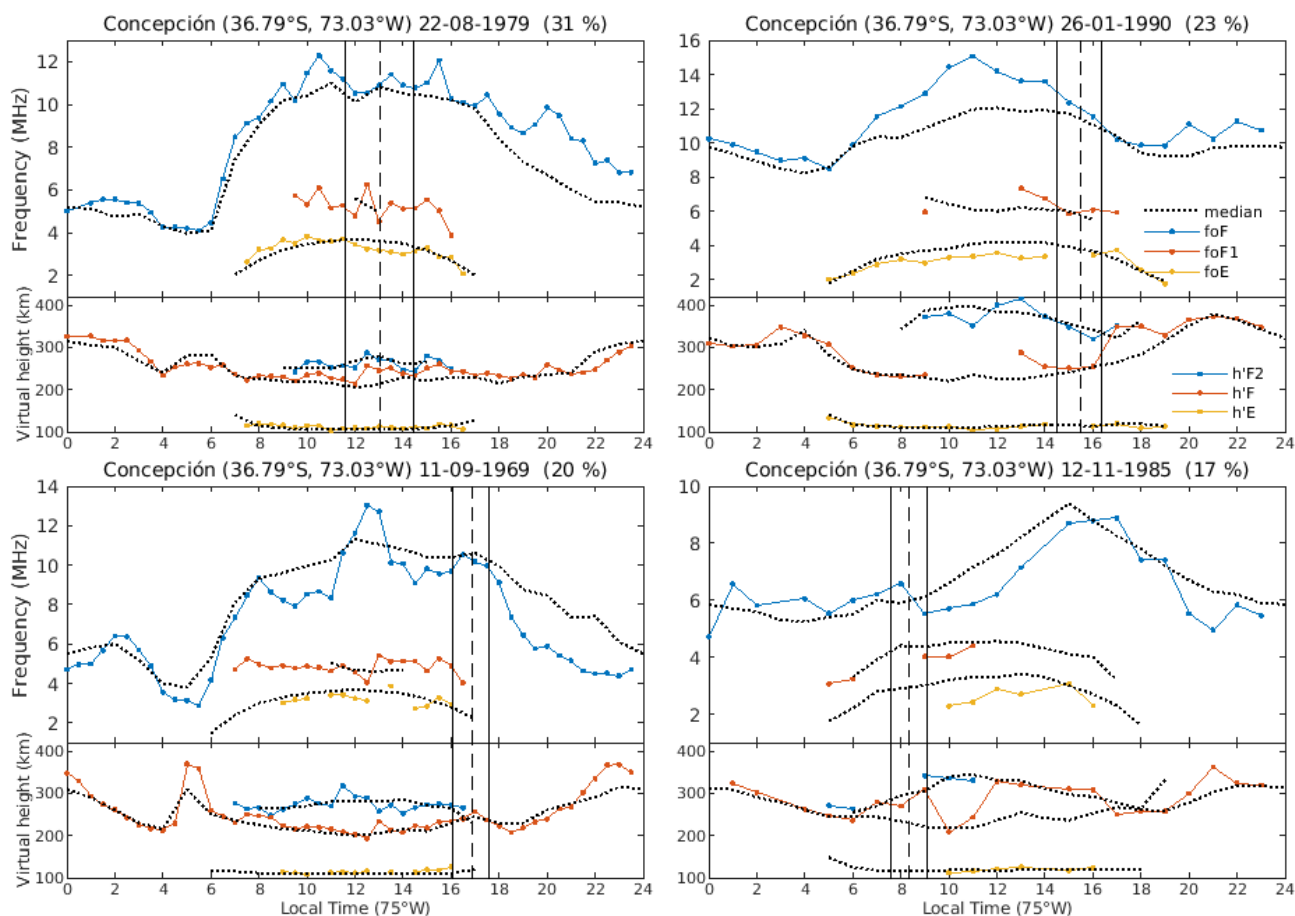
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164 Figure 1: Diurnal variation of observed critical frequencies and virtual height (dots) on days of various solar eclipses with
 165 darkness level > 55%, and of corresponding monthly median values (dotted line). Continuous vertical line indicates onset and end
 166 of eclipse. Slashline indicates the time of maximum darkness.



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168 **Figure 2:** As of Figure 1 but for darkness level between 34 % and 55 %.



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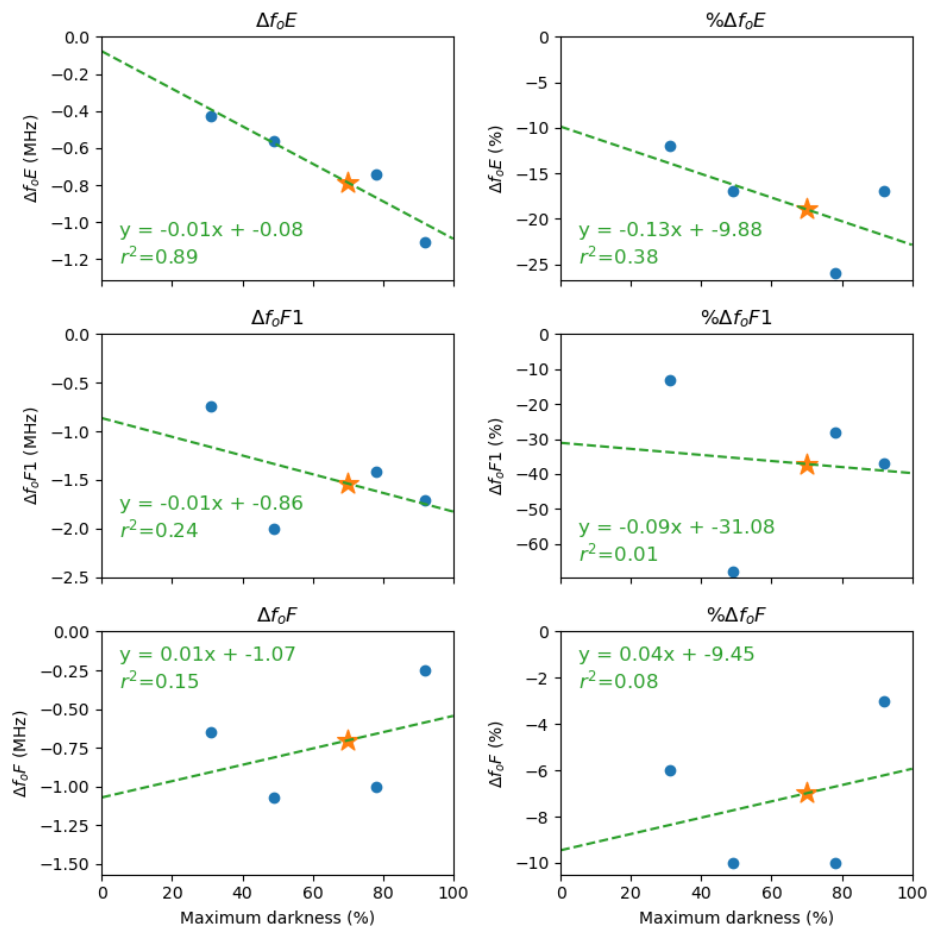
170 Figure 3: Same as Figure 1, but for darkness level between 17 % and 31 %.

171 As it is obvious, the clearer ionospheric effects of eclipses are seen during eclipses occurring just before or around local
172 noon. The maximum level of darkness ranges from 31% to 92% for these eclipses, thus allowing to determine a fairly
173 dependence of ionospheric effects on darkness level. The critical frequencies of the F1 and E layers show a typical dip
174 variation during the eclipses. While the critical frequency of the F2 layer has more complex variations, probably showing
175 two different stages, before and after the maximum darkness level, somehow following the variations of h'F2/F. The E layer
176 virtual height does not seem to significantly change during these eclipses.

177 It should be noted that the reference curves (dotted lines representing the monthly median hourly values) are shown only for
178 some eclipse events, corresponding to the months for which full-month ionograms had previously been scaled for the World
179 Data Center and for the 2020 eclipse event. For the other cases, reference values for the remaining days of the month were
180 not available.



We selected four events exhibiting clear ionospheric signatures and sufficient data coverage during the eclipse period for the regression analysis (Figure 4). The remaining 16 events were not considered due to one or more of the following limitations: (1) missing observations during critical eclipse phases (particularly around maximum obscuration), (2) eclipse occurrence near sunrise or sunset when ionospheric conditions are rapidly changing, making it difficult to isolate eclipse effects from diurnal variations, (3) severe film degradation preventing reliable parameter extraction despite multiple scaling attempts, or (4) obscuration levels below the detection threshold for significant ionospheric perturbations. It should be noted that the regression analysis was performed only on critical frequencies and not on virtual heights. Changes in virtual heights ($h'E$, $h'F1$, $h'F2/F$) were observed to be inconsistent—sometimes increasing, sometimes decreasing—making prediction difficult. These variations are likely influenced by additional factors such as neutral winds, plasma transport, and other dynamical processes, which complicate their response to eclipse conditions.



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Figure 4: Linear regression analysis of ionospheric parameter deviations versus solar obscuration percentage during four eclipse events (1957–2024, blue circles). Left column: absolute frequency deviations (MHz). Right column: percentage deviations (%). Green dashed lines represent least-squares linear fits with equations and r^2 values shown. Orange stars indicate predicted responses for the 06 February 2027 eclipse (70% obscuration at Chillán).



The E-layer critical frequency (foE) exhibited a robust linear response to solar obscuration, with absolute deviations showing the strongest correlation among all analyzed parameters ($r^2 = 0.89$, $n = 4$ events, Figure 4, upper left panel). The regression yielded a slope -0.01 of MHz per percent obscuration and an intercept of -0.08 MHz, indicating that foE decreases nearly proportionally to eclipse magnitude. This relationship implies that a hypothetical total eclipse (100% obscuration) would reduce foE by approximately 1.0 MHz relative to unperturbed reference conditions.

The high predictive power ($r^2 = 0.89$) reflects the rapid photochemical equilibrium characteristic of the E-region, where recombination timescales (20–40 minutes) are comparable to or shorter than typical eclipse durations. Consequently, E-layer ionization density responds almost instantaneously to variations in solar EUV flux, with minimal influence from dynamic processes such as neutral winds or plasma diffusion that complicate interpretation of higher-altitude layers.

When expressed as percentage deviations ($\% \Delta \text{foE}$, Figure 4, upper right panel), the correlation weakened substantially ($r^2 = 0.38$), with a regression slope of -0.13 % obscuration. This degradation reflects the additional variability introduced by diurnal, seasonal, and solar cycle variations in baseline foE values, which range from ~ 2 MHz during solar minimum to >4 MHz during solar maximum. A fixed absolute reduction (e.g., 0.7 MHz) thus translates to percentage deviations spanning 17–35% depending on background conditions, increasing scatter in the normalized representation.

Based on the established relationship, the 06 February 2027 eclipse (70% obscuration at Chillán) is predicted to induce a foE reduction of 0.7 MHz (orange star, Figure 4). This forecast will enable direct validation of the regression model and assessment of its predictive skill across different solar cycle phases.

Several campaigns were conducted historically to obtain ionograms at higher temporal resolution during eclipses, with observations every 5 minutes for significant events. However, most of these high-cadence data were never published. For the 2 July 2019 solar eclipse, there was a unique opportunity to measure the ionospheric response at two locations in Chile: Chillán (36.64°S , 71.99°W) and La Serena (29.9°S , 71.3°W). However, the ionosonde in Chillán failed during the event, so only the response at La Serena was published (Bravo et al., 2020). One of the analyzed events corresponds to the 14 December 2020 solar eclipse over Chillán, for which ionospheric responses were also studied by de Haro Barbas et al. (2022). Their results included calculations of the alpha and beta recombination coefficients, which were found to be consistent with values reported by previous authors, confirming the reliability of the ionospheric observations in this region. Inclusive, prior to the 2020 eclipse, a prediction of the ionospheric response over the Chillán station had been performed using the SUPIM-INPE model, estimating the expected variations in the different ionospheric layers during the event (Martínez-Ledesma et al., 2020). This prediction was later validated using the observed ionospheric data, as reported in Bravo et al. (2022), showing good agreement between the modeled and measured responses.



It is important to highlight the dedicated effort of ionosonde operators and technicians, particularly during the 1958–1994 period, who ensured continuous monitoring and undertook the considerable effort of recording frequent ionograms during eclipses.

The present study relied on a historical dataset that represents a significant rescue of scientific heritage. Many records were on obsolete 35 mm film, degraded, or even potentially flammable, and have now been digitized and standardized for analysis. Similar conditions exist at other older ionospheric stations, emphasizing the importance of preserving long-term ionospheric observations and fully exploiting their scientific value.

4 Conclusion

This work analyzed the response of the Concepción/Chillán ionosphere to 16 selected solar eclipses, out of a total of 21 identified events over the period 1958–2024, using a long-term historical ionogram dataset. Critical frequencies and virtual heights were extracted from scaled ionograms, and regression analysis was performed to quantify the relationship between solar obscuration and ionospheric parameter deviations. The study demonstrates that the E-layer responds nearly linearly to eclipse-induced reductions in solar radiation, while higher layers, particularly the F2 layer, exhibit more complex and variable behavior due to additional dynamical processes. High-resolution observations, when available, provided insights into short-term responses and enabled predictions for future eclipses.

Regression analysis focused exclusively on critical frequencies, as virtual heights often exhibited inconsistent behavior, reflecting the influence of neutral winds, plasma transport, and other dynamical factors that complicate their interpretation. It is important to note that only the ionospheric responses measured at Chillán during the 2 July 2019 and 14 December 2020 eclipses were published; no data from the remaining eclipse events have been published. The success of this study relied heavily on the dedication of ionosonde operators and technicians, particularly during the 1958–1994 period, who ensured frequent and reliable observations during solar eclipses. Moreover, this work represents a significant rescue of scientific heritage, digitizing and standardizing records that were previously on fragile or potentially hazardous 35 mm film. Preserving and exploiting these long-term datasets is crucial for advancing the understanding of ionospheric dynamics.

Predictions for the upcoming 06 February 2027 eclipse, with an expected 70% obscuration at Chillán, indicate a foE decrease of approximately 0.7 MHz, providing a clear opportunity to validate the regression models and assess their predictive skill across different solar cycle conditions.



251 Author contributions

252 AYG: writing (original draft preparation) and data curation; MAB: Conceptualization, writing (original draft preparation)
253 and formal analysis; CAC-R: data curation; MRC: data curation; BAU: methodology and data curation; AJF: supervision
254 and validation.

255

256 Competing interests

257 Manuel Bravo is the guest editor of the special issue.

258

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