

Maximum electron concentration and total electron content of the ionosphere over Concepción, Chile, prior to the 27 February 2010 earthquake

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Abstract

Ionospheric variability observed prior to mayor earthquakes has been studied for decades. In particular, in many such studies the identification of ionospheric precursors of large earthquakes has been regarded as a specific goal. This paper analyses the observations of the maximum electron concentration (NmF2) over Concepción (36.8°S; 73.0°W) and of the total electron content (TEC) for an area covering the rupture zone corresponding to the very large Chile earthquake of 27 February 2010. The analyses used here are similar to those published before for many earthquakes in Taiwan, Japan and Russia. Possible NmF2 and TEC precursors are compared with other precursors proposed for the same earthquake using different TEC determinations and satellite observations of electron/ion concentration, energetic particle bursts and electromagnetic emissions. Some possible precursors derived from the various observations are consistent with each other. However, none can be unambiguously associated to the Chilean earthquake.

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1. Introduction

Many attempts have been made to identify a variety of possible precursors of strong earthquakes over the last half century (e.g. Biagi et al., 2012). In the case of ionospheric precursors, some sort of reference for a given ionospheric characteristic is first derived and then an anomaly is calculated for hours to days before the earthquake. The anomaly is analysed to search for an ionospheric precursor (for a review see Pulinets and Boyarchuck, 2004). Possible mechanisms to justify the association between suggested ionospheric precursors and seismic activity have also been put forward for many years (e.g. Pulinets et al., 1998, 2003;

Sorokin et al., 2003; Surkov et al., 2003; Pulinets, 2009; Hayakawa et al., 2010; Oyama et al., 2011; Zolotov et al., 2012). However, the possibility to identify ionospheric precursors is somewhat controversial (e.g. Afraimovich et al., 2004; Liu et al., 2006; Rishbeth, 2006, 2007; Pulinets, 2007; Dautermann et al., 2007; Le et al., 2011; Astafyeva and Heki, 2011; Contadakis et al., 2012). To screen solar, geomagnetic and even tropospheric variability (Afraimovich and Astafyeva, 2008; Mendillo et al., 2002) from the observed ionospheric variability, so as to identify likely precursor ionospheric signatures is a main concern. The determination of ionospheric precursors and the development of techniques to use them would have a very valuable practical use; even if warnings at a very short notice (tens of minutes) could be issued as envisioned by Heki (2011). The purpose of this paper is to show whether some ionospheric precursors identified before are consistent with the ones that could be derived for the 27 February 2010

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Chilean earthquake using similar techniques. The earthquake ($M_w = 8.8$) started at 03:34:14 Civil Time (UTC - 3 or LT + 2), with epicentre at $35^{\circ}54'32''S$, $72^{\circ}43'59''W$, and hypocentre at 35 km depth.

2. Data analysis

Solar and geomagnetic conditions for January and February 2010 are depicted in Fig. 1 (1st panel) in terms of the solar activity index F10.7 and the geomagnetic activity

index Dst, respectively. As it can be seen, solar activity is very low for the whole interval, with 1, 4 January and 29 January–4 February corresponding to minimum F10.7, and 12 January and 8–13 February to maximum F10.7 for the interval. In the same way geomagnetic activity is low most of the interval, particularly during the week before the earthquake. Only around 20/21 January and 15–17 February Dst is below about -30 nT. These prevailing solar and geomagnetic conditions should make it easier than otherwise to identify possible ionospheric precursors.

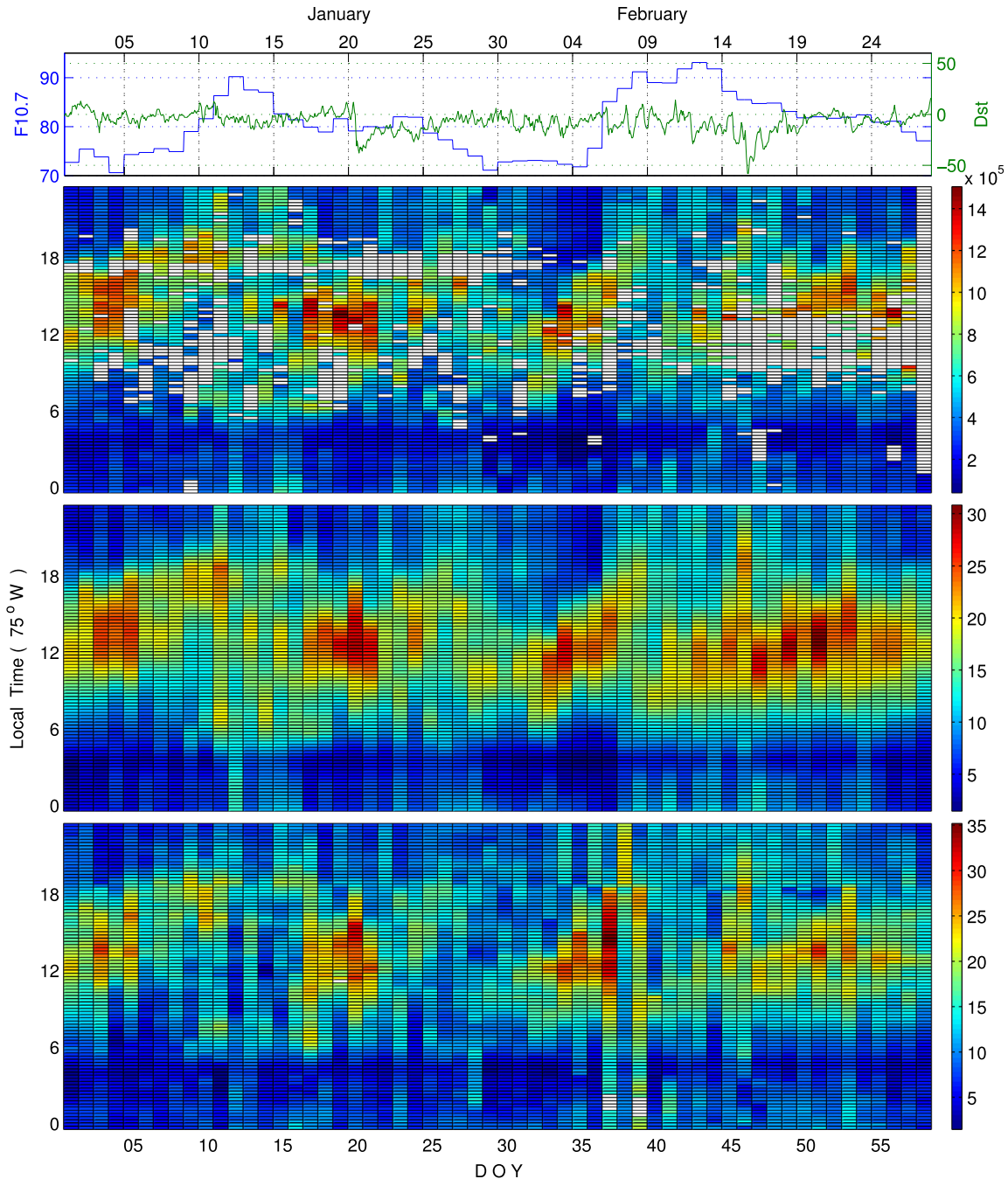


Fig. 1. (top panel) Values of F10.7 [$10^{-22} \text{ W m}^{-2} \text{ Hz}^{-1}$ – blue, left scale] and Dst [nT – green, right scale] for 1 January to 27 February 2010 (DOY 1–58). Values of NmF2 [cm^{-3}] (2nd panel) and TEC [TECU] (3rd panel, regional representation; bottom panel, local CONZ station) for the same interval observed over Concepción ($36.8^{\circ}S$; $73.0^{\circ}W$).

Values of the F-region maximum electron concentration, NmF2, derived from observed F-region critical frequency, foF2, at 15 min intervals over Concepción (36.8°S; 73.0°W), about 100 km from the epicentre are first analysed. Fig. 1 (2nd panel from top) shows these values for January and February 2010 using a colour code. Then values of the total electron content, TEC, derived for Concepción from a regional representation of TEC are considered (<http://cplat.fcaglp.unlp.edu.ar>). An account of this regional representation is given by Brunini et al. (2007) and a detailed discussion of the accuracy of the TEC determination is provided by Brunini and Azpilicueta (2009). The spatial resolution of the model is 1° latitude and 1° longitude. To determine TEC for Concepción, an interpolation is made using TEC values for nearest grid points at latitudes 36.0°S and 37.0°S and longitudes 73.0°W and 74.0°W. Although the TEC representation time-resolution is 1 h, here values have been interpolated at 15 min intervals for easy comparison with NmF2, as shown in Fig. 1 (3rd panel from top) and are denoted TEC RR CON. TEC values were also derived from observations of GPS stations CONT (36°50′34.18″S; 73°01′30.03″W) and CONZ (36°50′37.54″S; 73°01′31.73″W) located within the Concepción area, denoted here TEC CONT and TEC CONZ. GPS data were obtained from the IGSS Network (www.tigo.cl). A TEC calculation programme developed by Boston College, Institute for Scientific

Research, was used. At each station, signals from visible satellites lead to the determination of typically 8–12 TEC values per minute from which a median TEC and count were calculated for each minute. A 15 min running mean of the medians was then computed. Fig. 1 (bottom) shows these running means at 15 min intervals for TEC CONZ.

In some cases spatial analyses of possible precursors are considered as more useful than only local ones (e.g. Afraimovich et al., 2004; Dautermann et al., 2007; Liu et al., 2010; Astafyeva and Heki, 2011; Contadakis et al., 2012). Here TEC is determined from the regional representation (TEC RR) for another 71 locations (a total of 72 including Concepción) to perform this type of spatial analysis. An area (30.0–37.0°S; 67.0–75.0°W) covering the whole ~400 km earthquake rupture zone (Moscoso et al., 2011) is used. An example of TEC for this area corresponding to a few hours of 20 February is given in Fig. 2.

It has also been suggested that spatial analyses for an area away from the earthquake preparation zone should be made so as to have an independent comparison reference (e.g. Astafyeva and Heki, 2011). Here TEC is determined from the same regional representation (<http://cplat.fcaglp.unlp.edu.ar>) for 72 locations covering an area in northern Chile (18.0–25.0°S; 65.0–73.0°W) where a great earthquake is expected due to the long seismic silence

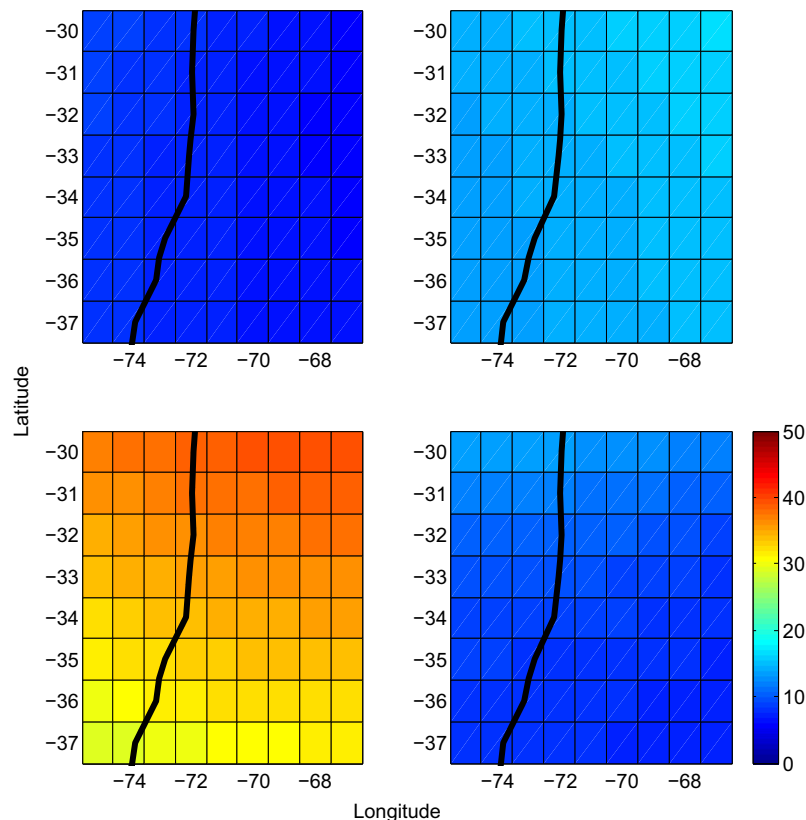


Fig. 2. Values of TEC [TECU] for 72 grid points over an area covering the whole ~400 km earthquake rupture zone (37.0–30.0°S; 67.0–75.0°W) corresponding to 4 h (LT 75°W) of 20 February (DOY 51). (top left) 02:00. (top right) 08:00. (bottom left) 14:00. (bottom right) 20:00.

observed (Barrientos, 2007; Métois et al., 2013). Figures are provided as Supplementary Material.

2.1. Diurnal variations

The same statistical procedures proposed by Chuo et al. (2001) in the case of three earthquakes in Taiwan are used. They determined reference lower boundaries for diurnal variations of foF2 in two ways: (a) the running mean value

for the last 15 days for a given local time minus 1.5 times the standard deviation of the mean, and (b) the median value minus the interquartile range. In the present analyses, NmF2 values are used instead of foF2. Moreover, the reference upper boundaries are also determined, i.e. mean plus 1.5 standard deviation and median plus interquartile range.

Times when NmF2 and TEC are below the reference lower boundary (LB) and above the reference upper boundary (UB) using median and interquartile range are

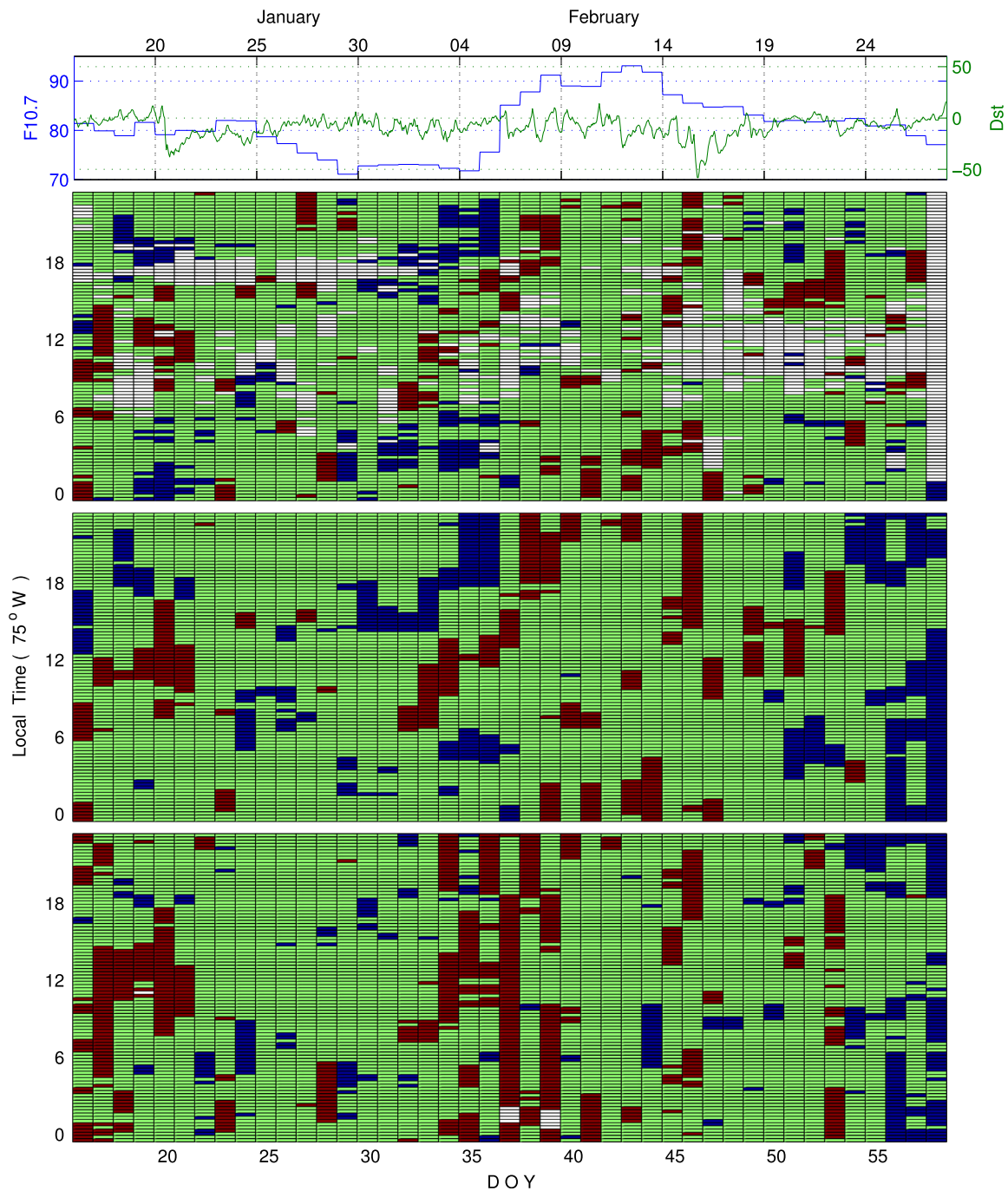


Fig. 3. (top panel) Same as Fig. 1. Times for which NmF2 (2nd panel) and TEC (3rd panel, regional representation; bottom panel, local CONZ station) are smaller than the reference lower boundary (previous 15-day running median minus interquartile range – blue) and larger than the reference upper boundary (previous 15-day running median plus interquartile range – red) from 16 January to 27 February 2010 (DOY 16–58) over Concepción (36.8°S; 73.0°W). Blank spaces indicate no data.

shown in Fig. 3. Also, similar figures (not shown) for the case of mean and 1.5 times the standard deviation, were produced. The latter include fewer cases than those identified on Fig. 3 since the corresponding reference boundaries are sometimes more restrictive.

Diurnal variations of observed NmF2 and TEC and also of corresponding LB and UB for seven days, two weeks and one week prior to the earthquake are given in Figs. 4 and 5, respectively. These are provided for easy comparison with similar figures published elsewhere (e.g. Yao et al., 2012).

The same statistical analysis described for the local case is made for each of the other 71 locations already mentioned. Figs. 6–8 show times when TEC RR is below the LB and above the UB for three weeks prior to the earthquake.

2.2. Day-to-day variations

A similar approach to that by Liperoyskaya et al. (2009) is followed. The mean value of NmF2 and associated standard deviation corresponding to the 11:00–16:00 LT inter-

val are first determined (from a maximum of 21 values since foF2 were observed at 15 min intervals) for every day between 1 January and 26 February (Fig. 9, top left). Then a 15-day running mean is calculated for the 8 January–20 February interval. To determine the 15-day running mean for the intervals 1–7 January and 21–27 February values for the 25–31 December 2009 and 27 February–5 March 2010 are needed. Since most of these for the 27 February–5 March interval are not available due to the earthquake, here a sort of “mirror values” is used. For example, observed values for the 25 February replace those unavailable for the 27 February; values for 24 February replace those for the 28, and so on. The same procedure is used for the 1–7 January for consistency reasons only, since values for at least some days during the 25–31 December 2009 could be determined. A standard deviation for 15-day running means covering the 1 January–26 February is also computed. Then the difference between the observed NmF2 and the 15-day running mean is determined for every day. Finally, the ratio between every difference and the standard deviation, the so-called F function, is calculated. A confidence range is determined as plus minus 2

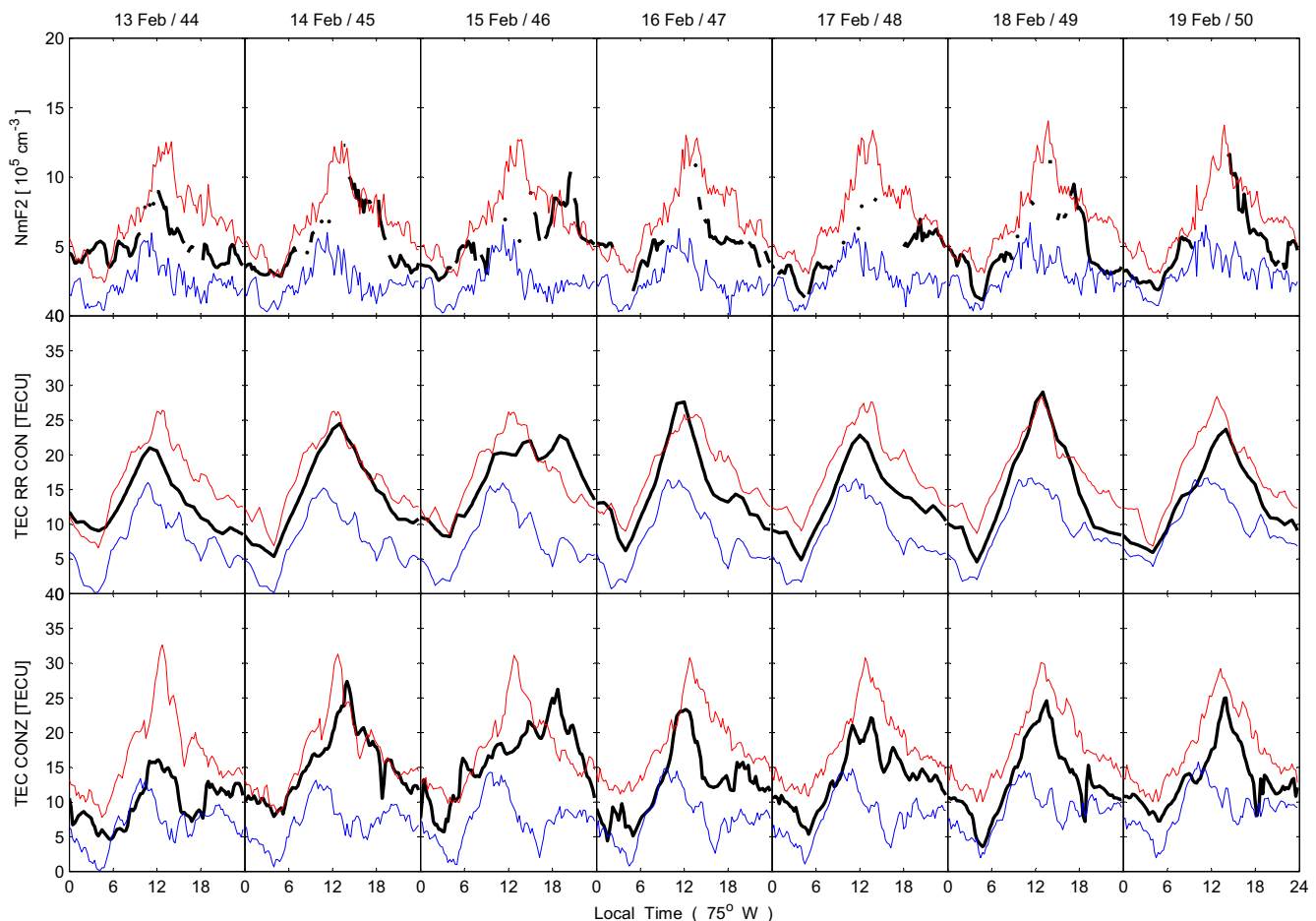


Fig. 4. Diurnal variations of NmF2 (top panel) and TEC (2nd panel, local CONZ station; bottom panel, regional representation) for 13–19 February (DOY 44–50), 2 weeks before the earthquake, over Concepción (36.8°S; 73.0°W). Observed values (black). Reference lower boundary (previous 15-day running median minus interquartile range – blue thin line) and reference upper boundary (previous 15-day running median plus interquartile range – red thin line). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

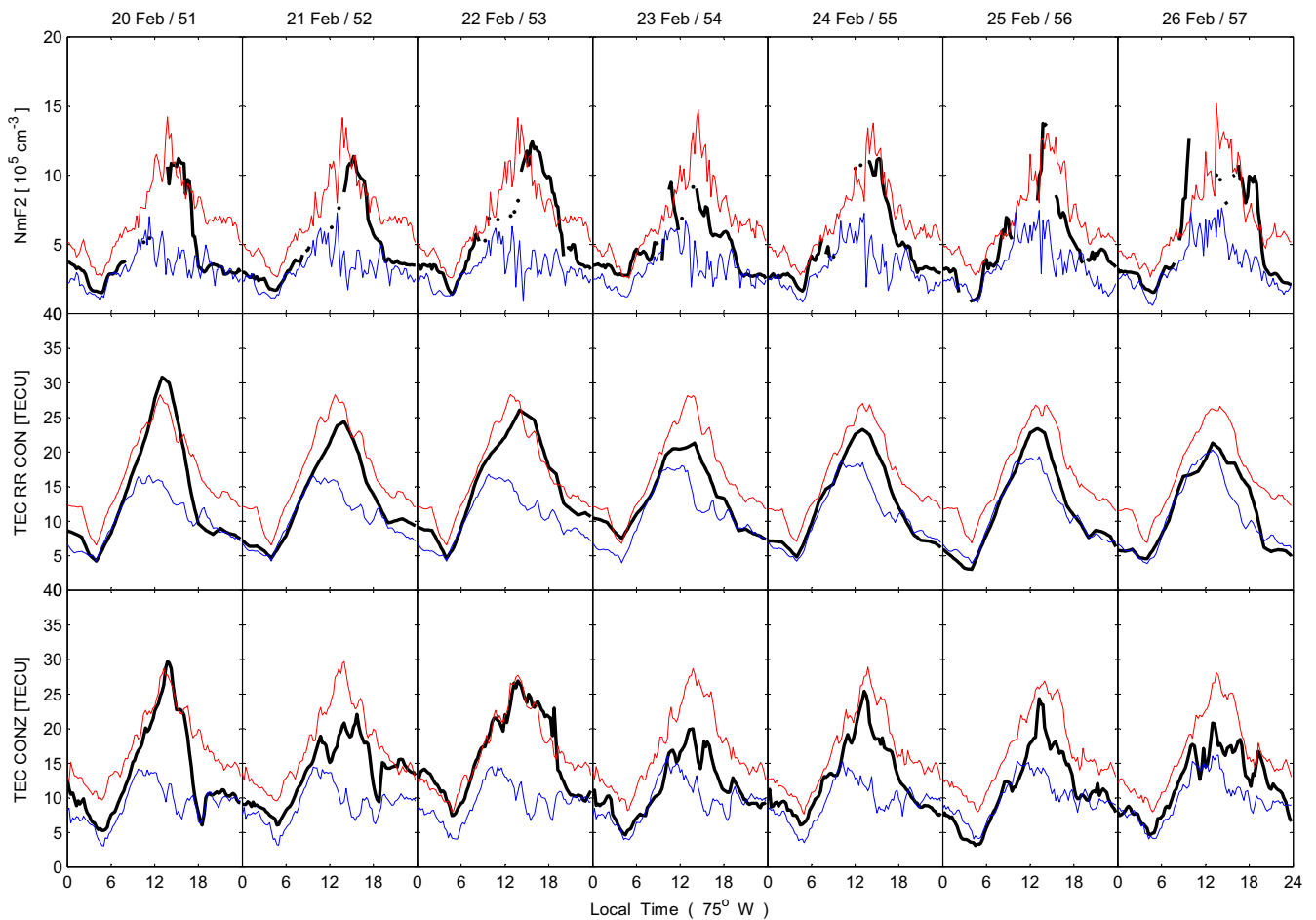


Fig. 5. Same as Fig. 4 for 20–26 February (DOY 51–57), 1 week before the earthquake.

standard deviations from $F = 0$ (Fig. 9, bottom left). The analysis by Liperovskaya et al. (2009) requires observed foF2 before and after the many earthquakes studied, thus it does not allow a kind of forecast capability.

The same analysis is made for TEC RR CON values. Due account is taken of the different time resolution of the data (Fig. 9, right). Furthermore, the case for both NmF2 and TEC, corresponding to a dawn interval (02:00–07:00 LT for NmF2) is depicted in Fig. 10.

The day-to-day variations approach is also applied to TEC RR corresponding to each of the other 71 locations already mentioned when discussing the diurnal regional variability. The results are pictured in figures using the same format of Figs. 9 and 10 (figures available as Supplementary Material).

3. Results

3.1. Diurnal variations

Fig. 1 shows the usual summer-time diurnal variations of NmF2 and TEC. Superimposed to these variations fairly clear quasi-periodic oscillations are observed, particularly during daytime. The period is about 25/26 days (near a

solar rotation) modulated by a shorter oscillation of about 12 days. The same pattern is observed for all other 71 locations for which TEC RR is derived; with the additional variability associated to the Equatorial Ionospheric Anomaly been more evident for the lower latitude locations of the analysed area (see figures of a similar format as that of Fig. 2 in the Supplementary Material). These quasi-periodic oscillations are not uncommon on time series of Concepción foF2 for other intervals. Thus, an attempt to identify possible ionospheric precursors should include ways to screen this type of variability.

Fig. 3 shows that TEC RR CON values are smaller than the LB and larger than the UB (abnormal values) for about 23% of the time during the 16 January–27 February interval. In the case of NmF2 it is about 21%, however, there are many instances when NmF2 is not available. TEC RR CON and NmF2 larger than UB occur almost the same number of times than values smaller than LB. For TEC CONZ there are about twice as many instances with larger values than smaller values.

To separate possible associations between the occurrence of abnormal values with solar activity level, the same analysis is made separately for 29 January–4 February, an interval of particularly low solar activity, and for 7–13 Feb-



Fig. 6. Times for which TEC (regional representation) at 72 grid points, over an area covering the whole ~400 km earthquake rupture zone (37.0–30.0°S; 67.0–75.0°W), are smaller than the reference lower boundary (previous 15-day running median minus interquartile range – blue) and larger than the reference upper boundary (previous 15-day running median plus interquartile range – red) from 6 to 12 February 2010 (DOY 37–43). (thin black line) Approximate coast line. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

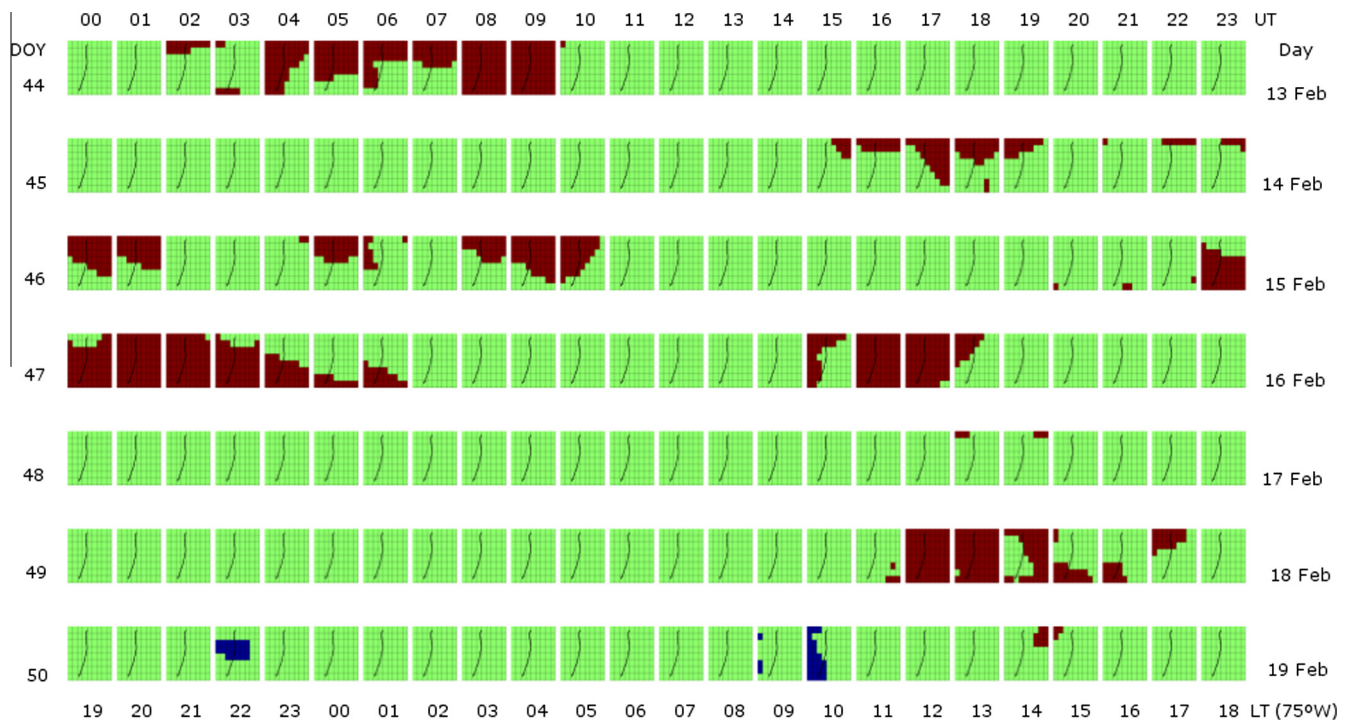


Fig. 7. Same as Fig. 6 for 13–19 February 2010 (DOY 44–50).

ruary, when solar activity was higher. Instances of NmF2 and TEC larger than UB are many times more frequent than values smaller than LB for the higher solar activity

interval. The opposite is found for NmF2 and TEC RR CON, although not so clearly, for low solar activity. In both cases the abnormal values are observed mostly during

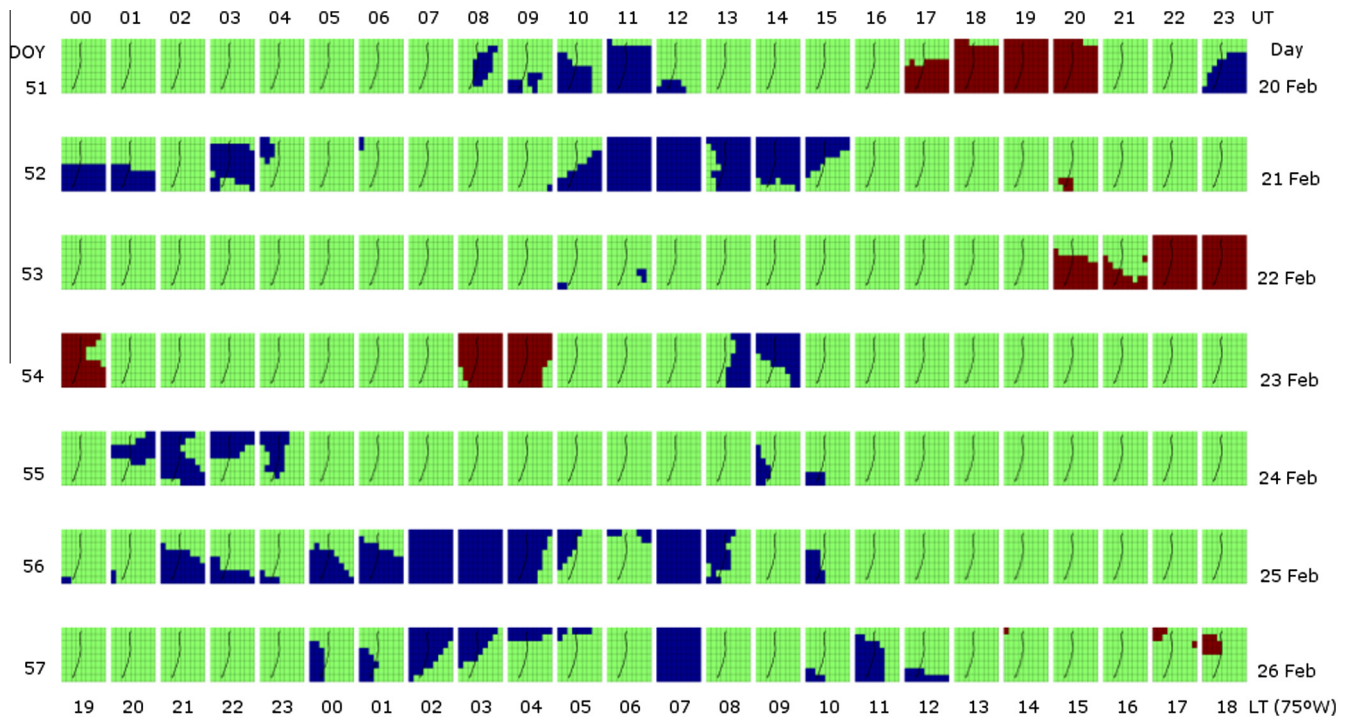


Fig. 8. Same as Fig. 6 for 20–26 February 2010 (DOY 51–57).

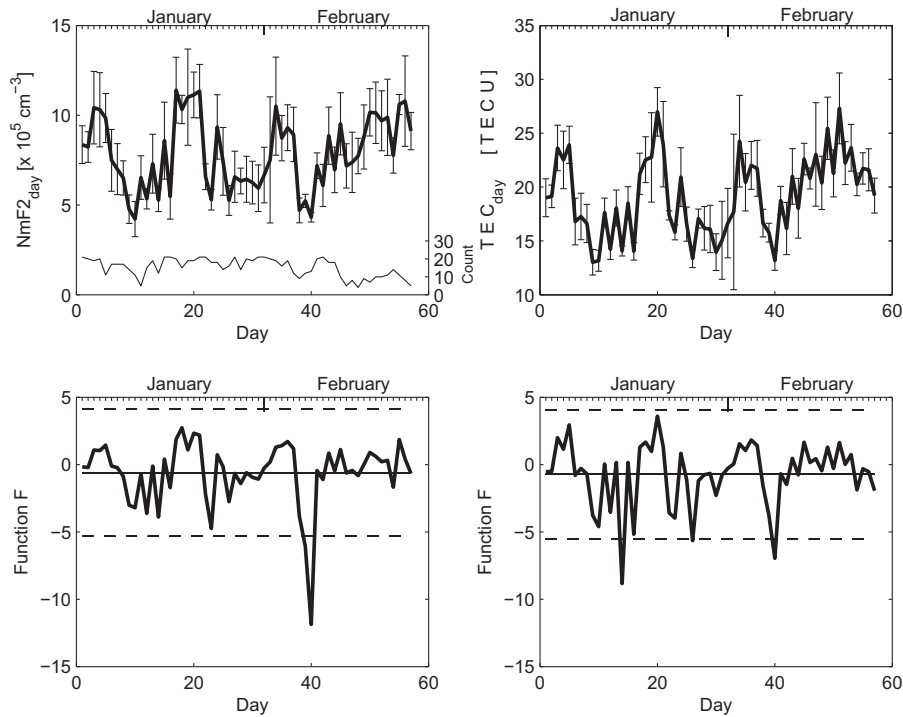


Fig. 9. (top panels) Day-to-day variation of daily mean NmF2 (left) and TEC (right, regional representation) corresponding to midday (11–16 LT) for 1 January to 26 February 2010 (DOY 1–57). Error bars give mean plus and minus the standard deviation. The count is also shown for NmF2. No missing values for TEC. (bottom panels) F-function for NmF2 (left) and TEC (right, regional representation) and confidence intervals (see text). Values for Concepción (36.8°S; 73.0°W).

night time. For TEC CONZ abnormally larger are more frequent than abnormally smaller values for the lower solar activity interval.

There are only three days (20/21 January and 15–17 February) for which geomagnetic activity could be considered at minor storm level (Dst below -30 nT, absolute

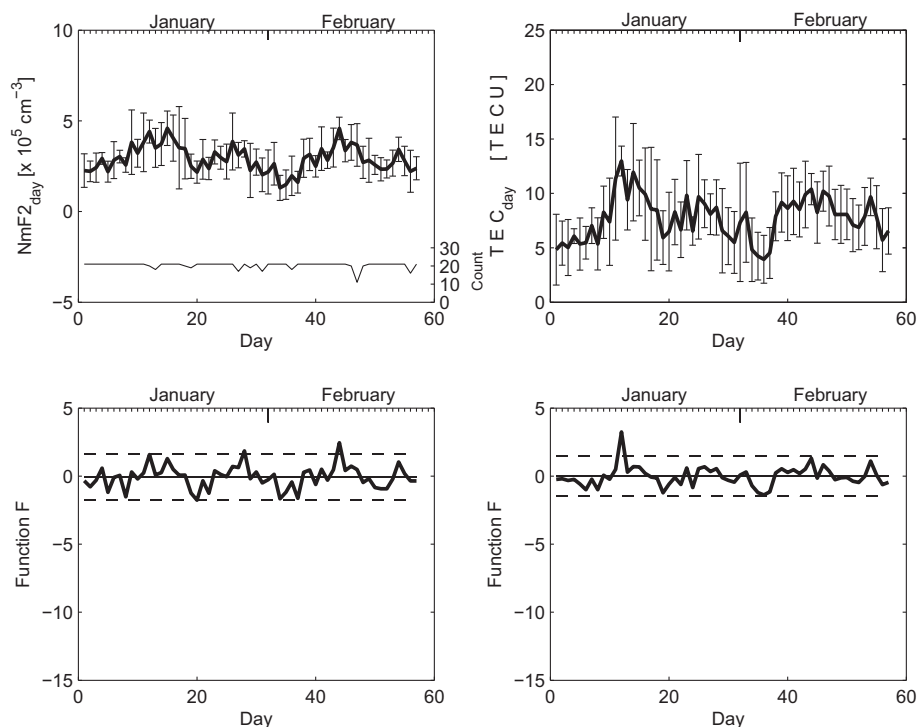


Fig. 10. Same as Fig. 9 for dawn (02–07 LT).

minimum of -58 nT). In both cases, NmF2 and TEC are larger than UB during most of the day.

Clear dependencies of NmF2 and TEC on solar and geomagnetic activity would be most useful at this stage. Unfortunately, these do not exist on an hour-to-hour or daily scale. A cross correlation analysis between TEC RR CON values for each hour and F10.7 shows that the largest correlation coefficient is only about 0.6 for the 02:00–05:00 interval and at 22:00 LT, with TEC lagging F10.7 for a day. Thus, although NmF2 and TEC RR CON are less than the LB for the lowest F10.7 of February and definitely NmF2, TEC RR CON and TEC CONZ are larger than the UB for highest F10.7 of February, there are other days when no such relations are observed. Similar ambiguities apply to the relations between NmF2 and TEC RR CON with Dst. For Dst near zero (20 and 21 February) NmF2 and TEC are larger in the afternoon and smaller in the evening, but are also larger during evening and night for the lowest Dst. The latter association seems to statistically prevail for moderate geomagnetic activity ($6 < \text{weighted ap} \leq 18$) over Concepción in summer (supplementary analyses to Arriagada and Foppiano, 1999). Furthermore, as already mentioned, due account should be taken of the inter-day quasi periodic oscillations observed on NmF2 and TEC diurnal variations. As a matter of fact, the diurnal variations of NmF2 and TEC for some of the lowest and largest F10.7 occur during the quasi-periodic oscillation phases of maximum, and so also the corresponding variations for most negative values of Dst.

Figs. 4 and 5 supplement the information already given in Fig. 3 corresponding to the two weeks prior

to the earthquake. Here the actual values of NmF2, TEC RR CONZ and TEC CON are given. For these 2 weeks geomagnetic activity is very low, except during 15–17 as discussed above. NmF2 and TEC RR CON are larger than UB in the early morning of 13 February, but not TEC CONZ. The same is true for some instances in the afternoon of 18 February, TEC RR CON and TEC CONZ are abnormally larger in the afternoon of 22 February and abnormally smaller before midnight and early morning the 25 February. Could these be considered as ionospheric precursors? Actually, at least for TEC RR CON and TEC CONZ, values are abnormally smaller for several hours, just before and after the earthquake (Fig. 3).

Diurnal variations of foF2 observed at New Delhi ($28.6^\circ\text{N}, 77.2^\circ\text{E}$) for 25 days before 11 Asian strong earthquakes are analysed by Dabas et al. (2007). They use reference boundaries determined as the differences between monthly median foF2 plus (and minus) the interquartile range and then a normalised deviation index using these differences is computed (as in Liu et al., 2004). They find that for geomagnetic activity corresponding to $-15 \leq \text{Dst} \leq +15$, on most cases (5 to 1), foF2 is increased (deviation index positive) for eight or more days before earthquakes. On possible precursors for less than 8 days increases and decreases of foF2 are equally likely. Sharma et al. (2010) further report observations at New Delhi for three more China earthquakes. In this case, increases of foF2 were identified occurring within 3 days prior to the three earthquakes. Results presented here could be considered consistent in the first case (eight or more days before)

but are certainly different in the second and third cases (less than 8 days or within 3 days).

Diurnal variations of TEC prior to seven large ($M = 7.0+$) earthquakes of 2010, including the Chilean one, have been analysed by Yao et al. (2012). To determine TEC they use the global ionosphere maps (GIM) provided by the International GNSS Service (IGS), the very same representation used in an earlier submission of the present paper. (By the way, the results presented in that submission are completely consistent with the ones presented now). They calculate medians using values for 30 days and determine LB and UB as the median ± 1.5 standard deviation. As expected from the earlier analyses, their results are very similar to those reported here on Figs. 4 and 5. In particular, they assign to geomagnetic disturbance the anomalies observed on 15–16 February. Although they consider the anomaly for 20 February as one not caused by spatial environment disturbances, they suggest it happens seven days before the earthquake and thus cannot confirm the relationship between the ionospheric anomaly and the earthquake. They conclude that there is this also no obvious ionospheric anomaly for the 4 April 2010 $M = 7.2$ Mexico earthquake.

Liu et al. (2010) make a diurnal statistical study of TEC for 100 $M > 6$ earthquakes over Indonesia during the 1998–2008 interval. They determine UB and LB as 15-day median + 1.5 times the median-(upper quartile) and 1.5 times the median-(lower quartile), respectively. They use the GIM of IGS. They find that although the seismo-ionospheric anomalies over Indonesia are rather complex, for earthquakes of $M > 7.0$ reduction anomalies (TEC below the LB) observed on day 5 prior an earthquake (including the Sumatra–Andaman) are reliable. On the contrary, results presented indicate NmF2, TEC RR CON and TEC CONZ are above the UB for some hours on 22 February, i.e. day 5 prior the earthquake.

In the present regional analysis it is found that for the studied interval (16 January–26 February, DOY 16–56), TEC RR $>$ UB over the whole selected area only 2.0% of the time (i.e. 19 out of 984 h); on the other hand, TEC RR $<$ LB for 2.6% of the time. Most of the time TEC RR is larger than UB or is smaller than LB only over part of the selected area; leading to or lagging from occasions when the conditions are fulfilled over the whole selected area. Sample occasions are 15 February 20:00 to 16 February 06:00 UT for TEC RR $>$ UB (Fig. 7) and 25 February 02:00–15:00 UT corresponding to TEC RR $<$ LB (Fig. 8). Sometimes the condition TEC RR $>$ UB seems to develop from the south to the north and back again, as it is the case for the first interval mentioned above. For the second interval, the development seems to end up over the lower latitudes. However, no single evolution pattern clearly emerges from this analysis. When only the last two weeks are considered, the week from 13–19 February (Fig. 7) exhibits mostly TEC RR $>$ UB. As already mentioned for the local analysis, this is most likely associated with geomagnetically disturbed conditions. For the week before

the earthquake (Fig. 8), most of the time TEC RR $<$ LB, particularly one and two days prior to the earthquake. During these two weeks whenever TEC RR $<$ LB for Concepción so it is for at least some other parts of the selected area, except during only 6 h (10:00 and 11:00 UT on 25 February and 07:00–10:00 on the 26). The only four hours for which TEC RR $<$ LB over the whole area are 07:00, 08:00 and 12:00 UT on 25 February and 12:00 UT on the 26, on the early local time morning.

Results from the regional analysis of TEC made for the selected area in the north of Chile, some 2000 km from the 27 February rupture zone, are almost the same indicated above. Obviously, TEC values are more variable there because the area is fully within the dynamic range of the Equatorial Ionospheric Anomaly. However, the percentage of time for which TEC RR $>$ UB and TEC RR $<$ LB are similar and the timing follows an equivalent sequence. Therefore, no distinction between anomalous TEC in the north and centre Chile seems to be possible.

Liu et al. (2010) also go onto determine what they consider a spatial signature of possible ionospheric precursor over an earthquake preparation zone of a radius of 10,000 km for the giant 26 December 2004 Sumatra–Andaman earthquake. To highlight the spatial signature, they determine the extreme minimum of a 30 day period for a given hour at each grid point over the preparation zone. The spatial shape of the extreme minimum resembles and almost coincides with the Equatorial Ionosphere Anomaly and develops from 10:00 to 14:00 LT over several time zones when it is superposed over the spatial distribution of the anomalies for 21 December, 5 days before the earthquake. They claim that this signature strongly suggests that the reduction anomaly is the seismo-ionospheric precursor of the earthquake.

Although the area selected in the present study only covers the rupture zone, TEC RR $<$ LB about half the time during the 3 days prior to the earthquake, a result that is thus consistent with the one of Liu et al. (2010).

Another report on TEC observations over a wide seismically active zone is that of Astafyeva and Heki (2011). They use TEC determinations from the Japanese dense array of GPS receivers for the April–September 2008 interval when 5 strong ($M > 6.8$) shook Tohoku and Hokkaido regions. Anomalies are calculated using essentially the same procedures of Liu et al. (2010). Careful screening of geomagnetic, solar, interplanetary magnetic field and UV radiation shows that positive anomalies are associated with parameters of the quoted variables. Comparison to GIM TEC equivalent calculations for a similar area in the south-western USA is provided to understand the spatial scale of the detected abnormal TEC in Japan. They conclude that their results do not corroborate previous works on ionospheric precursors of earthquakes, albeit do not disprove the possibility of the existence of such phenomena. Moreover, they point out the difficulties of searching of ionospheric precursors using TEC. Although results presented here are less comprehensive, they coincide with

those of Astafyeva and Heki (2011) in that positive anomalies tend to be associated with the higher solar activity and geomagnetic levels.

3.2. Day-to-day variations

Now turning to the day-to-day variability, the evolution of the F-function for NmF2 (Fig. 9, bottom left) can be considered as a representation of normal ionospheric conditions at least during the last 8 days before the 27 February earthquake. F-function values are near zero and are well within the confidence range ($-5 \leq F \leq +5$). It is only for days 39 and 40 (8 and 9 February) that values are significantly lower than the confidence range (almost 5 standard deviations below zero). This sharp decreasing could be interpreted as an earthquake precursor. However, such an anticipated precursor does not seem to be that frequent. For all earthquakes (264) in Japanese and east-Russian locations analysed by Liperovskaya et al. (2009), possible F-negative precursors for daytime conditions are found only with one day in advance, and less than four days for positive precursors.

Similar results are found for TEC RR CON (Fig. 9, bottom right) during the same interval. A possible negative precursor is visible on day 40 (9 February) as it was in the case of NmF2. Another possible precursor could be present on 14 January, but this is 44 days before the earthquake.

The day-to-day variability of NmF2 for dawn conditions is much less than that for midday, although the similar quasi periodic oscillations seem to be present (Fig. 10, top left). Consequently, the standard deviations for every mean value are also much smaller and so also the confidence ranges for the F-function (Fig. 10, bottom left). These same features are apparent for TEC RR CON (Fig. 10, right). For both NmF2 and TEC F-function values are mostly within the confidence range, except for hardly positive values on 13 February and 12 January, for NmF2 and TEC, respectively. The 13 February case for NmF2 is consistent with what is shown in Fig. 3 for TEC RR CON but not with TEC CONZ.

An equivalent analysis to that reported in the previous paragraphs gives quite different results when applied to NmF2 observed in Concepcion during 1–21 May 1960, before the greatest earthquake of recorded history (other analyses are given by Foppiano et al., 2008). The epicentre of this earthquake was located only some 300 km south of the epicentre of the 27 February 2010. The upper panels of Fig. 11 show the 15-day running means and standard deviations for dawn (left) and daytime (right). Corresponding F-function values are clearly within the confidence range for all days except hours before the earthquake. Thus, in this case, some kind of warning could have been issued if for the computation of the F-function “mirror values” had been used.

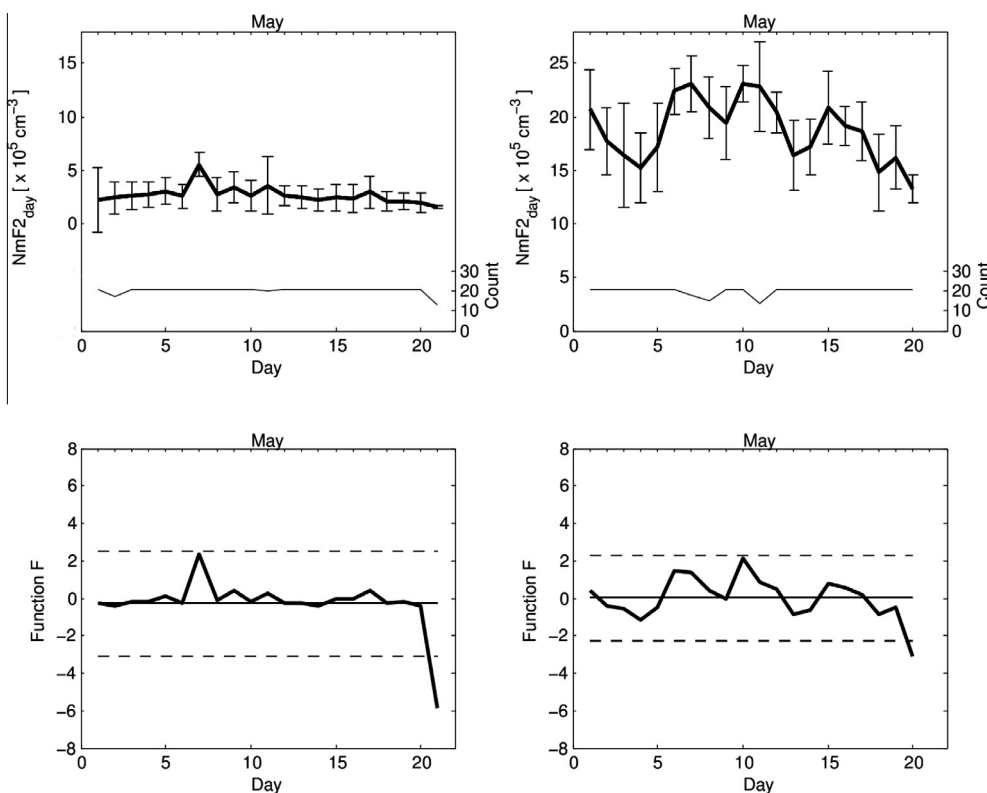


Fig. 11. Same as Figs. 9 and 10 for NmF2 only, corresponding to all days of May 1960 before the great Chilean earthquakes of 21 and 22 May. Midday (11–16 LT – right). Dawn (02–07 LT – left).

Obviously, the use of “mirror values” could be questioned. Nevertheless, on one hand, using the “mirror values” keeps the statistical weight of running means and associated standard deviations. On the other hand, it emphasises eventual anomalies if the variability associated with other known effects (e.g. solar or geomagnetic) is small during the last seven days. A test to the applicability of “mirror values” for the computation of the F-function can be made at least in the case of TEC since TEC values are available during and after the 27 February earthquake. This test indicates that the F-function thus calculated does not differ significantly from the function calculated using “mirror values”.

When the same analysis done for TEC RR CON is made for the TEC RR over the other 71 locations, almost identical features are found. TEC RR above the UB tends to occur after midnight and early morning while TEC RR below the LB is more frequent around midday. Nevertheless, they correspond to weeks before the earthquake. Furthermore, the F-function values above and below the confidence range for the singled out days decrease both northward and eastward away from the earthquake epicentre.

3.3. Satellite observations

The DEMETER satellite mission was specifically aimed at detecting possible ionospheric precursors of earthquakes using different sensors (Parrot, 2006). Results from statistical and case studies of many earthquakes have been published during the last few years, including the 27 February earthquake (e.g. Zhang et al., 2010, 2012; Píša et al., 2011, 2012; Anagnostopoulos et al., 2012).

Píša et al. (2011) focusses on ion concentration (mainly O^+) observations. These are for sun-synchronous orbits at a height of about 660 km. They find increased concentration only during night-time (northward half-orbits) for the 8 to 18 February (DOY 39–49) at distances within a 1000 km from the epicentre, during the 1 January–30 of March 2010 interval. The observation time along each half orbit is only about 7 min. In particular, the increased concentrations on the 10, 16 and 18 February at 03:20–03:30, 03:06–03:15 and 02:30–02:37 UT, respectively, are discussed. The increases are determined with reference to observations from 1 January to 30 March of 2007 to 2010. The results given here in Fig. 1 show that 10 February is approximately on a valley of the quasi periodic oscillation of NmF2, TEC RR CON and TEC CONZ already mentioned; F10.7 is relatively high and Dst is small. Unfortunately, only simultaneous NmF2 values are available for the 03:30 UT DEMETER observation, i.e. 22:30 LT of 9 February. Fig. 3 shows that although NmF2 is within the LB and UB at that time, later NmF2 is larger than the UB for a few hours. TEC RR CON and TEC CONZ are also above the UB at 22:00 and 23:00 LT. Furthermore, TEC RR (Fig. 6) is also above the UB for a small area northward and eastward from Concepción at 22:00 and

23:00 LT, the area increases at 00:00 to cover the whole selected area at 01:00, then decreasing during the following two hours.

The corresponding NmF2 anomalies observed over Concepción for the 10 February, as determined by the method of Liperovskaya et al. (2009), are negligible. The F-function is well within the confidence limits, and therefore Píša et al. (2011) results (ion increases) are not consistent with NmF2 changes. Neither is the fact that the NmF2 F-function values are well below the confidence limits for midday on 9 February and for TEC on 8 February (instead of 10 February). It could be argued that this is so because electron concentration and ion concentration measurements do not correspond to the same height range and strictly also to same distances from the earthquake epicentre.

NmF2 and TEC for 16 February are approximately on the crest of the quasi periodic oscillation; F10.7 is less than before and Dst is at minor geomagnetic storm level. Again, only simultaneous NmF2 values are available for the 03:15 UT DEMETER observation, i.e. 22:15 LT of 15 February. Although NmF2 is within the LB and UB at that time, it is larger than the UB before and after for a few hours. TEC RR CON is above UB all along from mid-afternoon and up to midnight; TEC CONZ is also above the UB for several hours up to 22:30. TEC RR (Fig. 7) is above UB over most of the selected area during at least 5 h before the DEMETER observation and the area decreases southward and westward for the next three hours. These results are almost certainly consistent with the geomagnetic storm and a seismic effect, if any, cannot be unambiguously identified.

On 18 February DEMETER observation, F10.7 is similar to that of 16 February and Dst is becoming less negative as appropriate to the later stage of the minor storm. NmF2 and TEC are still on the crest of the quasi periodic oscillation. However, neither NmF2 nor TEC CON and TEC CONZ are above UB or below LB for several hours within 21:30–21:37 LT of 17 February. Moreover, TEC RR is within the UB and LB all along.

On the other hand, Píša et al. (2011) do not find significant ion increases during the week prior to the earthquake. However, as already mentioned, there are several occasions when TEC RR is above the UB or below the LB (Fig. 8) and thus could be considered ionospheric precursors. The lack of association may be due to the fact that DEMETER observations cover only several minutes each night or that there is just no relation between the two types of observations.

Summarizing, it can be said that only the increased ion concentration on 10 February found by Píša et al. (2011) can be associated with NmF2 and TEC been above the UB, and thus considered as an eventual ionospheric precursor.

Zhang et al. (2010) and Anagnostopoulos et al. (2012) suggest that some energetic particle bursts observed using DEMETER detectors may be considered as earthquake

precursors. In the case of the Chilean earthquake, Zhang et al. (2010) identify energetic particle bursts on two orbits passing within about a hundred km from epicentre the 15 and 16 February. Clear procedures to determine reference values of particle counting rates and energy spectra are given, as well as arguments to conclude that the bursts are not related to geomagnetic or solar activity disturbances. The bursts are observed at 02:40:22–02:49:42 and 03:15:30–03:04:30 UT, corresponding to night-time conditions. Fig. 7 shows that for the first burst TECC RR is neither below the LB nor above the UB over the whole area within at least one hour. By contrast, during the second burst TECC RR is above the UB for several hours, and it coincides with the ion increase observed by the same satellite as already reported. Anagnostopoulos et al. (2012) presents, among five other cases elsewhere, a radiation-belt particle burst the 26 February at 16:01 UT, a day-time event, observed during a downward half orbit which passes over the ocean at about a thousand km from the epicentre. They argue that the burst almost certainly appeared due to the preparation processes on the giant earthquake since do account was taken of both the proper reference particle flux level and of the geomagnetic and solar activity conditions prevailing the interval. Fig. 8 shows that TEC RR can be abnormal between 16:00 and 17:00 UT but is below the LB.

Among ULF/ELF DEMETER observations prior to 32 earthquakes of Ms greater than 7.0 Zhang et al. (2012) find that for the Chilean case, the electrostatic perturbations obtained for 19.5–250 Hz signals occur during night-time 3 and 2 days before the earthquake over the areas 39°–42° and 39°–41° latitude south and 298.3°–299.5° and 291°–292° longitude east, respectively. Fig. 8 shows for 24 and particularly for 25 February TEC RR is below the LB for several hours during night-time and early morning.

At the time of writing new results for the 27 February 2010 Chilean earthquake have become available (Ho et al., 2013). They have identified seismo-ionospheric anomalies using TEC derived from a global representation (GIM) and electron concentration (Ne) observed by the DEMETER satellite. Their TEC local diurnal variability results are similar to those reported here, although they compute medians and upper and lower reference boundaries in a somewhat different way. Results presented in their Fig. 2 depict the same features than those shown here in Figs. 4 and 5 (bottom panel). Furthermore, for 13, 14, 15, 18, 20, 23–25 February their abnormal TEC GIM (larger or smaller than reference boundaries) generally occur at similar times than those corresponding to at least two of our data sets: NmF2, TEC RR CON or TEC CONZ (provided the coarser time resolution of TEC GIM is taken into account). When comparing day-to-day changes of TEC GIM and DEMETER Ne, values for daytime and night-time are grouped separately, and are given for 60 days interval centred on 27 February. DEMETER Ne values correspond to a few minutes around 10:30 and 22:30 LT,

respectively, and are for an area of 4.3° latitude times 21.7° longitude roughly centred on the epicentre. TEC GIM and DEMETER Ne are mostly within UB and LB for daytime 24 days prior to the earthquake. This is consistent with results of Piša et al. (2011) for DEMETER observations of ion concentration. TEC GIM and DEMETER Ne are larger than their UB at night-time several days from 8 to 18 February, particularly days 9, 10, 15–17. They are smaller than their LB several days between 20 to 26 February a feature consistent with TEC results presented here (Fig. 3). Ho et al. (2013) also present global anomalies of TEC GIM and DEMETER Ne (night-time) on fixed local time maps using data for 12, 14, 15 and 16 February, and 10 February, respectively. These show clear positive anomalies near (within spatial resolution) the 27 February earthquake epicentre also consistent with the results reported here (Figs. 6 and 7). However, as already mentioned, TEC values for the 14 to 17 February may be associated with increased geomagnetic activity. Moreover, there are several hour spells of TEC RR over the rupture zone that are larger than UB and even more that are smaller than LB that are closer to the earthquake (20 to 26 February), an interval that seems to be more likely to exhibit ionospheric precursors as indicated in published reports quoted before.

3.4. Comment on statistical results

It could be argued that different ionospheric precursors may be found depending on earthquake characteristics (depth, fault plane intersection with surface). However, this should be of no concern when discussing the statistical significance of possible ionospheric precursors. As suggested by Rishbeth (2006), contingency tables should be used for this purpose, i.e. determination of frequencies for entries “(I): EY/IY (positive prediction), EY/IN (failed prediction), EN/IY (false alarm), and EN/IN (null)”, where E is for Earthquake, I for ionosphere, Y for yes and N for No. “To be convincing, the ‘successes’ (EY/IY and EN/IN) must greatly outweigh the ‘failures’ (EY/IN and EN/IY), over a considerable period of time and over a widespread area, while resisting the temptation to introduce ‘maybe’ classes of events”. These issues have been addressed by Le et al. (2011). They analysed abnormally larger and smaller TEC globally for 736 earthquakes of greater than 6.0 magnitude and depths less than 40 km over the 2002–2010 interval. Careful exclusions relating geomagnetic activity and space and time coincidences were made. The occurrence rates of abnormal days (larger or smaller TEC) for a given earthquake kind (magnitude and depth) were found to increase with increasing magnitude, decreasing depth and closeness to the earthquake date. Occurrence rates for abnormally larger TEC were found to be greater than those for abnormally smaller TEC. The ratio between the occurrence rates for abnormal days for earthquakes and that for abnormal days away from earthquakes (space and time) was found to be significantly greater than 1, particularly for earthquake magni-

tude larger than 7, depth less than 20 km, and several days before the earthquake. As already mentioned in the present results for local diurnal variations, these rates are not consistent with those for the Chilean earthquake.

4. Summary and conclusions

Various statistical analyses of the ionospheric characteristics NmF2 and TEC for two months prior to the Chilean 27 February 2010 earthquake have been made, an interval characterised by fairly low levels of solar (F10.7) and geomagnetic (Dst) activities. NmF2 is for an ionospheric station located near the earthquake epicentre. TEC is derived for two local nearby GPS stations (CON and CONZ). It is also derived using a regional representation of TEC (RR) for 72 locations covering the whole of the fracture zone (including CON). To check the variability of TEC over the fracture zone TEC is derived from RR for 72 locations over an area of approximately the same size but at about two thousand km north of the fracture zone.

It is found that during the study interval TEC RR CON is larger than reference upper boundaries (UB) or smaller than reference lower boundaries (LB) for a little over 10% of the time each. The same is generally true for NmF2 although there are many gaps in the observations. TEC CONZ is larger than UB about twice as frequently as it is smaller than LB. Moreover, TEC RR CON and NmF2 larger than UB tend to be more frequent than are smaller than LB for some days for which solar activity (F10.7) and geomagnetic activity (Dst) levels are higher than the other days. These results are consistent with some published reports (e.g. Dabas et al., 2007; Yao et al., 2012) and definitely not consistent with others (e.g. Sharma et al., 2010; Le et al., 2011).

When regional results are concerned, TEC RR is larger than UB over the whole of the rupture zone about 2% of the time. TEC RR is smaller than LB slightly more frequently. Most of the time these conditions are fulfilled over parts of the zone but no single pattern arises. However, for the week prior to the earthquake TEC RR is definitely smaller than LB at least for some locations of the area about a third of the time. This is consistent with previous studies (e.g. Liu et al., 2010). By contrast, the week before last TEC RR is larger than UB at some locations also a third of the time. Similar results are found to apply for the selected area in the north of Chile.

Results from the midday day-to-day variation analysed using the F-function indicate negative anomalies on 8, 9 and 10 February for NmF2 and TEC RR CON, respectively. Whereas during dawn conditions, slight positive anomalies are found on 13 February and 12 January for NmF2 and TEC RR CON, respectively. Almost the same results are obtained when the F-function analysis is applied to all 72 locations covering the fracture zone. It is considered here that such early possible ionospheric precursors are not significant, particularly when no such anomalies

are found for the Chilean greatest earthquake in recorded history (22 May 1960).

Comparison of abnormal NmF2 and TEC presented here with abnormal electron and ion concentration, energetic particle burst and electromagnetic emissions determined using the DEMETER satellite published elsewhere (e.g. Zhang et al., 2010, 2012; Píša et al., 2011, 2012; Anagnostopoulos et al., 2012) also show some kind of coherence albeit the heights and distances from the epicentre where the latter are observed may be significantly different. It should be noted though that the time resolution of NmF2 and TEC used here is too coarse to make definite comparisons.

A way to separate local anomalies from the global dynamics of TEC has been suggested (Afraimovich and Astafyeva, 2008). However, an analysis along this line is quite beyond the scope of the present study.

It is concluded that found abnormal NmF2 and TEC cannot be unambiguously associated with eventual ionospheric precursors of the Chilean earthquake.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.asr.2013.07.005>.

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