On the origin of post-midnight equatorial spread F events during the 2008/2009 extreme solar minimum

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Abstract: Previous studies using satellite (C/NOFS) observations have suggested the potential role of low-latitude abnormal upward drifts detected around midnight in controlling the development of post-midnight equatorial spread F (ESF) during June and December solstices of the extreme solar minimum of 2008/2009 [Heelis et al., 2010; Stoneback et al., 2011].

In order to better understand the response of ESF morphology to varying solar flux conditions, and the origin of ESF (in LT) during the extreme solar minimum of 2008/2009, we used ground-based radar observations of the evolution (in time and height) of ESF irregularities made at the Jicamarca Radio Observatory (11.95°S, 76.87°W, ~1 dip latitude).

We found that, for the Peruvian sector, abnormal midnight drifts could have played a primary role on the development of ESF events in June Solstice. In December solstice, however, most of the ESF events originated in the pre-midnight sector. ESF continued to exist in the post-midnight sector, which indicates additional contribution of midnight upward drifts.

1. INTRODUCTION

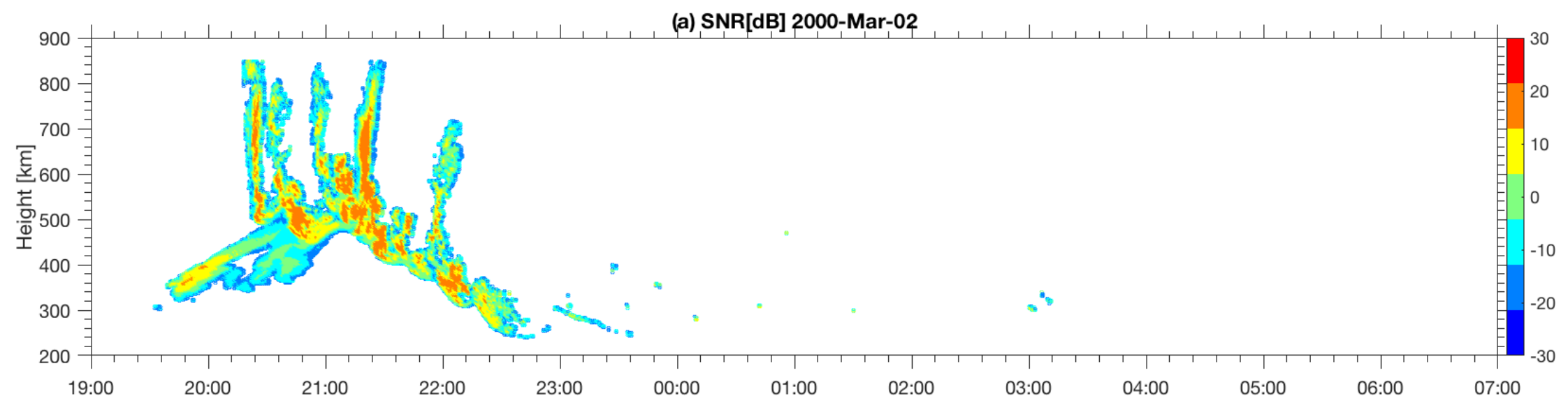
❑ A peak in the occurrence rate of equatorial spread F in the post-midnight sector during June and December solstices under the extremely low solar flux conditions of 2008/2009 has been observed based on C/NOFS satellite measurements [e.g. Heelis et al., 2010].
❑ Abnormal upward drifts near midnight were also observed by C/NOFS in most longitude sectors particularly during June and December solstices of 2008/2009. It has been hypothesized that these abnormal drifts could have been responsible for the high occurrence of post-midnight ESF [Stoneback et al., 2011].
❑In this study, we seek to address the following questions:
1 - What is the response of ESF morphology to varying solar flux conditions including those of the 2008/2009 deep solar minimum?
2 - What is the origin (in local time) of ESF events observed during June and December solstices of 2008/2009?

2. RESEARCH APPROACH

❑ We analyzed long-term, semi-continuous observations made by the coherent scatter radar mode (JULIA) of the JRO. Conventional JULIA observations provide information about the evolution in time and height of meter-scale irregularities associated with ESF. We must point out that while radar observations provide observations as a function of height and at an adequate temporal range, they are limited to the radar site location.
❑ For this study, we created maps of the quiet-time ESF occurrence rates as a function of local time, height, and season, and year (solar flux). Details about irregularity identification and occurrence rates are provided below:

- **Irregularity identification:** The occurrence of irregularities are identified for time-height bins of 15 mins and 20 km for each day. Irregularities are identified based on number of echoes with SNR > -20 dB. Only geomagnetically quiet conditions are considered (Kp at the time and previous 4 values cannot exceed 4). See Figure 1 for an example.
- **Occurrence rates:** 2457 days of observations between 1996 and 2015 were used in this study. Observations were grouped into Mar-Equinox, Jun-Solstice, Sep-Equinox and Dec-Solstice. Only seasons with at least 10 days of observations are considered. The results are summarized in Figure 2.

(a) SNR[dB] 2000-Mar-02



(b) Irregularity detection

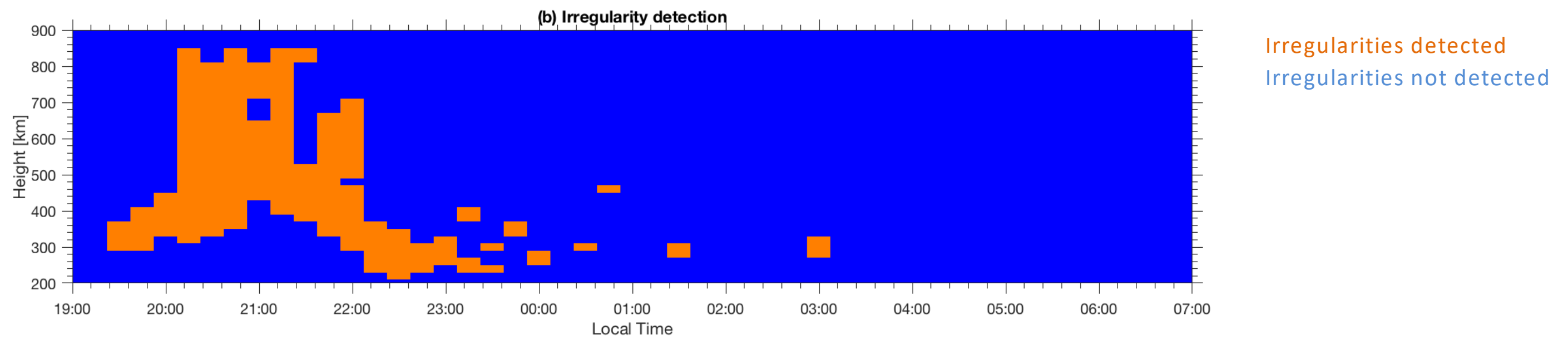


Figure 1 – [Irregularity identification] The top panel shows an example of the Range-Time-Intensity map of echoes measured by JULIA on March 2, 2000. The bottom panel shows the regions were ESF irregularities were identified based on number of echoes above a certain SNR threshold.

3. RESULTS

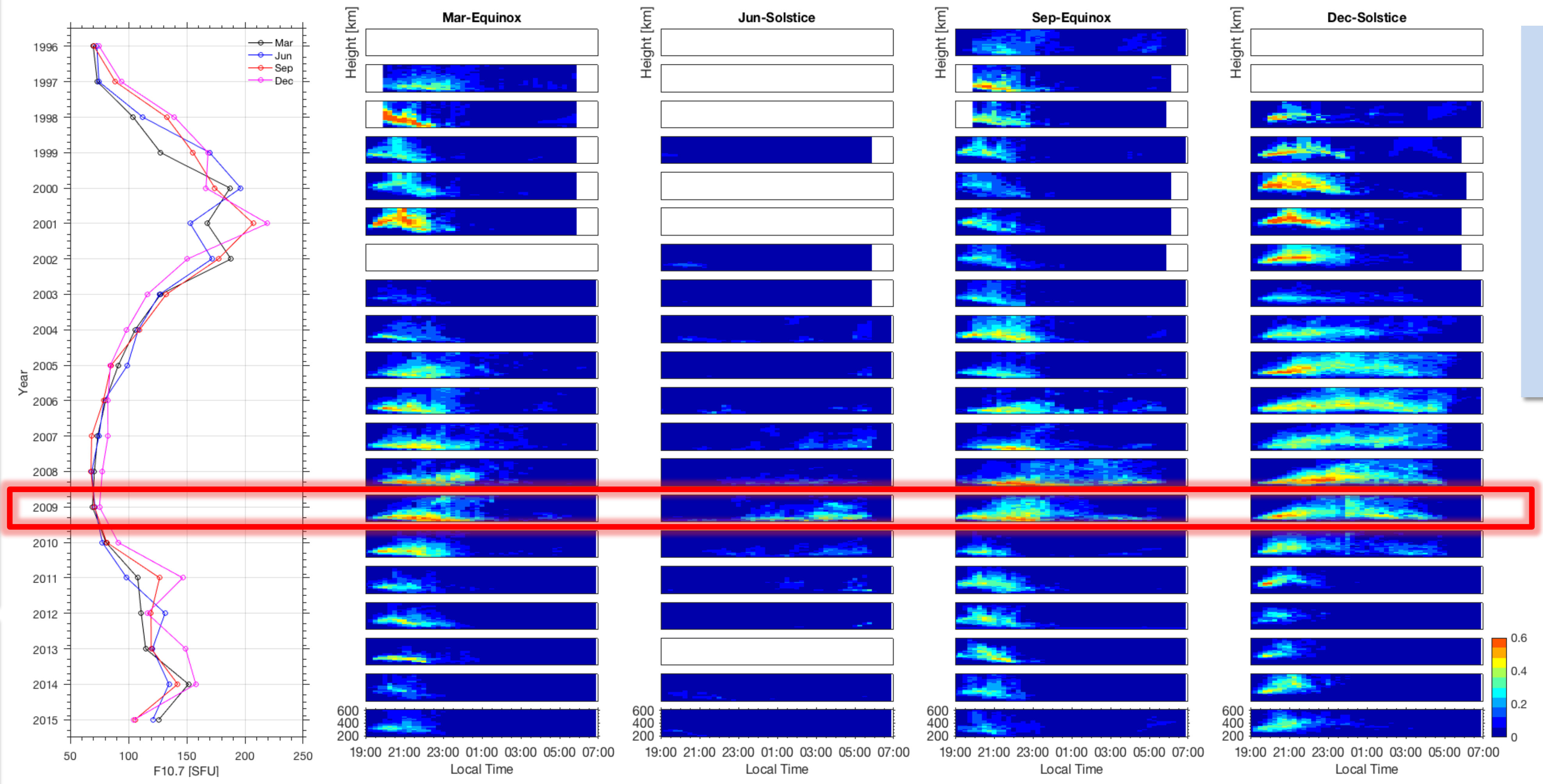


Figure 2 – [Occurrence rates of equatorial spread F] Summary of the morphology of ESF as observed by JULIA. The left side panel shows seasonal averages of the F10.7 for each year. The right side panels shows the evolution in local time and height of ESF occurrence rates for different seasons and years (solar fluxes). The red box highlights the period of interest

4. DISCUSSION

❑ Figure 2 shows the strong control of the solar flux conditions over ESF morphology. Some of the most striking points here include the long-last occurrence rates of ESF during low solar flux conditions, and the slow ESF rise into topside heights, particularly during December solstice. Figure 2 also shows that during the low solar flux conditions of 2009 (red box), post-midnight ESF events were observed with significant occurrence rates during June solstice. Results in Figure 2 also indicate that ESF started in the pre-midnight sector during December solstice and only reached the topside (and C/NOFS altitudes) around midnight.
❑ In order to confirm the local time origin of ESF during June and December solstices, we revisited JULIA observations along with collocated digisonde measurements. The observations in Figure 3 serve to confirm that ESF events start, predominantly, in the post-midnight sector in June solstice. Figure 3 also shows that Dec. solstice ESF starts in the pre-midnight sector but continues to exist after midnight. Digisonde data shows Dec. ESF is associated with the PRE, while June ESF is associated with small midnight/post-midnight apparent uplifts. Finally, nearly collocated JULIA-C/NOFS indicate favorable conditions for ESF development around midnight in December solstice.

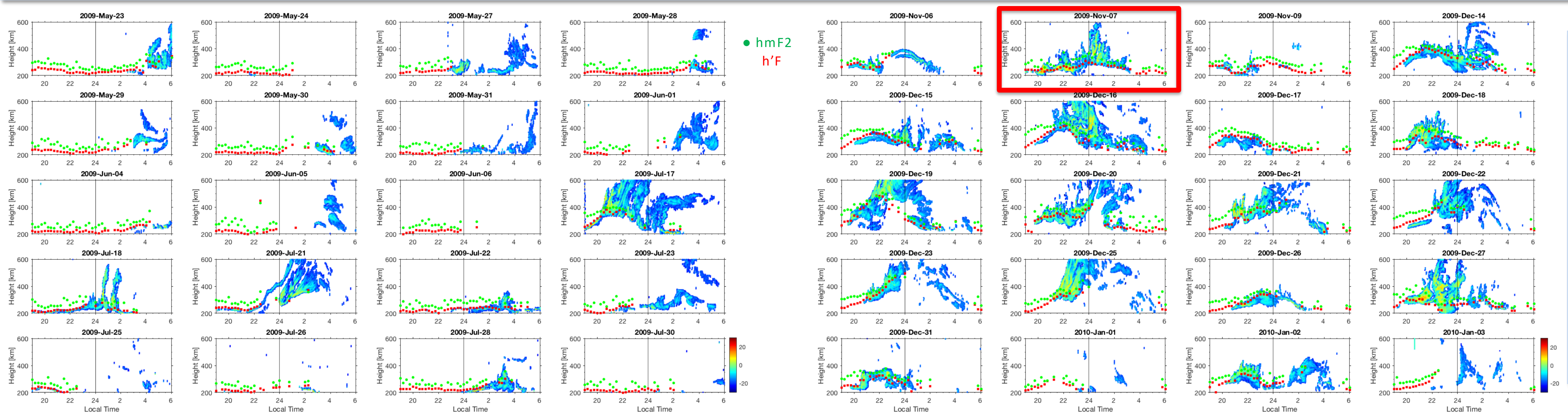


Figure 3 – [Collocated observations by JULIA and digisonde] Examples of JULIA RTI maps for June (left) and December (right) solstice 2009. Digisonde data are also shown.

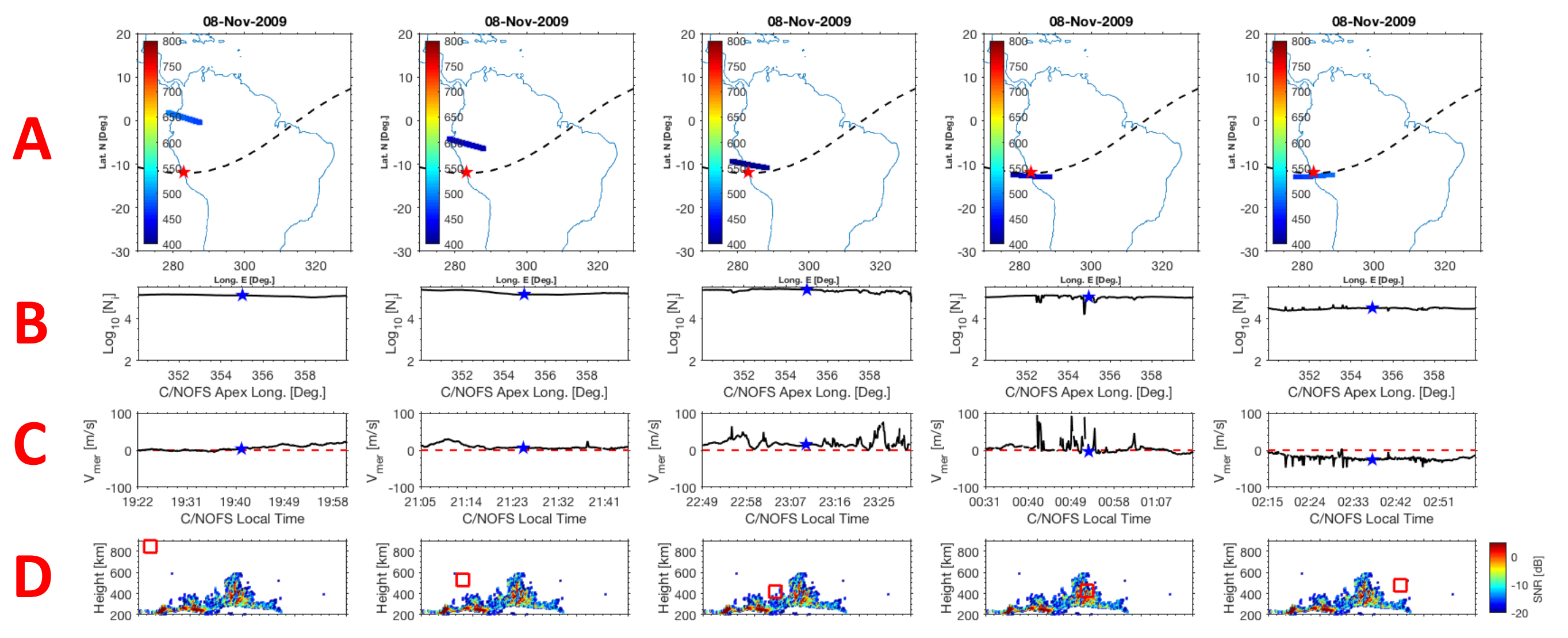


Figure 4 – [Joint observations by JULIA and C/NOFS]: (**A**) Tracks of the C/NOFS satellite near Jicamarca for Nov. 7-8, 2009. Color bar represents satellite height, and red star indicates the location of JRO. (**B**) C/NOFS Ion Velocity Meter (IVM) measurements of ion densities, and (**C**) meridional (vertical) drifts. The blue star indicates the magnetic meridian of Jicamarca. (**D**) JULIA observations of ESF. The red squares indicates the magnetic apex height of the satellite when passing by the JRO's magnetic longitude.

☞ IVM observations show upward drifts in the evening sector and around midnight indicating favorable conditions for ESF development during that time period. Adequate collocated JULIA and C/NOFS observations during June solstice were not available.

4. CONCLUSIONS

We conducted a comprehensive, multi-instrumented study of ESF. Some of the main findings of this study include:
❑ In agreement with previous studies, ESF is heavily controlled by solar flux conditions. Interestingly, ESF is more active during low solar flux conditions, in the sense that it lasts longer (in LT).
❑ Post-midnight June solstice ESF events observed in Peruvian sector during the 2008-2009 deep solar minimum originated in the post-midnight sector. Post-midnight ESF events during December solstice, however, started in the pre-midnight sector and extended through midnight into post-midnight hours.
❑ While the abnormal upward drifts near midnight observed by C/NOFS could have played a primary role in June solstice ESF, they seem to have played a secondary, but still important, role for the morphology of ESF in December Solstice in the Peruvian sector.
❑ Opportunities for a better assessment of drift conditions across the midnight sector will be possible with ICON and COSMIC-2.

References:

1. Heelis, R. A. et al. (2010), *J. Geophys. Res. Sp. Phys.*, *115*, A10321. 2.Stoneback, R. A. et al. (2011), *J. Geophys. Res. Sp. Phys.*, *116*, A12327.