The Evolution of Complex $E_s$ Observed by Multi Instruments Over Low-Latitude China

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Abstract

A complex daytime sporadic $E$ ($E_s$) case with extremely high critical frequency ($f_cE_s$) was observed over the low latitude of China on 19 May 2018. Simultaneous observational results from two very high frequency (VHF) radars, two ionosondes, and multiple Global Navigation Satellite System total electron content and scintillation receivers are analyzed to investigate the evolution of the complex $E_s$ occurrence, which consisted of a relatively weak ambient $E_s$ layer ($f_cE_s < 8$ MHz) and band-like strong $E_s$ structures ($f_cE_s > 17$ MHz) drifting from higher latitude. The strong $E_s$ structures elongated more than 500 km in the northwest-southeast direction, drifted southwestward at a speed of ~65 m/s. VHF radar backscatter echoes were generated when the strong $E_s$ structures passed the radar field of view, with different echo patterns due to different radar and antenna configurations. No VHF radar backscatter echo was associated with the ambient $E_s$ layer. The mechanisms responsible for the formations of the ambient $E_s$ layer and band-like strong $E_s$ structures are addressed and discussed.

1. Introduction

The ionospheric sporadic $E$ ($E_s$) layer has been intensively investigated for decades since its first discovery in the 1930s. It is a thin metallic layer in the height of 90–130 km, with peak density much higher than the background $E$ region of ionosphere. Under some specific conditions, the plasma density of $E_s$ can be even higher than the $F$ layer. Thus, $E_s$ is capable of causing scintillations of radio signals and influences the radio communications of high-frequency and very high frequency (VHF) bands, which are greatly dependent upon the ionosphere. Although the occurrence of $E_s$ used to be thought as unpredictable and sporadic, but quantities of recent studies revealed that its occurrence obeys a local time (LT) preference of daytime and postsunset period as well as a seasonal preference of local summer (e.g., Arras et al., 2009; Zhou et al., 2017). The characteristics and mechanisms of $E_s$ have been comprehensively studied in the past and summarized in several review papers (Haldoupis, 2011; Mathews, 1998; Whitehead, 1989). The wind shear theory was generally accepted as the main mechanism for the formation of $E_s$ layer especially in the middle latitude. In addition, physical factors such as the electric fields, shear instability, and atmospheric gravity waves are believed to be responsible in modulating the morphology of $E_s$ structures (e.g., Abdou et al., 2014; Hines, 1960; Otsuka et al., 2008; Wan et al., 1999; Woodman et al., 1991; Yokoyama et al., 2004).

Traditionally, ground-based radars such as ionosondes and VHF radars are the most fundamental means to investigate the $E_s$ layer. Ionosondes are most widely used owing to the capability of deriving the crucial parameters of $E_s$, such as the critical frequency ($f_cE_s$), blanketing frequency, and virtual height. One can easily get an intuitive view of $E_s$ features from ionograms, thus is most likely to notice the $E_s$ occurrence from the observation of ionosondes. VHF radars are mainly used to get backscatter echoes of field-aligned irregularities in different regions of the ionosphere. As for the $E$ region, two main types of radar echoes were mostly investigated and reported, the continuous radar echoes (e.g., Ning et al., 2013; Ogawa et al., 2002) and the quasiperiodic echoes (e.g., Woodman et al., 1991; Yamamoto et al., 1991). Based on a series of simultaneous observations of coordinated VHF radars and ionosondes, both types of radar echoes have been revealed related closely to $E_s$ (e.g., Chen et al., 2015; Chu et al., 2011; Hussey et al., 1998; Lee et al., 2000; Li et al., 2013; Maruyama et al., 2006; Ogawa et al., 2002; Pan et al., 1998; Patra et al., 2009; Riggin et al., 1986). However,
ground-based radars usually suffer a limited field of view and a low spatial distribution, and the temporal resolution for most operated ionosondes is far from high enough. Thus, the radar-illuminated volume is not always happening to cover the $E_s$ occurrence region, and the operating cycle may just miss the moment when $E_s$ occurs. So the evolution of $E_s$ structures in a large horizontal scale is basically impossible to be revealed if only ground-based radars are used despite the possible presence of $E_s$ structures of multiple scales. Regarding to this, total electron content (TEC) observation from ground-based Global Navigation Satellite System (GNSS) is a perfect supplement. Ever since Maeda and Heki (2014) first presented the fact that $E_s$ structures with $f_sE_s$ high enough can cause pulse-like increases in Global Positioning System (GPS) TEC, they have succeeded in revealing the evolution of strong $E_s$ structures over Japan using dense ground-based GPS network TEC in a series of articles (Maeda et al., 2016; Maeda & Heki, 2014, 2015). Sun et al. (2018) also showed an extreme case of strong $E_s$ with larger scale observed in the middle latitude of China. However, ground-based GNSS TEC is only sensitive to strong $E_s$ with high $f_sE_s$, because the background TEC is dominated by the electrons in the $F$ region, even small turbulence in the $F$ region can obscure the $E_s$ signatures in TEC time series.

Besides these mentioned above, multiple other kinds of techniques have been frequently employed in $E_s$ detection, such as incoherent scatter radar (e.g., Hysell et al., 2009; Yamamoto et al., 1991), GPS radio occultation (e.g., Yue et al., 2015, 2016), ionospheric scintillations (e.g., Seif et al., 2015, 2017), airglow imager (e.g., Kane et al., 1993; Mikhailov et al., 2008), and rocket sounding (e.g., Bernhardt et al., 2005; Pan et al., 1998). But none of these techniques alone is able to reveal all the features of $E_s$ occurrence since each kind of instrument has its disadvantages and limitations. So it is of great importance to combine different detection techniques to compensate for each other. Comprehensive analysis of multiple observations and comparison between detection results from different equipment facilitate us to get deeper insight into the inner nature of things from multiple surface phenomena.

Up to now, though numerous possible candidates have been proposed to account for $E_s$ occurrence, the insufficiency of observations on the horizontal structures, temporal evolution, and movement of $E_s$ makes it difficult to substantiate which candidate is predominant over different geographic regions during different periods of LT. Most previous studies on $E_s$ focused on the occurrences over middle latitude and during nighttime. $E_s$ evolution over low-latitude regions especially during daytime has not been intensively studied yet. The features and mechanism of strong $E_s$ over low latitude still remain confusing. Difference between strong $E_s$ structures and the relatively weaker ones is an essential issue to be solved. In this paper, we will present a strong $E_s$ case observed simultaneously with multiple instruments over low latitude of China, including VHF radars and ionosondes at two adjacent stationary stations and GNSS TEC and/or scintillation receivers from multi observational sites. Data source and the instruments will be described in section 2. We will then show the observational results in section 3 and provide some discussion in section 4. The whole paper will be summarized in section 5.

2. Data and Instrumentation

Table 1 shows information of the stations where the instruments are located. Instruments types, data temporal resolution, and data sources are also listed. Most stations mentioned in this paper are within the area of Hainan, China.

The Sanya VHF radar was built by the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS). The Fuke VHF radar was built under the support of the Chinese Meridian Project. Both radars are sensitive to ionospheric irregularities of 3-m scale size (Li et al., 2017; Xue et al., 2016), with operating frequency of 47.5 MHz (Sanya) and 47 MHz (Fuke) and peak power of 24 kW (Sanya) and 54 kW (Fuke), respectively. For Sanya (Fuke) radar, the pulse repetition frequency is 160 Hz (200 Hz) with a 4 bit complementary (13 bit Barker) code. The Sanya VHF radar can be operated at either ionospheric irregularities detection mode or meteor radar mode for different purposes. For the ionospheric irregularities detection mode, the radar is set to detect different ionospheric regions, distinguished as $E$ region and $F$ region modes, respectively. Please refer to Ning et al. (2012) and Li et al. (2014) for detailed parameters of different radar modes. In our study, the Sanya VHF radar was operated at $E$ region mode without radar beam steering, so the radar beam was pointing toward geographic due north at a zenith angle of 23° with a 3-dB beam
width of 10° in east-west and 24° in north-south. The range and temporal resolution were 0.9 km and 1 min, respectively. The Fuke VHF radar beams steered in seven directions within ±22.5° in azimuth along the east-west direction. Beam 4 pointed due north with a zenith angle of 22.8°. The horizontal and vertical 3-dB beam width of Beam 4 was ~5° and 21°, respectively (Chen et al., 2015). The detecting range of each beam was between 80 and 680 km. The range and temporal resolution were 0.711 km and 3 min, respectively. The geographic locations and the corresponding altitude in different beam directions of the two VHF radars can be seen from Figure 1 of Li et al. (2017).

Two different types of ionosondes at Sanya and Fuke were employed to provide ionograms and $f_{o}E_s$ data. The Sanya ionosonde used in this case is called PDI (portable digital ionosonde), which was developed by IGGCAS together with the South Central University for Nationalities. Lan et al. (2018) have introduced PDI in detail and showed some valuable observational results. Briefly, PDI is small in size and low in power consumption by employing a low-power transmitter and small-size antennas, thus easy to be quickly assembled and set up at temporary field stations. What is more important is its capability of being operated at a rapid detection mode with temporal periods down to a few minutes, employing the techniques of complementary code pulse multiplexing and polarization separation by software. In this study, the ionosonde was operated at a fast Doppler-ionogram mode with temporal resolution of 1 min. The Fuke ionosonde was built under the support of the Chinese Meridian Project. The type of the ionosonde is DPS-4D, with temporal resolution of 15 min.

The GNSS receivers at Sanya, GXBH, HNCM, SYNB, SYHT, and SYYL can track signals of GPS, GNSS of Russia (GLONASS), and Chinese Beidou Navigation Satellite System (BDS) with the sampling rate up to 5 Hz and derive TEC of the three GNSS constellations (Hu et al., 2017). It is noteworthy that besides TEC observation, the Sanya GNSS receiver is also capable of deriving both amplitude and phase scintillation index of the tracked satellites. We also used GNSS data from six sites of National Satellite Meteorological Center (NSMC) and three sites of Crustal Movement Observation Network of China (CMONOC) to get the TEC maps (Ding et al., 2014). These sites are all around Hainan and are also listed in Table 1. Note that the GNSS receivers at these sites were not able to track signals of BDS.

### 3. Observational Results
#### 3.1. Sanya Ionosonde and VHF Radar Observations

Strong $E_s$ structures with $f_{o}E_s$ reaching 17 MHz were observed by the Sanya ionosonde on 19 May 2018, during a rapid detection experiment with the temporal resolution of 1 min. Ionograms during 0421–0520
universal time (UT, LT = UT + 7.3) are shown in Figure 1. $f_{0}E_{s}$ began to increase since 0421 UT and reached 17 MHz at 0423 UT. Please note that the working frequency in this experiment was limited within 17 MHz; thus, we were not able to get the exact $f_{0}E_{s}$ of the strong $E_{s}$ structures. The $f_{0}E_{s}$ that is higher than 17 MHz lasted for 11 min until 0434 UT and began to decrease after 0434 UT, with a minimum of 11 MHz at 0452 UT. After that, $f_{0}E_{s}$ increased up to higher than 17 MHz again and lasted for 10 min during the period of 0502–0512 UT.

Coincidently, two clusters of $E$ region backscatter echoes were recorded by the Sanya VHF radar, nearly simultaneously with the strong $E_{s}$ detection with the Sanya ionosonde, as illustrated in Figure 2a, which shows the range-time-intensity (RTI) plot of the signal-to-noise ratio (SNR) of radar echoes. The maximum recorded SNR of echoes reached 27 dB, which we get from the raw data and is not shown in the figure. The white areas inside the RTI plot of each cluster of radar echoes were due to data gaps. A negative range rate is shown for each cluster of echoes, followed by a positive range rate, forming a V-shape in the RTI plot. The first cluster of intense V-shape echoes appeared during 0402–0442 UT, range extending 100–200 km. The second cluster of V-shape echoes appeared in a somewhat unorganized structure during 0445–0525 UT, presumably consisting of multiple V shapes, with lower SNR and smaller range extent than the first cluster of V-shape echoes. The SNR of the two clusters of V-shape echoes showed a primary descending trend with the increase of range, and a secondary peak at the ranges of 130–150 km. The two clusters of $E$ region echoes

Figure 1. Ionograms of Sanya ionosonde on 19 May 2018 during 0421–0520 UT. Red and green colors represent O- and X-mode echoes, respectively. Strong $E_{s}$ with $f_{0}E_{s}$ reaching 17 MHz was detected during the period of 0423–0434 and 0502–0512 UT. Since the working frequency of the ionosonde was limited within 17 MHz, we were not able to know whether $f_{0}E_{s}$ exceeded 17 MHz or not. Temporal resolution of the ionograms was 1 min, but intervals between selected ionograms may be larger.
corresponded well in time with the two peaks of $f_oE_s$ recorded by the Sanya ionosonde, which is the white dotted curve in Figure 2a. But we should also note that the two clusters of $E$ region echoes both appeared several minutes earlier than the $f_oE_s$ peaks. Besides the V-shape radar echoes, we also observed weaker echoes with smaller range extent during the period of 0340–0404 UT, corresponding to $f_oE_s$ of ~11 MHz.

Figure 2b shows the Doppler velocities of these $E$ region backscatter echoes. Negative and positive Doppler velocities represent the movements of irregularities toward and away from the radar, respectively. As is evident, predominantly negative (positive) range rates are associated with negative (positive) Doppler velocities in the left (right) wings of the V-shape echoes, but the values of Doppler velocity fluctuate within certain limits in each wing. Figure 2c shows Doppler spectral width of the radar backscatter echoes. The spectral width of the earliest and weakest echoes during 0340–0404 UT was around 25 m/s. For the first cluster of V-shape echoes, the spectral width was up to 55 m/s and remained relatively high values, which nearly did not change with range. For the second cluster of V-shape echoes the spectral width varied between 20 and 55 m/s with higher values at larger range.

### 3.2. Fuke Ionosonde and VHF Radar Observations

Strong $E_s$ was also detected with the ionosonde at Fuke station, which is located northwest of Sanya. Ionograms of Fuke ionosonde are shown in Figure 3. The maximum $f_oE_s$ reached 16 MHz at 0415 and...
0500 UT, which was lower than the Sanya observation (the working frequency of Fuke ionosonde was up to 20 MHz). We also refer to the observational results of Fuke VHF radar for contrast, as shown in Figures 4a–4g, which illustrate the RTI plots of backscatter echoes of the seven radar beams, respectively. \(f_0E_s\) measurements by the coordinated ionosonde are presented as white dotted curve in Figure 4d, which represents the central beam RTI plot of the Fuke radar. Similar to the Sanya observation, two clusters of \(E\) region backscatter echoes were detected by each radar beam during 0400–0410 and 0430–0510 UT, respectively, corresponding well with the two peaks of \(f_0E_s\) curve, which also appeared several minutes later than the \(E\) region backscatter echoes of the radar central beam. The earlier cluster of radar echoes appeared with high power in the RTI plots of Beams 2–4 but lasted for only ~5 min and was very weak in the RTI plots of Beams 1 and 5–7. The later cluster of radar echoes appeared with high power in the RTI plots of all the seven radar beams and lasted longer (~30 min), consisting of two to three separated parts in the RTI plot of each beam. Different from the Sanya radar echoes, the Fuke radar echoes did not appear as V shapes. The radar echoes in the RTI plot of each beam extended ~100–130 km and showed repeated and symmetric multi-layer echo patterns, with a relatively weaker secondary power peak above and below the main power peak (at ~115 km), respectively. Another feature noted from Figure 4 is that both the two clusters of radar echoes appeared earlier in the RTI plots of the eastern beams than the western beams.

3.3. Doppler Ionogram Observation

The raw observational data of Sanya ionosonde were recorded with temporal resolution as high as 1 min during our experiment, from which we can derive high-resolution Doppler ionograms as shown in Figure 5. Negative (positive) Doppler velocities represent the movements of plasma toward (away from) the ionosonde, which is in accordance with the VHF radar observation. From the sequence of Doppler ionograms in Figure 5, four main evolution processes can be seen.
(1) The first panel of Figure 5 shows an existing \( E_s \) layer with \( f_{oE_s} \) and virtual height of ~8 MHz and ~105 km, respectively, at 0340 UT. Then a relatively higher \( E_s \) layer (with virtual height of ~120 km) with \( f_{oE_s} \) of ~12 MHz appeared at 0344 UT. The higher layer descended gradually with negative Doppler velocity and merged with the lower layer at 0400 UT. (2) A much higher layer with \( f_{oE_s} \) no lower than 17 MHz appeared at the virtual height of ~150 km at 0408 UT, descended gradually with negative Doppler velocity and merged with the lower layer at 0428 UT. Then the Doppler velocity of the layer with higher \( f_{oE_s} \) turned positive at 0432 UT and ascended gradually until 0452 UT when it reached the virtual height of ~150 km and disappeared. (3) A process similar to (2) repeated during the period of 0456–0526 UT. (4) A layer with \( f_{oE_s} \) of ~12 MHz ascended gradually with positive Doppler velocity and disappeared after 0534 UT, while \( f_{oE_s} \) of the lower layer decreased gradually.

From the four main evolution processes, three main facts can be concluded. (1) Positive (negative) Doppler velocity was always associated with positive (negative) virtual height rate. (2) When a higher layer merged with the lower layer, its Doppler velocity turned nearly zero. (3) The Doppler velocity of the lower layer kept nearly zero during the whole process.
Figure 5. High-resolution Doppler ionograms of Sanya ionosonde during 0340–0538 UT on 19 May 2018. Negative (positive) Doppler velocity represents irregularity motion toward (away from) the ionosonde. Temporal resolution of the ionograms was 1 min, but intervals between selected Doppler ionograms may be larger.
3.4. GNSS TEC and Scintillation Observation

In order to investigate the evolution process of the complex $E_s$ occurrence in a larger spatial scale, we employed the GNSS TEC observation to trace the strong $E_s$ structures. As revealed by previous studies (e.g., Maeda & Heki, 2014), strong $E_s$ structures with $f_sE_s$ high enough can be distinguished as pulse-like positive disturbances in GNSS TEC time series. Using the data processing method of subtracting the 10-min running average from each vertical TEC time series, we get the detrended TEC (DTEC) of three adjacent GNSS sites, named SYNB, SANY (actually, the Sanya station and the site name represent the prefix of GNSS data for a common format with other sites), and HNCM, respectively. Locations of the GNSS sites are shown as stars of different colors (red, blue, and gray for SYNB, SANY, and HNCM, respectively) in Figure 6a. Geographic locations of ionospheric pierce points (IPPs) of five BDS GEO satellites at the height of 100 km for each GNSS site are marked as large dots. (b) DTEC time series (solid curves) and $S_4$ index time series (dashed curves, SANY only) of BDS GEO satellites during 0300–0600 UT on 19 May 2018, each offset by the longitude of the corresponding IPP in (a). IPP markers in (a) and DTEC time series in (b) are colored as the corresponding sites.

![Figure 6](https://example.com/figure6)

**Figure 6.** (a) Geographic locations of three GNSS sites, marked as red, blue, and gray stars for SYNB, SANY, and HNCM, respectively. Geographic locations of ionospheric pierce points (IPPs) of five BDS GEO satellites at the height of 100 km for each GNSS site are marked as large dots. (b) DTEC time series (solid curves) and $S_4$ index time series (dashed curves, SANY only) of BDS GEO satellites during 0300–0600 UT on 19 May 2018, each offset by the longitude of the corresponding IPP in (a). IPP markers in (a) and DTEC time series in (b) are colored as the corresponding sites.

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Figure 7. Time evolution of the GNSS DTEC maps from 0330 to 0530 UT on 19 May 2018 over low-latitude China. Temporal resolution of the maps was 1 min, but intervals between selected maps may be larger. Green areas indicate that DTEC was low and no strong $E_s$ structure was detected, while yellow areas indicate strong $E_s$ occurrence. Positions of the two stationary stations Sanya and Fuke are marked in the maps, labeled as SY and FK, respectively.
the two sites are aligned nearly along the same latitude of ~18.0°N between ~107.5°E and ~111.2°E. The five IPPs of HNCM are aligned along ~19.2°N between ~108.3°E and ~111.8°E.

From Figure 6b, we can see pulse-like strong $E_s$ disturbances appeared in every DTEC time series along ~18.0°N during 0430–0500 UT and DTEC time series of the four eastern IPPs along ~19.2°N during 0345–0415 UT, as indicated by the black and gray solid arrow, respectively. Strong $E_s$ disturbances also appeared along ~18.0°N during ~0530–0545 UT, but only at the western IPPs with weak amplitudes, as indicated by the black dashed arrow. Besides, the westernmost IPP of the ~19.2°N chain also detected strong $E_s$ structure at ~0520 UT, but the DTEC pulse deviated the extension line of the gray solid arrow. These strong $E_s$ disturbances indicated by the same arrow always appeared earlier in DTEC time series of the eastern IPPs than the western IPPs along the same latitude. Though different arrows had the same slopes, we cannot distinguish whether the disturbances indicated by different arrows belong to the same strong $E_s$ structure or not from Figure 6.

So we collected GNSS data from totally 15 GNSS sites around Hainan and succeeded in making the DTEC maps as illustrated in Figure 7. The two integrated observation stations, Sanya and Fuke, are marked as red stars on the maps, labeled as SY and FK, respectively. We can see strong $E_s$ first showed appearance at the northeast corner of the map (top-right corner of the panel) in the first panel of Figure 7 at 0330 UT. It moved southwestward gradually and showed band-like shape since 0350 UT, which elongated northwest-southeast (NW-SE). The strong $E_s$ band continued its southwestward movement; passed over Fuke and Sanya at 0415 and 0425 UT, respectively; showed last appearance at the southwest corner of the map (bottom-left corner of the panel) at 0510 UT; and then moved out of our scope of observation. Besides the strong $E_s$ structure that showed apparent band-like appearance (bright yellow dots on the maps), the maps also recorded a relatively weaker $E_s$ structure, which also came from the northeast corner of the map and moved southwestward but was later than the stronger one. It showed first appearance at 0415 UT at the top-right corner of the panel and lasted to 0420 UT. Then no evident appearance was shown until 0455 UT when it was not far from Sanya. The relatively weaker $E_s$ structure appeared as dark orange color on

Figure 8. $S_4$ index of multi-GNSS constellations during 0200–0700 UT on 19 May 2018 derived with the Sanya GNSS receiver.
the maps and passed over Sanya and Fuke during 0500–0510 UT, but its horizontal shape could not be distinguished most of the time due to the low DTEC amplitudes. The SANY GNSS receiver is capable of obtaining amplitude scintillation index S4 of the tracked GNSS signals. The S4 index of the five BDS GEO satellites signals are shown as black dashed curves in Figure 6b, offset by the longitudes of corresponding IPPs. The S4 index of different GNSS constellations is shown in Figure 8, and an elevation angle threshold of 30° was employed for all the tracked satellites signals. As we can see from Figure 6b, the S4 index of five BDS GEO satellites all kept a low level around zero. The S4 index of different GNSS constellations showed different features in Figure 8. Weak amplitude scintillations of GPS, GLONASS, and Galileo signals were caused during 0400–0530 UT but with different magnitudes where GPS > Galileo > GLONASS. No scintillation of BDS signals was caused.

4. Discussion

4.1. On the Movement of Strong Es Structures

As revealed by Figure 7, the strong Es structures drifted from higher latitude, which were out of the coverage of our data set. Since there were some uncovered areas of GNSS TEC observation over the sea, the band-like strong Es structure seemed like two separated parts at times in Figure 7 (e.g., 0400 and 0405 UT). But they actually belonged to the same structure, since they moved together toward the same direction at the same speed. The eastern and western ends of the band-like strong Es structure were out of our scope of observation, so we cannot tell the exact horizontal scale. But its largest extension that the map could record appeared at 0450 UT, which was ~540 km. The width of the band-like strong Es structure was no more than 50 km. But the spatial resolution of GNSS DTEC map was not high enough to get a more accurate width, so we will discuss it later based on other observational results. Looking through all the maps, the band-like strong Es structure mainly drifted perpendicular to its elongation, that is, southwestward. The mean drifting velocity can be calculated using the formula \( V = \frac{D}{T} \), where \( D \) and \( T \) refer to the displacement of strong Es structure perpendicular to its elongation and the consuming time, respectively. Through rough calculation, we get the drifting velocity of the strong Es structure of ~65 m/s. The pulse-like DTEC disturbances along ~18.0°N and ~19.2°N during 0430–0500 and 0345–0415 UT, respectively, in Figure 6 were all due to the band-like strong Es structure, which passed over the northern and eastern IPPs earlier. The weaker pulse-like DTEC disturbances along ~18.0°N during ~0530–0545 UT as indicated by the dashed arrow in Figure 6b were due to the later but weaker strong Es structure.

The movements of strong Es structures were also responsible for the observational results of Doppler ionograms (Figure 5). The higher Es layers in the Doppler ionograms were actually off-vertically reflected signals from the drifting strong Es structures due to the wide beam of the antenna. The larger virtual heights were due to longer raypaths of off-vertical signals (Lee et al., 2000). Figure 9a schematically illustrates the field of view of Sanya VHF radar and Sanya ionosonde. Figure 9b schematically shows a scenario where strong Es structures are passing the field of view of the ionosonde. Negative (positive) virtual height rates and negative (positive) Doppler velocities can be observed when the strong Es structures drift toward (away from) the ionosonde. The scenarios of “higher” Es layers merged with the “lower” Es layer (e.g., 0428 and 0508 UT in Figure 5) actually correspond to the drifting strong Es structures right above the ionosonde, with the smallest virtual height and radial Doppler velocity of nearly zero, which correspond well in time with the GNSS TEC observation when strong Es structures passed over Sanya (e.g., 0430 and 0510 UT in Figure 7). The smallest virtual height of the drifting strong Es structures represents the real virtual height, which is the same with the virtual height of the ambient Es layer (the “lower” Es layer in Figure 5), so the drifting strong Es structures and the ambient Es layer were at the same altitude. Another evidence to confirm the horizontal rather than vertical movement of the strong Es structures is shown in Figure 10, which is the comparison between the Doppler ionograms within the E region altitude and the common ionograms up to the F region altitude. When the strong Es structures passed over Sanya, the upper F layer was gradually blanketed. When the strong Es structures drifted away, the F layer trace gradually appeared again.

The wide beam width of various types of ionosondes was suggested by many previous researches, which enables the capability of ionosondes to receive off-vertically reflected signals (Bowman, 1985; Hussey et al., 1998; Maruyama et al., 2006). Ogawa et al. (2002) proposed that the beam width of the ionosonde
they used was ~60°, which coincides with the beam width of Fuke DPS-4D ionosonde as Chen et al. (2015) pointed out. For relevant details about the wide beam width of ionosondes, please refer to the manual of DPS-4D. Reflected echoes from off-vertical directions could be seen as different colors from the vertically reflected echoes in the Fuke ionograms (Figure 3), such as the yellow trace, the light blue trace, the purple trace, and the pink trace, marked as A, B, C, and D in the figure, respectively. These traces used to be mistaken as multilayers of Es at different altitudes since most of the previous ionosondes were not able to obtain Doppler velocity and the temporal resolution was not high enough to record the complete process of drifting strong Es structures passing over the field of view of ionosondes. In our case, the complete process was recorded by the Sanya ionosonde, and the result was also verified by GNSS TEC observation.

Assuming the movements of the strong Es structures were predominantly horizontal, the drifting velocity can be calculated based on the data of the Doppler ionograms. As the strong Es structure drifted into the field of view of the Sanya ionosonde, Doppler velocity $V_d$ derived from Doppler ionograms of the Sanya ionosonde.

$$V_d = V_0 \times \sin \theta,$$

where $V_0$ is the horizontal drifting velocity of the strong Es structure and $\theta$ is the angle between the line of sight of the strong Es structure and the vertical direction, as schematically illustrated in Figure 9(b). The angle $\theta$ can be given as

$$\theta = \cos^{-1} \frac{H_0}{R},$$

where $H_0$ and $R$ are the virtual height of the ambient Es layer and the line-of-sight virtual height of the strong Es structure, respectively. $V_d$ and $R$ are both accessible from the Doppler ionogram data. $H_0$ can be derived as the average of the virtual height of signals between the frequency of 3.5 and 7.5 MHz, which covers the frequency range of the ambient $E_s$ layer. Through some data calculation, we get the horizontal drifting velocity $V_0$ of ~64 m/s, which was extremely consistent with the one we obtained with GNSS data. Maeda and Heki (2014) got the drifting velocity of strong Es of 60 m/s for an eastward drifting case and 80 m/s for a southwestward drifting case, respectively. Our result agrees with these cases in the same order of magnitude.
4.2. On the Generation of Radar Backscatter Echoes and GNSS Scintillation

The generation of \(E\) region VHF radar backscatter echoes associated with \(E_s\) occurrence have been presented by many coordinated observations of ionosondes and VHF radars (e.g., Chu et al., 2011; Maruyama et al., 2006; Ogawa et al., 2002). Multiple previous studies have presented \(E\) region backscatter echo striations with negative or positive slopes due to patches or clouds of \(E_s\) ionization drifting in the horizontal plane (e.g., Chen et al., 2005; Chu & Wang, 1997; Hysell & Burcham, 2000; Haldoupis et al., 2001). The temporal consistency of \(E\) region radar backscatter echoes with \(f_{o}E_s\) peaks for both Sanya and Fuke in our case indicated the occurrence of strong \(E_s\) structures might be responsible for the generation of radar backscatter echoes. Since the strong \(E_s\) structures drifted southwestward from higher latitude, they would drift into the field of view of the VHF radars earlier than that of the coordinated ionosondes, as schematically illustrated in Figure 9a. So for both stations, the \(f_{o}E_s\) peaks appeared several minutes later than the radar backscatter echoes. The southwestward movement of strong \(E_s\) structures was also responsible for the earlier
With respect to the V-shape backscatter echoes of Sanya radar, which extended to the range larger than 200 km, three main possible reasons could contribute to this: (1) the movement of the strong $E_s$ structures, (2) the wide radar beam, and (3) the sidelobe detection by the radar. The wide beam of the Sanya VHF radar allows irregularities embedded in the strong $E_s$ structures to be detected far from the beam center. Thus, negative (positive) range rate and negative (positive) Doppler velocity could be seen in the RTI plot as the irregularities moved nearer to (away from) the radar. Using radar imaging technique, Hysell et al. (2002) demonstrated radar echo striations due to scattering regions at a common altitude drifting through the radar-illuminated volume. Even though their observation was during nighttime, which was different from our case, there are still some similarities in explaining the radar echo striations in RTI plots as the trails of the drifting scatters, which are in analogy with the trails of stars in long-duration photographic exposure.

But the echo striations in previous studies usually had smaller range extent limited to relatively narrow radar beam widths. Recently, the newly developed capability of all-sky meteor radar in detecting $E$ region irregularities has illustrated V-shape echoes generated by drifting $E_s$ patches, which extended to more than 200 km owing to the extraordinary wide radar beam (Wang et al., 2019; Xie et al., 2019). Though the beam width of the Sanya VHF radar is considerably wide, it is much narrower than that of all-sky meteor radars. What is more, the radar echoes by all-sky meteor radars tend to show lower intensities with larger ranges, but the V-shape echoes by the Sanya VHF radar in our case showed secondary SNR peaks at the ranges of 130–150 km (Figure 2a). So the large range extent of Sanya radar backscatter echoes was not only due to the wide radar beam but may also owing to other reasons. A similar case of U-shape backscatter echoes detected by the Gadanki radar associated with daytime strong $E_s$ occurrence was presented by Patra et al. (2012). In their case, there were multiple secondary SNR peaks with larger ranges in both wings of the U-shape radar echoes, which were verified to be detected by the sidelobes of the radar antenna, and they argued that the sidelobe detection of the plasma irregularities must be related to unusually large electron density structures linked with the intense $E_s$ activity. So the Sanya radar echoes with ranges larger than 130 km in our case were most probably due to the sidelobe detection of the antenna. But our case differs from Patra et al. (2012) in that the main lobe of the Sanya VHF radar antenna was wider than that of Gadanki radar. So in their case the radar backscatter echoes detected by the main lobe of the antenna were limited below the range of 110 km while in our case the main lobe detection may extend to the range of ~130 km.

Considering the range rate of Sanya radar backscatter echoes, we can see from Figure 2a that it costs the echoes ~20 min to descend from 200 to 100 km, with a range rate of ~83 m/s, which was comparable to the predominant Doppler velocity derived from Figure 2b but a little larger than the drifting velocity calculated for the strong $E_s$ structures in section 4.1. Li et al. (2013) argued that the detection by VHF radar is closely related to the movement of background $E_s$ structures, the angle between the radar beam and the $E_s$ drifting velocity, and the possible polarized electric field embedded in the $E_s$ structures. Thus, the ranges are dependent upon which part of the irregularities generated the backscatter, which may lead to an overestimate or underestimate. In spite of this, the range rate of radar backscatter echoes was comparable to the drifting velocity of strong $E_s$ structures and was consistent with previous studies (e.g., Chu & Wang, 1997; Haldoupis et al., 2001; Wang et al., 2019).

For the backscatter echoes of the Fuke VHF radar (Figure 4), the repeated and symmetric multi-layer echo patterns with a weaker secondary power peak above and below the main power peak of each cluster of radar echoes respectively were also observed in previous studies and were attributed to the radar design such as the sidelobe of Barker code (Shang et al., 2014; Xue et al., 2016). Here we concentrate our discussion on the central layer of each echo cluster at ~115 km. Different from that of the Sanya VHF radar, the beam width of Fuke VHF radar is narrow. Each beam was like a probe that can only detect a small portion of the irregularities within a limited field of view. So the backscatter echoes of slimmer drifting irregularities would last shorter in the RTI plot. Since the first cluster of strong $E_s$ structure in our case was slim band-like, the generated backscatter echoes were also “slim” in the Fuke RTI plots. The second cluster of strong $E_s$ structures did not cause strong enough disturbances in the GNSS DTEC maps (Figure 7); thus, the horizontal shape could not be obtained, and the generated Sanya radar backscatter echoes were unorganized, presumably
consisting of multi V shapes but unable to be distinguished from each other. Nevertheless, this cluster of radar echoes appeared as three clear separated parts in the RTI plots of Fuke Radar Beam 4 (Figure 4d). So it is likely that the second cluster of strong $E_s$ consisted of at least three separated slim band-like structures. Since they were detected over both Fuke and Sanya with the same time interval (±40 min) posterior to the first cluster of strong $E_s$ structures, they were believed to elongate hundreds of kilometers in the same direction (NW-SE) with the earlier and stronger one.

Since the Fuke radar beam is narrow, the width of each distinguished band-like strong $E_s$ structure generating radar backscatter echoes can be approximately calculated through multiplying the drifting velocity by the duration of the backscatter. Each separated cluster of radar backscatter echoes lasted for 5–6 min in the RTI plot of Figure 4d, and the drifting velocity was ~65 m/s (obtained in section 4.1), so the horizontal widths were estimated to be ~20 km. Employing the similar method, the horizontal spacing between the four clusters of strong $E_s$ structures, they were believed to elongate hundreds of kilometers in the same direction (NW-SE) with the earlier and stronger one.

The wind shear theory is widely accepted as the primary driven source for $E_s$ occurrence (Whitehead, 1989). The daytime complex $E_s$ in our case was composed of strong band-like $E_s$ structures drifting from higher latitude and a relatively weak ambient $E_s$ layer. The ambient $E_s$ layer with $f_oE_s$ lower than 8 MHz but higher than 6 MHz for most of the time in our case would be considered as strong in previous studies but was associated with no radar backscatter echoes, and the Doppler velocity of this layer remained nearly zero (Figure 5). Previous studies suggested that the high $f_oE_s$ is a necessary but not sufficient condition to generate radar backscatter echoes (e.g., Hussey et al., 1998; Maruyama et al., 2006). Besides the high plasma density, the inhomogeneity inside the plasma is also required to provide essential density gradient for coherent scattering to occur (Riggin et al., 1986). During daytime, the ambient $E_s$ layer driven by wind shear is usually homogeneous due to high ionization rate of optical ionization process, which results in the high conductivity of the $E$ region and is unfavorable for the generation of radar backscatter echoes (e.g., Shalimov et al., 1998).

However, intense radar backscatter echoes were associated with the drifting strong $E_s$ structures, indicating the inhomogeneity inside the structures. The similar case reported by Patra et al. (2012) was attributed to either gradient drift process or Kelvin-Helmholtz (KH) instability. Maeda et al. (2016) proposed that the vertical shear of zonal wind is the primary driver for the formation of the observed band-like strong $E_s$ structures and the KH instability together with wind shear caused ion perturbation in the neutral atmosphere. Based on the theory of Larsen (2000), the measured Doppler velocity inside the KH billow depends on
which part generates the backscatter. In our case, though the Doppler velocity of the left (right) wing of the V-shape radar echoes was predominantly negative (positive) and was comparable to the range rate, there still was variance inside the same stratiﬁon. The high Doppler spectral width of the radar echoes also indicated severe perturbation inside the layer. So the dense $E_s$ structures were most likely to be produced by the convergent ion motion driven by zonal wind shears at higher latitude and then became unstable and inhomogeneous through shear instability, possibly the KH instability (Hysell et al., 2002, 2014). These structures then drifted with neutral wind and generated radar backscatterers when passing the radar ﬁeld of view.

However, we could not locate the primary source region of these strong $E_s$ structures based on the present data set. Li et al. (2019) reported two crossed GNSS observational chains with elaborately selected site distribution along 110°E and 23°N, respectively, which can be employed in investigating strong $E_s$ structures. The possible source region for similar strong $E_s$ occurrence was expected to be oriented in future studies.

5. Conclusion

In this study, a case of daytime complex $E_s$ producing VHF radar backscatter echoes and weak GNSS amplitude scintillations over low-latitude China was investigated with multi-instruments including ionosondes, VHF radars, and GNSS TEC and scintillation receivers. We draw the conclusions below:

1. The complex $E_s$ was composed of band-like strong $E_s$ structures ($f_c E_s > 17$ MHz) and a relatively weak ambient $E_s$ layer ($f_c E_s < 8$ MHz). The strong $E_s$ structures elongated more than 540 km in the NW-SE direction and drifted southwestward from higher latitude at the speed of ~65 m/s. At least four band-like strong $E_s$ structures with different separation distances were observed.

2. Backscatter echoes were generated by drifting strong $E_s$ structures and observed by the Sanya and Fuke VHF radars, showing different echo patterns due to different radar code and antenna conﬁgurations. The unique V-shape Sanya radar echoes were mostly due to the wide radar beam and sidelobe detection of the antenna.

3. The ambient $E_s$ layer was considered to be generated by zonal wind shears, which remained homogeneous with Doppler velocity of nearly zero. The band-like strong $E_s$ structures were possibly generated under wind shear, became unstable through KH instability, and drifted with neutral wind.

Data Availability Statement

We acknowledge the usage of GNSS data, VHF radar data, and Digisonde data from the Chinese Meridian Project (https://data.meridianproject.ac.cn/) and the Data Center for Geophysics, National Earth System Science Data Sharing Infrastructure at BNOSE, IGCCAS (http://wdc.geophys.ac.cn).

References


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