Multilayered Sporadic-E Response to the Annular Solar Eclipse on June 21, 2020

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Abstract  A moon shadow of annular solar eclipse passed through East Asia in the afternoon on June 21, 2020, which was a good opportunity to study the rapid ionospheric response to the solar radiation variations. In the study, the high-frequency echoes recorded by the ionosondes at Wuhan (82.4% obscuration), Xiamen (97.8% obscuration), and Nanning (81.1% obscuration) are analyzed to examine the variations in sporadic-E (Es) during the obscuration over the East China area. The echoes show not only the variations in the typical signal Es layer below 130 km, but for the first time also the multilayered Es at altitudes from 130 to 190 km. The relationship between the formation of the multilayered Es and the uplifted Es near the center path of the moon shadow are examined in the study. The small-scale atmospheric gravity waves play a key role in modulating the Es behaviors during the eclipse.

Plain Language Summary  The sky’s darkness due to the eclipse obscuration can reduce the air temperature and induce wind and atmospheric waves, which makes a bit windy and chill people suddenly during the obscuration. Following the famous total solar eclipses on July 22, 2009 and August 21, 2017, the annular solar eclipse occurred on June 21, 2020 is another wonderful opportunity for us to examine the ionospheric and atmospheric responses to the sudden darkness. The impact of the annular solar eclipse on the ionosphere and atmosphere shall be weaker than that of a total solar eclipse. However, it is surprising for us to see that the ionospheric behaviors between 100 and 200 km altitudes during the 2020 annular eclipse are as prosperous as those during the total solar eclipses. The morphology of sporadic-E (Es) during the annular solar eclipse is examined here in detail. The results reveal that the atmospheric gravity waves play a key role in modulating the Es behaviors over eastern China during the 2020 annular solar eclipse.

1. Introduction

Solar eclipse is a unique space weather phenomenon that can induce rapid variations in ionospheric structures. It provides us rare opportunity to study the responses of the ionospheric and atmospheric structures and dynamics to the sudden reduction in solar radiation. Strong temperature gradients in the obscuration area can induce atmospheric gravity waves (AGWs) (Chimonas, 1970). The AGW-induced windshear interacting with metallic ions can form Sporadic-E (Es). Furthermore, the eclipse-generated AGWs can modulate the Es behaviors that are highly variable and different between the eclipse events in the areas of Asia, Africa, and Europe (Chen et al., 2010; Datta, 1972; Jakowski et al., 2008; Manju et al., 2014; Muller-Wodarg et al., 1998; Stoffregen, 1955; Tiwari et al., 2019).

Datta (1972) reported that the Es is strong between the beginning and maximum obscuration of the partial eclipse over Haringhat (67% obscuration), India, on June 20, 1955. Chen et al. (2010) and Yadav et al. (2013) showed that the Es intensity reached its maximum near the end of the total solar eclipse on July 22, 2009. Tiwari et al. (2019) found that the top frequency of the Es layer during the 2009 eclipse was much higher than that on the reference days. By contrast, several studies showed that the Es can attenuate during several
eclipses. Stoffregen (1955) found that the $E_s$ ionization decreased significantly and even disappeared near the totality path on June 30, 1954. Nayak et al. (2012) reported the weakened $E_s$ layer over Tirunelveli (84% obscuration) during the annual solar eclipse on January 15, 2010. However, Pezzopane et al. (2015) suggested that the AGWs can influence the persistence, rather than the intensity, of the $E_s$ layer during the solar eclipse on March 20, 2015. Bullett and Mabie (2018) reported no discernible change in the $E_s$ layer near the totality path over North America during the 2017 eclipse. Additionally, several studies showed the $E_s$ oscillations with periods ranging from $\sim$10 to 100 min during the eclipses on 2009, 2010 (Chen et al., 2010; Manju et al., 2014; Tiwari et al., 2019; Yadav et al., 2013). They attributed the formation of the oscillations to the eclipse-generated AGWs.

The $E_s$ behaviors being different between the eclipses should relate to the unique shadow geometry, season, and $E_s$ climatology for each eclipse. A moon shadow of an annular solar eclipse passed through eastern China from $\sim$06:00 to $\sim$09:00 UT on 21 June 2020 (summer solstice) under geomagnetic quiet condition (Figure S1). It can be expected that the $E_s$ layer highly occurs over Asia in the summer (Qiu et al., 2019). Accordingly, the June 2020 eclipse is another great opportunity for investigating the $E_s$ response to the eclipse.

This study utilizes three ionosondes sited in Wuhan (30.5°N, 114.4°E, 82.4% obscuration), Hubei Province, Xiamen (24.2°N, 118.07°E, 97.8% obscuration), Fujian Province, and Nanning (22.7°N, 109.25°E, 81.1% obscuration), Guangxi Province, within the 80% obscuration area (Figure 1a) to observe the eclipse effect. The three ionosondes are operated by the National Satellite Meteorological Center (NSMC) and the Chinese Meridian Project (CMP). The three ionosondes recorded the ionograms every 5 min from 19 to 21 June 2020 except over Xiamen on June 19, 2020 (15 min). The high-temporal resolution benefits to capture the rapid changes in ionospheric structures during the eclipse. This study focuses on the ordinary-mode (O-mode) high-frequency (HF) echoes between 100 and 200 km altitudes for studying the $E_s$ behaviors. The critical frequency of the $E_s$ layer ($f_oE_s$) and its altitude that are derived from the O-mode reflection echoes are manually scaled from the ionograms using the SAO explorer software.

2. Results

The right panels of Figure 1 illustrate examples of the O-mode HF echoes recorded by the three ionosondes over Wuhan, Xiamen, and Nanning. The signal-layered echoes with frequency $>3.0$ MHz (Pignalberi et al., 2014) below 130 km altitude (virtual height) is the typical single $E_s$ layer. Note that, hereinafter, the altitude stands for the virtual height of the echo reflection point. The term “$E_s$ layer” stands for the typical signal $E_s$ layer. In Figures 1b and 1c, the typical $E_s$ layers with $f_oE_s > 5.0$ MHz are observed over Wuhan and Xiamen. However, several echoes appear at 145, 155, 165, 175, 190 km altitudes over Nanning at 09:06 UT (Figure 1d). The group of the multilayered echoes consisting of five sublayers distributes within 130–190 km altitudes that are much higher than the typical $E_s$ altitude. The multilayered echoes may be the electron density ledge between the $E$ and $F_2$ layers.

In Figure 2, we construct the height-time-amplitude (HTA) of the echoes to examine the altitude and temporal evolution of the $E_s$ during the eclipse. The HTA is the integration of the echo amplitude over the sounding frequencies ranging from 1.0 to 15.0 MHz at each altitude from each ionogram. The $E$ layer distributes near 105 km altitude over Xiamen during the eclipse, while it becomes weak near the maximum obscuration (08:10 UT). On the other hand, the $E_s$ layer near 115 km altitude is weakened and uplifted since 07:30 UT that is 47 min after the beginning of the obscuration. The $E_s$ layer reaches its highest altitude near 150 km, which is higher than the typical $E_s$ altitude, near the maximum obscuration (08:10 UT). It eventually descends back to $\sim$110 km at 09:55 UT that is near a half hour after the obscuration. Moreover, it can be seen that the $E_s$ layer is widely scattered within the altitude ranging from 140 to 180 km near the maximum obscuration.

The echoes of the $E_s$ layer are strong and stable near 110 km over Nanning during the obscuration. Besides the typical $E_s$ layer, the multilayered echoes suddenly appear since the maximum obscuration and vanish after 09:06 UT (near end of obscuration). The multilayered echoes mainly distribute at the altitudes ranging
Space Weather

from 130 to 190 km that are much higher than the typical $E_s$ altitude. The echoes over Wuhan are much weaker than that over the other two stations. The echoes near 110 km altitude are weak and even disappear between the beginning and maximum obscuration. Thereafter, an echo suddenly appears at $\sim 150$ km altitude near the maximum obscuration, and descends to $\sim 118$ km around the end of obscuration. The time series of the $f_{E_s}$ and multilayered echoes are displayed in Figures 3 and 4, respectively, for showing the $E_s$ behaviors in detail.

Figure 3 displays the comparison between the variations in the $f_{E_s}$ that is mainly below 130 km on the eclipse day and 2 days before. To avoid the contamination of the long-period variability to the examination of rapid changes in ionosphere due to a space weather phenomenon, the ionosonde observations on the 2 days before are chosen as the reference for the further comparison. The $f_{E_s}$ over Wuhan during the eclipse
period is much lower than that on the reference days (Figure 3a). It almost vanishes between the beginning and maximum obscuration. Thereafter, it appears again and gradually enhances after the maximum obscuration. The $f_E$ reaches its maximum over Xiamen near 07:10 UT, and rapidly decreases to its minimum near the maximum obscuration (Figure 3b). It can be noted that both the variations in $f_E$ of the two stations contain the long-period tendencies responding to the obscuration. The $f_E$ oscillates periodically over Xiamen during the eclipse period. The wavelet spectrum (Figure 3c) shows that the period of the $f_E$ oscillations ranges from 15 to 60 min during the solar eclipse period. However, the $f_E$ over Nanning is highly fluctuated during the three days (Figure 3d). There is no obvious tendency over Nanning, and it is hard to attribute the variations in the $f_E$ to the eclipse effect.

Figure 4 further shows the characteristics of the multilayered echoes within the 3.0–5.0 MHz frequency band at 130–190 km altitude over Nanning. The multilayered echoes are most intense within the frequency band according to all the ionograms over Nanning during the obscuration (Figure S2). No multilayered echoes can be observed on the reference days (Figures 4a and 4b, S3, S4). However, clear multilayered echoes consisting of 3–5 sublayers appear mainly at 130–190 km altitudes between 08:36 and 09:06 UT on the eclipse day (Figure 4c). There are spans between the nearby sublayers in the vertical direction at each time step. The mean vertical spans are 22.6, 19.9, 19.8, 17.1, 17.7, and 11.4 km at 08:36, 08:41, 08:46, 08:51, 09:01, and 09:06 UT, respectively.

**Figure 2.** Height-time-amplitude (HTA) plots over Wuhan, Xiamen, and Nanning, during the eclipse. The HTA is the total echo amplitude as a function of virtual height and universal time (UT). The horizontal line at 130 km (virtual height) indicates the altitude where the typical signal $E_s$ layer always occurs below. The vertical lines indicate the begin (b), maximum (M), and end (e) of the obscuration.
3. Discussion

The prominent reduction in the $f_{Es}$ over Xiamen during the obscuration (Figure 3b) is similar to the weakness of $E_s$ as reported by Stoffregen (1955) and Nayak et al. (2012) during the solar eclipses on June 30, 1954 and on January 15, 2011, respectively. It is well known that the photochemical and transport processes...
mainly control the behaviors of plasma in the ionosphere. The weakness of the $E$ layer during the eclipse period can be expected, because the molecular ions are highly controlled by the photochemical process due to the variations in solar radiation. However, the reduction in solar radiation during an eclipse has little effect on the $E_s$ ionization that mainly consists of metallic ions (Pezzopane et al., 2015; Whitehead, 1989). Therefore, the reduction in $f_o E_s$ seems irrelevant to the photochemical process. Rishbeth (1968) suggested that the thermal contraction and the reduction in conductivity can contribute to the vertical transport in the obscuration area. The prominent uplift of the $E_s$ layer over Xiamen suggests the vertical transport being significant in the $E$ region around the path of maximum obscuration (Figure 2b), which was rarely observed. Meanwhile, the large scatter of the $E_s$ layer during its uplift would reduce the $f_o E_s$. The descending movement of the echo over Wuhan is similar to the descending $E_s$ layer over Xiamen from the maximum obscuration to the end of eclipse. The uplifted $E_s$ layer around the path of maximum obscuration may extend poleward along the geomagnetic field lines to the northern 80% obscuration area. That may be the reason for the sudden appearance of the echo at $\sim 150$ km altitude over Wuhan after the maximum obscuration.

The enhancement of the $f_o E_s$ over Xiamen near the beginning of obscuration is similar to the results of Datta et al. (1972) and Yadav et al. (2013). They attributed the $E_s$ enhancement to the upward or downward propagating AGWs, which can be activated due to the photochemistry and temperature changes caused by the moving cooling spot of the Moon's shadow (Chimonas, 1970; Fritts & Luo, 1993). The presence of AGWs during an eclipse can cause a strong convergence of wind and introduce a wind shear condition, which further induce an intensification of the $E_s$ ionization (Chen et al., 2010). Furthermore, the oscillations with the period of 15–60 min over Xiamen, further verify the appearance of the AGWs during the eclipse. The period of the observed waves mainly agrees with the previous studies (Tiwari et al., 2019; Walker et al., 1991; Yadav et al., 2013).

Figure 4. Multilayered echoes appear over Nanning during the period of 08:26–09:16 UT that is mainly between the maximum and the end of the obscuration. The color represents the echo amplitude. The multilayered echoes are mainly observed within the frequency band of 3.0–5.0 MHz. The vertical line divides the ionograms.
Most of all the previous studies reported the enhancement or attenuation of the typical $E_s$ layer below 130 km during the eclipses. However, the appearance of the multilayered echoes near 130–190 km altitudes over Nanning is unexpected. The multilayered echoes are similar to those of the $E_s$ simulation by Didebulidze et al. (2020). Their simulation results show that the $E_s$ can be multilayered under the influence of the small-scale AGWs in nighttime. The AGWs with a vertical wavelength of 15 km can form the $E_s$ with four (60/15) sublayers at the altitudes from 90 to 150 km. The vertical span between the nearby sublayers approximates the vertical wavelength of the AGWs. Figure 4c shows that the multilayered echoes consist of the 3–5 sublayers with the corresponding spans ranging from 11.4 to 22.6 km distributed also within a wide altitude range. The agreement between the observation (Figures 2 and 4c) and the independent numerical simulations performed by Didebulidze et al. (2020) suggests that the appearance of the multilayered $E_s$ can be attributed to the small-scale AGWs due to the obscuration. Chen et al. (2011) also showed $E_s$ being largely scattered around the 137–190 km altitude between the one- and two-hop regular $E_s$ echoes by employing the HF fixed frequency ionosonde during the 2009 solar eclipse. However, there is no obvious stratification in their $E_s$ observation. The different observation equipment and operational modes, such as fixed frequency versus sweep frequency, may be responsible for the different observation results.

Vadas (2007) suggested that AGWs have larger vertical scales as they propagate upward into the upper atmosphere. Oliver et al. (1997) showed that the vertical wavelength of AGWs is proportional to altitude, and it is near 100 km at the altitude around 150 km. However, the wavelengths of the AGWs are short (from 11.4 to 22.6 km) during the eclipse (Figures 4 and 51). Therefore, the origin of the small-scale AGWs may be closer to the $E_s$ layer at ~50 and ~90 km altitudes where the atmospheric cooling rates are sensitive to the obscuration (Brasseur & Solomon, 2005).

On the other hand, metallic ion is another major factor for the formation of $E_s$ layer. Thampi et al. (2010) suggested that the sudden withdrawal of solar radiation can deplete the background $E$-region electron density, thereby unmasking the long-lived metallic ions, because the recombination rate of the metallic ions is much weaker than that of the molecular ions during the obscuration. In Figure 2, the $E_s$ layer around the center path of the solar eclipse are significantly uplifted and scattered near the maximum obscuration. The widely distributed metallic ions (140–180 km) are the ingredient for forming the multilayered $E_s$ above the typical altitude of the $E_s$ layer (130 km).

The multilayered $E_s$ appear only over Nanning (southern 80% obscuration), while there is no similar phenomenon over the other two stations. It is well known that the cooling region during an eclipse can act as a continuous source of the AGWs that propagate away from the path of maximum obscuration (Chimonas, 1970). The moon shadow moving eastward can induce the AGWs that mainly propagate northward and southward. The poleward thermospheric wind in daytime can filter out the northward-propagating AGWs in the Northern Hemisphere. The ions influenced by the AGWs prefer to propagate equatorward along the geomagnetic field lines (Otsuka et al., 2006). Those may explain why the multilayered $E_s$ appear over Nanning but not over Wuhan and Xiamen (Figure 2). The north-south asymmetry in the $E_s$ behavior also agrees with the results of the Global Navigation Satellite System (GNSS) total electron content (TEC) observation over East Asia during the July 22, 2009 solar eclipse (Liu et al., 2011). They also showed that no TEC fluctuations/waves moved poleward on the northern side of the totality path. In contrast, the TEC fluctuations/waves associated with the eclipse-generated AGWs mainly propagated equatorward beyond the southern 85% obscuration.

Scientists have comprehensively examined the ionospheric responses to the eclipses on July 22, 2009 over East Asia and August 21, 2017 over North American due to the development of the dense ground-based GNSS networks and numerous ionosondes in recent decades. Most studies analyzed the ionosonde observations and reported that the $E_s$ behaviors are highly variable in different areas of Asia during the 2009 eclipse (Brahmamandam et al., 2013; Chen et al., 2010; Thampi et al., 2010; Tiwari et al., 2019; Yadav et al., 2013). However, most of the ionosondes do not detect the $E_s$ layer or its obvious variation during the 2017 eclipse over North American. Bullett and Mabie (2018) recorded the $E_s$ at Lusk, Wyoming (near the totality path); however, the $E_s$ layer has no discernible change during the eclipse. The ionospheric waves associated with the 2017 eclipse were mainly recorded by the GNSS networks over North American (Nayak & Erdal, 2017; Mrak et al., 2018; Perry et al., 2019; Sun et al., 2018; Zhang et al., 2017). It can be expected that the moon shadows can induce AGWs that propagate in the ionosphere. However, the different wavy structures in the ionosphere were detected by the different instruments during the two eclipses in the similar season (summer).
In the 2020 eclipse, the ionosondes record the prosperous $E_s$ behaviors over Asia again, which reveals that the $E_s$ is sensitive to the eclipse-generated AGWs in the Asia area near the summer solstice. Accordingly, the results recommend that the examination and simulation of the eclipse-generated ionospheric/atmospheric disturbances should consider the specific condition, such as the climatology of $E_s$ (Qiu et al., 2019), in different areas all over the world.

4. Conclusion

This study performs an experiment for understanding the response of sporadic-$E$ ($E_s$) to the annular solar eclipse over eastern China on June 21, 2020. This is for the first time to observe the multilayered $E_s$ appearing at 130–190 km altitude over Nanning (81.1% obscuration) on the southern side of the obscuration path. However, no multilayered $E_s$ is observed over Xiamen (97.8% obscuration) near the center path and Wuhan (82.4% obscuration) on the northern side. The formation of the multilayered $E_s$ may take the following steps: (1) The typical single $E_s$ layer being uplifted and scattered over Xiamen can act as a reservoir of metallic ions at the high altitudes (130–190 km). (2) The moon shadow induces small-scale AGWs that propagate upward and equatorward. (3) The AGWs encountering with the metallic ions results in the multilayered $E_s$ over Nanning. The vertical span between the nearby sublayer of the multilayered $E_s$ ranges from 11.4 to 22.6 km. Whether the eclipse generates waves in the $F$ region (mainly above 200 km altitude) can be further examined.

Data Availability Statement

The authors acknowledge the use of data from the Chinese Meridian Project https://data.meridianproject.ac.cn/ and the National Satellite Meteorological Center (NSMC) http://www.nsmc.org.cn/en/NSMC/Home/Index.html.

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