Ionospheric F-Layer Scintillation Variabilities Over the American Sector During Sudden Stratospheric Warming Events

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Abstract The present study investigates the ionospheric F-layer scintillation responses in the American sector (90°W–0°, ±50° dip latitude) during the Northern Hemisphere winter sudden stratospheric warming events of 2007–2008, 2008–2009, 2009–2010, and 2012–2013. The scintillation data used in this work are obtained from the radio occultation observations of the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) mission. The important results of this study are described as follows: the occurrence altitude and rate of ionospheric F-layer scintillation over the American sector decrease by an average of 13.48 km and 17%, respectively, during the sudden stratospheric warming (SSW) periods compared with the pre-SSW periods. We find that ionospheric F-layer scintillation over the American sector shows similar inhibitory responses to each SSW event, although these SSW events have diversities in some aspects, such as SSW types and solar and geomagnetic activities. To our knowledge, this study is the first to discover that an SSW event under low solar activity, including a minor warming event, can obviously affect the generation of ionospheric irregularities. Additionally, the types of SSW events may influence the decrease in altitude but not the occurrence rate. The decreased plasma vertical drift during prereversal enhancement, together with the changed meridional wind, are the possible mechanisms for the above results. In addition, we find that the enhanced planetary wave and lunar semi-diurnal tide activities may be responsible for the decreases in the occurrence rate of ionospheric F-layer scintillation before the peak warming of the 2008–2009 and 2009–2010 SSW events.

Plain Language Summary Sudden stratospheric warming (SSW) is a large meteorological process in the winter polar stratosphere. During an SSW event, the zonal temperature increases by several tens of degrees and the westerly winds become weaker or even reverses to easterly winds. SSW have a significant effect on large-scale ionospheric morphological structure (e.g., equatorial ionospheric anomaly) in previous majority literatures. Nevertheless, the effect of SSW on the small-scale structure in ionosphere is not well understood. Ionospheric F-layer irregularities is kind of small-scale structure, which can affect the trans-ionospheric radio wave, leading to so-called ionospheric scintillation phenomenon. The role of SSW on the small-scale structure in ionosphere can be reflected by studying the characteristics of ionospheric scintillation during SSWs. In this work, we investigate the variation of the equatorial premidnight F-layer scintillation using COSMIC/FORMOSAT-3 data during the four SSW events. We found that the occurrence frequency and altitude of ionospheric F-layer scintillation obviously suppressed during SSW events. It suggests that the SSW event has a significant effect on the small-scale structure in the Earth’s ionosphere, having potential application for satellite navigation and communication.
1. Introduction

Sudden stratospheric warming (SSW) is a large-scale meteorological event that mainly occurs in the polar stratosphere of the winter Northern Hemisphere. This event is characterized by the polar vortex of westerly winds abruptly slowing down (minor warming) or even reversing direction (major warming), accompanied by an increase in polar stratospheric temperature by at least 25 Kelvin (K) (Charlton & Polvani, 2007; de Paula et al., 2015). According to Matsuno (1971), enhanced quasi-stationary planetary wave activity in the atmosphere is the main mechanism that triggers an SSW event. Although SSW events occur in the polar stratosphere, numerous observations and model simulations have demonstrated their influence on the large-scale electrodynamic and morphological variations in the global ionosphere and thermosphere, especially in equatorial and low-latitude regions (e.g., Chau et al., 2009; Chen et al., 2016; Fagundes et al., 2015; Fejer et al., 2010; Goncharenko, Chau, Condor, et al., 2013; Goncharenko, Chau, Liu, et al., 2010; Goncharenko, Coster, et al., 2010; Goncharenko & Zhang, 2008; H. Liu et al., 2011, 2014; J. Liu et al., 2019; Owolabi et al., 2019; Upadhyaya & Mahajan, 2013; Yamazaki, 2013; Yue et al., 2010; Zhang et al., 2020). Goncharenko and Zhang (2008) reported alternating warming in the lower thermosphere and cooling above 150-km altitude, which was confirmed to be related to the SSW event rather than the seasonal trend, solar flux, or geomagnetic activity. Subsequently, H. Liu et al. (2011) studied neutral density in the thermosphere observed from the Challenging Minisatellite Payload (CHAMP, 325-km altitude) and Gravity Recovery and Climate Experiment (GRACE, 475-km altitude) satellites to infer information on strong thermospheric cooling during the January 2009 SSW event. The most remarkable responses to SSW events are the semidiurnal variation pattern in ionospheric parameters, such as the equatorial vertical $\mathbf{E} \times \mathbf{B}$ ($\mathbf{E}$ and $\mathbf{B}$ are the electric and geomagnetic fields, respectively) plasma drifts, peak height ($\text{hmF}_2$), peak electron density ($\text{NmF}_2$), and total electron content (TEC) (e.g., Chau et al., 2008; Pedatella, Fullin, & Maute, 2015; Yamazaki, 2013). Although SSW-induced variations in the global ionosphere have been widely reported in the literature, there is a lack of comprehensive understanding of how equatorial F-layer irregularities (EFIs) respond to changing neutral atmospheric dynamics during SSW events (Goncharenko et al., 2018; Yu et al., 2020). The EFIs, shown as small-scale ionospheric structures, are depleted plasma regions with a variety of spatial scales, ranging from a few centimeters to several hundred kilometers (Carter et al., 2013). Generally, EFIs are generated by the growth rate of the generalized Rayleigh-Taylor instability near the sunset terminator (Abdu, 2001; Jose et al., 2017). EFIs can cause scattering and diffraction of radio waves crossing unstable ionospheric regions and produce rapid fluctuations in the amplitude and/or phase of the received signals, leading to so-called ionospheric scintillation (Alfonsi et al., 2013; Yeh & Liu, 1982). The occurrence of EFIs/ionospheric F-layer scintillation makes it difficult to make accurate predictions because it has large variability as a function of local time, day-to-day, season/month, latitude, longitude, and solar and magnetic activities (de Paula et al., 2015). In particular, how the day-to-day variability in EFIs/ionospheric F-layer scintillation responds to SSW events remains an open question. de Paula et al. (2015) reported long-lasting weakening of ionospheric scintillation during three SSW events in 2001–2002, 2002–2003, and 2012–2013 under high solar activities over a low-latitude ground station in Brazil. Similarly, de Jesus, Batista, Jonah, et al. (2017) reported that the occurrence of ionospheric irregularities is less frequent on SSW days than on non-SSW days during the major SSW event of 2013–2014. However, de Jesus, Batista, Fagundes, et al. (2017) reported no similar decrease in ionospheric irregularities at multiple low-latitude locations in Brazil during the 2006 minor SSW event under low solar activity. By using COSMIC/FORMOSAT-3 observations, Yu et al. (2020) found that the inhibition of ionospheric F-layer scintillation was mainly seen in the American sector and then in the African sector during the SSW event of 2012–2013. However, they did not investigate the response characteristics in other years within low solar flux levels and/or different SSW types (i.e., major warming and minor warming). In addition, the variability in the zonal electric field and vertical plasma motion during SSW events might have a significant effect on the occurrence altitude of ionospheric F-layer
scintillation. Therefore, more work needs to be done to study the response characteristics of ionospheric F-layer scintillation during SSW events.

In this study, we used radio occultation (RO) data collected by the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC/FORMOSAT-3) to examine how ionospheric F-layer scintillation/EFIs respond to SSW events over the American sector during multiple years of different background conditions. The results suggested that the occurrence rate of ionospheric F-layer scintillation was obviously suppressed during SSW events, accompanied by a significant decrease in altitude. The data are described in Section 2, while our analytical results and discussion are included in Section 3. Our summary and conclusion are presented in Section 4.

2. Data

The variations in the equatorial and low-latitude ionospheric F-layer scintillation over the American sector during SSW events are illustrated by the S4 scintillation index obtained from the COSMIC/FORMOSAT-3 RO data set. The scintillation S4 index data can be downloaded from the COSMIC Data Analysis and Archive Center (CDAAC) website (http://cdaac-www.cosmic.ucar.edu/cdaac). The COSMIC/FORMOSAT-3 constellation system consists of six identical microsatellites launched in April 2006 and fully deployed in early 2007. The S4 scintillation index here was not directly measured by the COSMIC/FORMOSAT-3 GPS Occultation Experiment (GOX) but calculated from the root mean square of the intensity fluctuations over a 1-s interval with additional auxiliary assumptions and steps (Carter et al., 2013; Ko & Yeh, 2010). Most authors prefer to use the value of the average S4 over 9 s around the maximum S4 ($S4_{max9s}$) and its corresponding tangent point position information to represent an ionospheric scintillation event, which is associated with EFIs or Sporadic-E (Es), for statistical analysis (e.g., Carter et al., 2013; Dymond, 2012; Ko & Yeh, 2010; Yu et al., 2020). The advantage of using $S4_{max9s}$ instead of $S4_{max}$ is to avoid the case in which the maximum S4 is an outlier in the 1 Hz S4 distribution. According to previous work (Yu et al., 2020), the $S4_{max9s}$ threshold value of 0.3 was considered to be appropriate for identifying ionospheric F-layer scintillation events. In addition, Yu et al. (2020) focused on scintillation events occurring in the 150–600-km altitude range and premidnight (19.5–24 LT) during the January 2013 SSW event, which are closely associated with EFIs. Therefore, the objective of this study is premidnight ionospheric F-layer (150–600 km) scintillation events with an $S4_{max9s}$ threshold value of 0.3. In addition, the present work also adopted the same region range of the American sector (i.e., 90°W–0°, ±50° dip latitude) as defined by Yu et al. (2020).

We check the COSMIC RO data set and find that both occultation and scintillation events are randomly scattered in longitude and dip latitude and never tend to be clustered (not shown here). The influence of the spatial sampling on the results should be small.

In this study, we use the zonal wind and temperature data of the National Centers for Environmental Prediction (NCEP)/National Center for Atmospheric Research (NCAR) reanalysis data set to describe the variations in stratospheric parameters. The NCEP/NCAR reanalysis data set is produced by the NCEP/NCAR, which uses a state-of-the-art analysis/forecast system to perform data assimilation using past data from 1948 to present (Jia et al., 2015; Kalnay, 1996). The characteristics of SSW events are recognized by the zonal-mean zonal wind at 60°N and 10 hPa and the zonal-mean temperature at 90°N and 10 hPa. In addition, background geomagnetic and solar activities are illustrated by daily Kp and F10.7 indices, which are downloaded from the Center for Space Standards and Innovation (http://www.celestrak.com/SpaceData/).

3. Results and Discussion

3.1. SSW Event of 2009

The well-known 2008–2009 major SSW event is the strongest and most long-lasting (over a month) recorded event with low solar and geomagnetic activity, providing ideal conditions to study the global ionospheric effects driven by lower atmospheric processes (Goncharenko, Chau, Liu, et al., 2010; Goncharenko, Coster, et al., 2010; J. Liu et al., 2019; Oyama et al., 2014). Figures 1a–1d summarize the stratospheric, solar, and geomagnetic conditions during the three winter months from December 2008 to February 2009. During this event, stratospheric zonal-mean temperatures at 90°N sharply increased by ~60 K, while peak warming was reached on January 23, 2009, as displayed in Figure 1a. Figure 1b shows that the zonal-mean zonal wind at
60°N first weakened and then reversed its direction from westerly to easterly, indicating a major warming event. According to Goncharenko, Coster, et al. (2010), this SSW event was possibly driven by the enhancement of planetary wave 2 and began as the breakdown of the polar vortex. Figures 1c and 1d show that the solar and geomagnetic activities remained at a very low and steady level during this event, with daily Kp ≤ 2 on most days and an F10.7 index of ~68 solar flux units (sfu, 1 sfu = 10^{-22} W m^{-2} Hz^{-1}). Accordingly, it offers a good opportunity to gain important insight into the ionosphere F-layer scintillation response to major SSW events under low solar activity.

Figure 1f presents the 3-days moving average ionospheric F-layer scintillation occurrence rate premidnight over the American sector. Only COSMIC RO events with an S4 max9s index larger than or equal to 0.3 were considered in the analysis. In addition, the new (full) moon phases described by the shaded (unshaded) circle aimed to investigate the possible influence of the lunar gravitational factor (de Paula et al., 2015; Fejer & Tracy, 2013). Notably, the occurrence rate of ionospheric F-layer scintillation is relatively high, with values...
from 55% to 75% in December, indicating the high occurrence of EFIs. With the onset of the SSW event and even earlier, a long period of suppression was observed in the ionospheric scintillation occurrence rate, except for a high occurrence rate of February 6–9, 2009, which lasted until the end of February 2009. Moreover, a prominent feature can be noted in Figure 1e: the average occurrence altitude decreased from 260 to \(\sim 220\) km during the peak period of the SSW event. To distinguish the SSW-induced ionospheric effect, we choose the 10 days starting from the day of maximum temperature as a reference SSW period, aiming to have a uniform standard for each SSW event. The results have relatively high credibility by using a similarly consistent methodology for the selection of the pre-SSW, SSW, and post-SSW time periods. In this SSW case, the 10 days from January 23 to February 1, 2009 were selected as the SSW period, as shown in the light red shadow area in Figure 1. Considering that the lunar semi-diurnal tide can affect the vertical drifts during SSW events (Fejer et al., 2010, 2011; Jonah et al., 2014), the 10 days from December 24, 2008 to January 2, 2009 were selected as the pre-SSW period, which is approximately a lunar month before the SSW period, ensuring that they are approximately under the same lunar phases. For the post-SSW period, considering the influence of both data and seasonal factors, we select the 16 days at the end of February as the reference in the text. In this case, the 16 days of February 13–28, 2009 were chosen as the reference post-SSW period, although the temperature and zonal wind had yet recovered to their prior level. The light blue and light green shadow areas in Figure 1 display the pre-SSW and post-SSW periods, respectively. Figure 1e shows that the average occurrence altitude during the SSW period is at the lowest level among the three months. Figure 1f also shows that the occurrence rate of ionospheric F-layer scintillation during the SSW period is lower than that during the pre-SSW period. Therefore, the results demonstrate that the 2008–2009 major SSW event under low solar activity had a significant effect on reducing the occurrence rate of ionospheric F-layer scintillation over the American sector.

Further analyses were conducted to investigate the response characteristics of ionospheric F-layer scintillation over the American sector as a function of day and/or LT. First, the characteristics of the detected data set are presented in Figure 2a. Observational ionospheric scintillation events filled with black were easily observed in December and relatively rarely observed in the next two months owing to SSW events. The occurrence frequencies were generally under 50 percent, prevailing in most bins of 5 days \(\times\) 0.5 LT hours during the SSW period, although the high occurrence rate occasionally appeared in some individual bins. To investigate temporal sampling and the local time effect, Figures 2b and 2d show the variation in ionospheric scintillation within four selected local time slots at 19:30–24:00, 19:30–21:30, 20:45–22:45, and 22:00–24:00. When the number of occultation events and scintillation events are less than 4 and 3, respectively, we do not count the occultation rate and altitude on the corresponding statistical unit to improve the reliability of the analytical results. For example, Figure 2e shows two absent data points on the labeled 20 and 20.5 LT during the SSW period, indicating that the number of scintillation events is less than 3. Figure 2b shows that the weakening trend of the occurrence rate during the SSW period is similar in different local time slots. However, there are also some differences, such as the relatively high occurrence rate on labeled days 55 (51–55) and 60 (56–60) at 20:45–22:45, corresponding to the appearance of yellow bins in Figure 2a. On the other hand, Figures 2d and 2e show the decreased occurrence altitude of ionospheric F-layer scintillation, especially in later hours premidnight, further suggesting the SSW-induced inhibition of EFIs. Figure 2c shows that the occurrence rates in the early hours after sunset during the SSW period were significantly lower than those during the pre-SSW period, post-SSW period, and the average of the three months. The SSW event also modulates the start time of the EFIs (Jose et al., 2017; Yu et al., 2020), possibly resulting in a high occurrence after 21.5 LT, as shown in Figure 2c. The impact of temporal sampling may be small because the detections are sufficient at nearby local times. It is also noted in Figure 2c that the SSW event has an effect on reducing the occurrence rates of ionospheric F-layer scintillation during the defined post-SSW days, which is still at the end of the recovery phase of the 2008–2009 SSW event. With regard to the variation in occurrence altitude, the average occurrence altitude of ionospheric F-layer scintillation descended obviously in Figure 2e during the SSW period.

Table 1 summarizes the average value of ionospheric F-layer scintillation over the American sector for the three periods, that is, pre-SSW, SSW, and post-SSW periods. Quantitatively, Table 1 shows that the average occurrence altitudes of ionospheric F-layer scintillation during the pre-SSW, SSW, and post-SSW periods are 255.85, 237.72, and 248.13 km, respectively. Table 1 also shows that the occurrence rates of ionospheric F-layer scintillation during the pre-SSW, SSW, and post-SSW periods are 55%, 44%, and 44%, respectively.
Figure 2. Characteristics of the ionospheric scintillation variation as a function of day and/or local time for the SSW event of 2008–2009. (a) Temporal variation in ionospheric scintillation events and occurrence rate. The black circles represent the individual COSMIC RO event, filled with black for the observational ionospheric scintillation event. The colored squares indicate the occurrence rate within a bin of 5 days × 0.5 LT. The light blue, light red, and light green horizontal shadow areas under the X axis indicate the reference pre-SSW (days 24–33), SSW (days 54–63), and post-SSW (days 75–90) time periods, respectively. The occurrence rate of ionospheric scintillation versus (b) day for four selected local time slots and (c) local time for the time periods of pre-SSW, SSW, and post-SSW days and all days together. The average occurrence altitude of ionospheric scintillation versus (d) day for four selected local time slots and (e) local time for the time periods of pre-SSW, SSW, and post-SSW days and all days together.

Table 1
Statistical Characteristics of the Ionospheric Scintillation Variation for the Four SSW Events

| SSW background condition | Altitude (km) | Occurrence rate (×100%) |
|-------------------------|---------------|-------------------------|
|                         | Pre-SSW | SSW | Post-SSW | Average | ΔSSW | Pre-SSW | SSW | Post-SSW | Average | ΔSSW |
| Year                    | Type    | Averaged F10.7 |          |          |       |          |      |          |        |      |
| 2008                    | Minor   | 74.7 | 252.54 | 252.39 | —      | 267.17 | 0.15 | 0.61      | 0.55  | —      | 0.68  | 0.06 |
| 2009                    | Major   | 69.6 | 255.85 | 237.72 | 248.13 | 256.05 | 18.13 | 0.55      | 0.44  | 0.44  | 0.50  | 0.11 |
| 2010                    | Moderate* | 80.7 | 254.62 | 237.72 | 248.13 | 256.05 | 18.13 | 0.55      | 0.43  | 0.63  | 0.55  | 0.17 |
| 2013                    | Major   | 113.6 | 341.44 | 252.39 | 248.13 | 256.05 | 18.13 | 0.55      | 0.43  | 0.63  | 0.55  | 0.17 |
| Average                 |         |      | 276.11 | 262.63 | 293.63 | 284.04 | 13.48 | 0.64      | 0.47  | 0.59  | 0.60  | 0.17 |

Note. ΔSSW = (pre-SSW) – SSW. The average F10.7 is the 90-days average of the F10.7 index during the corresponding period. The pre-SSW period of the 2010 SSW indicates the first reference pre-SSW period (days 1–10).

*Moderate: The 2010 SSW case is actually between the typical major and minor events, which is also recognized as a “moderate” SSW event in the present work (Liu et al., 2019).
Obviously, the occurrence rate and altitude of ionospheric F-layer scintillation, which decreased from the pre-SSW period to the SSW period, were 11% and 18.13 km, respectively. This result suggests that the 2008–2009 SSW event had obvious effects on suppressing the generation of ionospheric F-layer scintillation during a low solar activity period.

The possible mechanisms affecting the generation of ionospheric irregularities during the SSW period have been tentatively discussed and analyzed. According to de Paula et al. (2015) and Yu et al. (2020), the evening prereversal enhancement (PRE) of vertical drift plays a very salient role in modulating the generation of ionospheric irregularity during SSW events. Chau et al. (2010) reported that the vertical drift differences during the 2008–2009 SSW event were negative in the afternoon, observed at the magnetic equator over Jicamarca, and appeared to start a few days before the peak warming. The vertical drift observations are also supported by simulation results at Jicamarca longitude (Fang et al., 2012). Thus, from the above simulations and observations, it can be inferred that the suppression of evening PRE may exist in the vertical drift during the 2008–2009 SSW event. During this event, Paes et al. (2014) reported that the equatorial ionospheric anomaly (EIA) was strongly suppressed over the Brazilian region around sunset, including the time interval of the evening PRE. In addition, Fagundes et al. (2015) reported that the decrease in the critical frequency of the F2 layer (foF2) occurs in the afternoon-evening sector and reaches 2–6 MHz at two ionosonde stations over the South American sector. This finding further confirms the decrease in PRE vertical drift, which is not conducive to the uplift of ionospheric F2 layer peak height (hmF2) after sunset, resulting in the poor development of irregularity generation and hence the inhibition of ionospheric F-layer scintillation. Our results show that the range of days in which the scintillation occurrence rate changes significantly is greater than that of the occurrence altitude. Compared with the generation of irregularity, the variation in occurrence altitude may require a larger vertical drift change. Note that the decreased altitude mainly occurred during the peak temperature, corresponding to the large negative value of vertical drift observed by Chau et al. (2010). Additionally, the deviation in scintillation occurrence altitude is 18.13 km, which decreases from the pre-SSW period to the SSW period, consistent with the magnitude order of ΔhmF2 observed by COSMIC in the afternoon (Yue et al., 2010). Zhang et al. (2020) reported that the disturbance meridional wind made an important contribution to the disturbance field-aligned drifts, inducing the hemispheric difference in the TEC responses to the 2008–2009 SSW event. Similarly, meridional wind can enhance the field line integrated Pedersen conductivity and may also play a role in reducing ionospheric irregularity activity during the SSW period (de Paula et al., 2015). However, de Jesus, Batista, Fagundes, et al. (2017) argued that the 2005–2006 SSW event, also under a low solar flux level, did not affect the generation of large-scale irregularities observed by using GPS in Brazil. As noted by Yu et al. (2020), ground-based GPS TEC phase fluctuations (rate of change in TEC, ROT) may fail to detect variations in small-scale ionospheric irregularities during SSW events. Generally, the possible contributions of seasons, solar and geomagnetic activity to the development of EFIs also need to be considered. In this case, the very low and stable solar activity, as shown in Figure 1c, makes no notable contributions to the variation in occurrence rate. According to Carter et al. (2014), even relatively small changes in the Kp index might have a measurable effect on PRE vertical drift and further cause a high degree of variability in the occurrence of EFIs. Notably, the level of geomagnetic activity in this case is too low to have a great impact on the change in the occurrence probability. Thus, the contribution of geomagnetic activity can be roughly ignored. Owing to the long-lasting 2008–2009 SSW event, the superimposed seasonal ionospheric scintillation behavior is difficult to identify. However, a 9-years statistical result from Zhao et al. (2021) shows that the occurrence rate of kilometer-scale irregularities is a relatively slight decrease from December to February based on GPS receivers over the American longitude sector. Thus, the following SSW events need to be combined to distinguish the seasonal scintillation behavior. In the following text, the 2007–2008 SSW event was chosen as an important case to examine whether ionospheric scintillation has an analogous response to minor SSW events with low solar activity conditions.

### 3.2. SSW Event of 2008

During the 2007–2008 SSW events, four brief peak warmings occurred continuously on January 24, February 6, February 16, and February 23, 2008 (Goncharenko, Chau, Liu, et al., 2010). The first three warmings were regarded as minor warmings, while the last warming was a major warming because the zonal-mean zonal wind at 60°N changed direction during this period. According to Paes et al. (2014), the last major
warming is possibly triggered by the previous successive occurrence of minor warmings because the polar vortex weakens after the winter solstice, making it more susceptible to complete vortex breakdown. Figure 3a shows that the first peak warming, occurring on January 24, 2008, has the largest temperature variation during these SSW events, with the temperature increasing by >60 K within 4 days. Moreover, Figure 3b presents the sharp slowing of stratospheric zonal winds during the same period. Subsequently, the stratospheric zonal winds continue to slow gradually under the second and third minor warmings. Eventually, only the last warming is characterized as the major SSW under the conditions that the stratospheric zonal wind at 60°N turned westward and the temperature at 90°N increased by 40 K. The four peak warmings were driven by planetary wave 1 activity, accompanied by the displacement of the polar vortex off the pole (Goncharenko, Chau, Liu, et al., 2010). To maintain a uniform standard, we selected the 10 days starting from the day of maximum temperature of the first peak warming as a reference SSW period. Thus, the 10 days from January 25 to February 3, 2008 were chosen as the SSW period, although the first minor warming has a very short duration (even less than 10 days) compared with other SSW events. Similarly, the SSW period is shown in the light red shadow area in Figure 3. Then, the 10 days from December 26, 2007

Figure 3. Same as in Figure 1 but for the 2007–2008 SSW event. The light blue and light red vertical shadow areas indicate the reference pre-SSW (days 26–35) and SSW (days 56–65) time periods, respectively.
to January 4, 2008 were selected as the pre-SSW period, which is also approximately a lunar month before
the SSW period. The light blue vertical shadow area in Figure 3 indicates the pre-SSW period. As shown in
Figure 4a, data gaps exist in the COSMIC RO observations in late February, which may bring about some
analytical error. In addition, late February was a period of major warming. Accordingly, there is no appro-
priate time period for the selected reference post-SSW period. Figure 3c shows that the solar activity is low
and stable after December 20, 2007 with F10.7 values of ∼70–80 sfu. The daily Kp index in Figure 3d is not
>4, indicating relatively quiet geomagnetic conditions, although every 3 h, the Kp index has exceeded 4 in
a few moments (not shown here). Figure 3e presents a clear decline in the average occurrence altitude of
ionospheric F-layer scintillation during the first and second peak warmings. However, Figure 3f shows that
the decreased occurrence frequency of ionospheric F-layer scintillation mainly occurred around the first
peak warming. Notably, many gaps existed in the COSMIC data set during the third minor warming event
(February 14–19, 2008) and during the last major warming event (February 20–28, 2008), as presented in
Figure 4. However, this finding suggested that the last major warming may have more important effects on
the inhibition of ionospheric irregularity than prior to this warming, as shown in Figures 3e and 3f. More-
ever, Figure 3f displays the weakening trend of ionospheric F-layer scintillation before the third peak tem-
perature, which cannot rule out the impact of the missing data. As also reported by Paes et al. (2014), EIA
suppression is expressive in the afternoon/early-evening hours, particularly during the first peak warming.
Afternoon EIA suppression is an important signature generated by the variation in plasma vertical drift
during the first peak warming (Goncharenko, Coster, et al., 2010). According to Chau et al. (2010), the
equatorial drift differences exhibit a large negative value during the first warming. Additionally, the after-
noon equatorial electrojet (EEJ) strength during the four peak warmings is weakened in the Asian zone,
while it becomes negative (i.e., counter electrojet) only during the first peak warming (see Upadhayaya & Mahajan [2013] of Figure 9). Our results agree with those observations. Generally, the suppression of ionospheric scintillation that occurred during the first peak warming has a relatively large confidence and variation magnitude. This event is a well-examined case in which ionospheric F-layer scintillation also has an inhibitory response to minor SSW events under low solar activity.

Figure 4 presents the characteristics of the ionospheric scintillation variation as a function of day and/or local time during the 2007–2008 SSW events. As mentioned before, we only compare the results between pre-SSW and SSW periods during this SSW case. To improve the reliability of the analysis results, when the number of occultation events and scintillation events are less than 4 and 3, respectively, we do not count the occultation rate and altitude on the corresponding statistical unit in Figures 4b–4d. As we can see from Figure 4b, the weakening occurrence frequency of the ionospheric F-layer scintillation is obviously observed in the four local time slots during the first peak warming (days 60, 56–60). The occurrence rate of ionospheric F-layer scintillation decreased by ~15% during the first peak warming in comparison with labeled day 30 (days 26–30), showing an inhibitory effect on the occurrence rate during minor SSW events. However, the second and third peak warmings have not seen the same feature of magnitude weakening. Figure 4b shows that there is a drastic decline in the occurrence rate of ionospheric F-layer scintillation during the last major warming, despite fewer observation data. Figure 4c reveals that the occurrence rate of ionospheric F-layer scintillation during the defined SSW period is significantly less than that during the pre-SSW period, excluding the 20.5 and 23.5 LT slots. Figure 4d shows that the average occurrence altitude of ionospheric F-layer scintillation is slightly decreased after the first peak warming. Figure 4d shows an enhancement in the occurrence altitude during late February. The ionosphere is rapidly elevated to higher altitudes under the action of the evening PRE and then gradually drops to lower altitudes over time (Su et al., 2008; Yu et al., 2018). Therefore, one possible cause is that the statistical scintillation event mainly occurred in the early postsunset hours, owing to the data gaps in later hours. The decreased occurrence altitude during the SSW period can be clearly seen before 22.5 LT in Figure 4e. However, there is an unexpected increase after 23 LT, which is not consistent with the decreased behavior. Generally, the average altitude of most points during the SSW period is below or comparable to that during the pre-SSW period, showing a relatively complex variation.

As seen in the statistics in Table 1, the average occurrence altitude of ionospheric F-layer scintillation is only a 0.15 km decrease from 252.54 km during the pre-SSW period to 252.39 km during the SSW period, and the decrease in altitude is very small. Table 1 shows that the occurrence rates of ionospheric F-layer scintillation during the pre-SSW and SSW periods are 61% and 55%, respectively. Compared with the pre-SSW period, this statistical result illustrates the 6% drop in occurrence frequency during the SSW period, showing no remarkable inhibitory effect on the generation of EFIs. This result may explain why de Jesus, Batista, Fagundes, et al. (2017) reported no decrease in ionospheric irregularities in Brazil under similar geophysical conditions. However, if we focused on the five-day duration of the first peak warming, the occurrence rate of ionospheric F-layer scintillation decreased by ~15%. This result illustrates that minor warming influences the occurrence rate mainly during peak warming. In other words, the selection of 10 days is somewhat lengthy, which may not be a good choice to maintain a uniform selected standard for the reference SSW period in this case. As mentioned before, the changing meridional wind may also have an important effect on the growth of the ionospheric irregularity during these SSW events (de Paula et al., 2015). In addition, local seasonal effects may also affect the generation and development of EFIs in this particular longitude sector (Su et al., 2008).

### 3.3. SSW Event of 2010

During the 2009–2010 SSW event, the solar activity was relatively low to moderate, and the geomagnetic activity was quiet and stable. Figures 5a–5d show a summary of stratospheric, solar, and geomagnetic conditions during the three winter months from December 2009 to February 2010. Figure 5a presents an increase in the stratospheric zonal temperatures starting on January 19, 2010, accompanied by a slight change in the direction of zonal-mean zonal wind in Figure 5b. Although this peak warming can be classified as a major warming event based on the previous definition, this case is actually between the typical major and minor events, which is also recognized as a “moderate” SSW event in the present work (J. Liu et al., 2019). This
SSW event, similar to the following 2012–2013 SSW event, was driven by amplification in planetary wave 1 activity (Goncharenko, Hsu, et al., 2013). Notably, there was warming on December 8, but with a smaller amplitude than the major warming during this SSW event period. According to J. Liu et al. (2019), the enhancements of planetary wave 1 and 2 activities during the same period may account for this lesser warming. Figure 5c shows that the solar activity varied from a low to moderate level during the whole period, with a mean F10.7 index value of $\sim 80$ sfu. On the other hand, Figure 5d presents a quiet geomagnetic activity condition with daily Kp $< 3$ during this period (Buhari et al., 2017). Thus, the quiet geomagnetic activity contributes less to the variation in ionospheric scintillation. Figure 5e shows a clear decrease in the average occurrence altitude of ionospheric F-layer scintillation after the start of the "moderate" SSW event. Moreover, there is a distinct reduction in the occurrence rate of ionospheric F-layer scintillation during the same period, as shown in Figure 5f. Paes et al. (2014) reported a favorable condition in which the TEC difference tends to be strongly suppressed in Brazilian longitude around the afternoon/early-evening hours, indicating a possible decrease in the F-layer peak height ($h_mF_2$). As shown in Figure 8 of Paes et al. (2014), EIA suppression intensified and became prominent from January 29, 2010 (the day of maximum temperature),
consistent with our observed result of the average occurrence altitude. Thus, the decrease in the F-layer peak height can contribute to suppressing the development of ionospheric irregularity during this period. As also reported by J. Liu et al. (2019), a distinguishable time-shifted semidiurnal pattern was seen in the TEC parameter over the American sector following the peak temperature of the major warming. This finding suggests that this “moderate” SSW event has an important modulation on the variation in ionosphere parameters. Another interesting characteristic in Figure 5f is the obvious weakening in the occurrence rate of ionospheric F-layer scintillation between days 20 and 50, far later than the smaller warming mentioned above. Notably, the time-shifted semidiurnal pattern was clearly seen during the corresponding period in Figure 6d of J. Liu et al. (2019). Our results, in terms of the time range, are consistent with the results of J. Liu et al. (2019). The planetary wave-tide interaction is recognized as the primary mechanism coupling SSWs to ionospheric variability (Goncharenko, Hsu, et al., 2013; Pedatella & Forbes, 2010; Xiong et al., 2013). Therefore, the persistent enhancement of planetary wave 1 and the lunar semidiurnal tide (see J. Liu et al. [2019] of Figure 5) during this period may be responsible for both the scintillation weakening feature and the TEC time-shifted semidiurnal pattern (de Paula et al., 2015, and references therein). Notably, the possible mechanism needs further investigation in future works.

Figure 6 presents the characteristics of the ionospheric scintillation variation as a function of day and/or local time during the 2009–2010 SSW events. Unlike the 2007–2008 SSW events, Figure 6a shows that there are no obvious gaps in the data distribution. The number of detections on the statistical unit is relatively sufficient during the three months from December 2009 to February 2010. During this case, we still choose the
10 days starting from the day of maximum temperature as a reference SSW period. Thus, the days of January 29 to February 7, 2010 (days 60–69) and February 13–28, 2010 (days 75–90) were chosen as representatives for the SSW and post-SSW periods, respectively. Owing to other possible mechanisms between days 20 and 50 mentioned above, we choose the day of December 1–10, 2009 (days 1–10) as the first reference pre-SSW period with a lunar phase similar to that of the SSW period. Days 30–39 were selected as the second reference pre-SSW period, as shown in Figures 5 and 6. There may be concern that this selection leads to a bias in the results. Except for the pre-SSW period, both the post-SSW period and the 90-days average are used as a reference in the analysis. We note that the individual COSMIC RO event is relatively easy to see in Figure 6a during the “moderate” SSW event, showing the low occurrence frequency of ionospheric scintillation during this SSW period. In addition, a large number of individual COSMIC RO events also existed between days 20 and 50, consistent with the previous statistics in Figure 5f. Correspondingly, Figure 6b further shows the prominent scintillation weakening feature in the two periods mentioned above. At the same time, we find a notable decrease feature in the average occurrence altitude of ionospheric F-layer scintillation during the SSW period in Figure 6d. However, between days 20 and 50, there was an upward trend in the average occurrence altitude, corresponding to the observational result in Figure 5e. To determine what causes the unexpected variation in occurrence frequency and altitude during this non-SSW peak period, the possible mechanism needs future research, which is beyond the scope of the present study. Figures 6c and 6e show that the occurrence rate and the average occurrence altitude of ionospheric F-layer scintillation during the SSW period are commonly lower than other statistical periods in the local time axes. These results illustrate that the “moderate” SSW event has a strong inhibitory effect on the occurrence of ionospheric scintillation associated with EFIs.

Table 1 gives the statistical results of the ionospheric F-layer scintillation over the American sector for the three periods, i.e., pre-SSW, SSW, and post-SSW periods. Table 1 shows that the average occurrence altitudes are 254.62, 247.86, and 287.16 km during the pre-SSW, SSW, and post-SSW periods, respectively. The results display a 6.76 km decrease in the average occurrence altitude from the pre-SSW period to the SSW period. Table 1 shows that the occurrence rates of ionospheric F-layer scintillation during the pre-SSW, SSW, and post-SSW periods are 60%, 43%, and 63%, respectively. Obviously, the occurrence rate of ionospheric F-layer scintillation decreased by 17% during the SSW period in comparison with the pre-SSW period, while the occurrence rate that occurred in the post-SSW period recovered to the pre-SSW level. Compared with the seasonal factor, the SSW-induced inhibitory effect might play a more important role during the SSW period. To some degree, our statistical results quantitatively show that the “moderate” SSW event plays an important role in reducing scintillation activity.

3.4. SSW Event of 2013

The 2012–2013 major SSW event occurred in the winter Northern Hemisphere under moderate-to-high solar activity, which is one of the strongest and most prolonged SSW events (Goncharenko, Chau, Condor, et al., 2013; Jonah et al., 2014; Yu et al., 2020). The occurrence frequency and distribution of ionospheric F-layer scintillation was investigated by using COSMIC RO observations during this event in the earlier study of Yu et al. (2020). To study the ionospheric scintillation responses in detail, we further investigate the variation in occurrence altitude and reproduce the occurrence rate of ionospheric F-layer scintillation during the 2012–2013 SSW event over the American sector. Figures 7a–7d show the stratospheric, solar, and geomagnetic conditions during the three winter months from December 2012 to February 2013, similar to Figure 1. The temperature at 90°N started to increase on January 04, 2013 and rapidly reached 220 K, even exceeding 240 K on January 06, 2013. Moreover, the zonal-mean zonal wind changed its direction to easterly with the rapidly increasing temperature, suggesting a major SSW event. This SSW event was triggered by a strong amplification in planetary wave 1 and started as a vortex shift event (Goncharenko, Chau, Condor, et al., 2013). Figure 7c displays a drastic increase in the F10.7 index in the starting period of the SSW event, which might influence the ionosphere effects. In addition, the daily Kp ≤ 4 illustrated in Figure 7d indicates the relatively quiet geomagnetic activity condition during this SSW event. Figure 7f presents the low occurrence rate of ionospheric F-layer scintillation over the American sector during the period from January 15 to the end of warming (Yu et al., 2020). Interestingly, the average occurrence altitude also exhibits a similar decreasing trend during the same period, as shown in Figure 7e. However, we note the very low occurrence altitude at the end of February. This result may be caused by the absence of COSMIC detection
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In addition, we note that unexpectedly high occurrence rates are observed on the starting days of this SSW event. As pointed out by de Paula et al. (2015), this finding may be attributed to the drastic enhancement in the solar flux that occurred during this period.

Generally, the 2012–2013 major SSW event provides a good opportunity to study the variation in ionospheric F-layer scintillation/EFIs resulting from lower atmospheric processes under relatively quiet geomagnetic activity and moderate-to-high solar conditions (de Paula et al., 2015; Yu et al., 2020). To avoid the influence of the drastic increase in the F10.7 index, the days January 17–26, 2013 (days 48–57), beginning from the day of the third temperature maximum, were chosen as the SSW period. The days December 18–27, 2012 (days 18–27) and February 13–28, 2013 (days 75–90) were selected as representatives for the pre-SSW and post-SSW periods, respectively. The pre-SSW and SSW periods were approximately under the same lunar phases, indicating the potentially similar effects of lunar tides on scintillation occurrence (de Paula et al., 2015; Fejer & Tracy, 2013; Yu et al., 2020). Figure 8 shows the characteristics of the ionospheric scintillation variation as a function of day and/or local time during the 2012–2013 SSW events. Notably, we adopt the same data filtering criteria as the case of the 2008–2009 SSW event because the COSMIC RO observation is

**Figure 7.** Same as in Figure 1 but for the 2012–2013 SSW event. The light blue, light red, and light green vertical shadow areas indicate the reference pre-SSW (days 18–27), SSW (days 48–57), and post-SSW (days 75–90) time periods, respectively.
insufficient or even absent in some bins. As reported by Yu et al. (2020), the high occurrence frequencies were relatively easy to see in the bins of pre-SSW and post-SSW periods, with the bins mostly filled by black solid circles that represent individual events of ionospheric F-layer scintillation. During the SSW period, there were more black hollow circles in each bin, as shown in Figure 8a, suggesting the reduction in scintillation occurrence caused by the SSW-induced effect. Figures 8b and 8c display the remarkable feature of the decreased occurrence frequency during the SSW period, which agrees with the results in Figure 8a. As mentioned before, we mainly focus on the variation in the occurrence altitude in this case. Figure 8d shows an intriguing connection in which the average occurrence altitudes descend to lower altitudes during the SSW period when the occurrence rates of ionospheric F-layer scintillation are relatively low. Although the average occurrence altitudes on labeled day 30 of Figure 8d are relatively low during the four selected local time slots, the average occurrence altitudes at that time are still higher than those during the SSW period except for the 19:30–21:30 local time slot. Combined with Figure 8a, we find that the insufficient number of COSMIC RO observations during the early hour of the 19:30–21:30 local time slot may be responsible for the lower average occurrence altitude. On the other hand, Figure 8e clearly shows that the occurrence altitude during the SSW period is lower than that both during the pre-SSW period and during the whole period (marked as Average) at most local time points. As shown in Figures 8b and 8c, the similar variation in different LT slots further excludes the temporal sampling effect. These results suggest that not only the occurrence rate but also the occurrence altitude of ionospheric F-layer scintillation decreased during the 2012–2013 major SSW event.

Figure 8. Same as in Figure 2 but for the 2012–2013 SSW event. The light blue, light red, and light green horizontal shadow areas under the X axis indicate the reference pre-SSW (days 18–27), SSW (days 48–57), and post-SSW (days 75–90) time periods, respectively.
Table 1 shows the statistical results of the ionospheric F-layer scintillation over the American sector for the three periods, i.e., pre-SSW, SSW, and post-SSW periods. Table 1 shows that the average occurrence altitudes are 341.44, 312.56, and 345.61 km during the pre-SSW, SSW, and post-SSW periods, respectively. As shown in Table 1, the occurrence rates are 80%, 45%, and 71% during the pre-SSW, SSW, and post-SSW periods, respectively. Therefore, the occurrence altitude and rate of ionospheric F-layer scintillation, which decreased from the pre-SSW period to the SSW period, were 28.88 km and 35%, respectively. We note that the occurrence rates during the post-SSW period eventually recovered to a similar level during the pre-SSW period. It can be concluded that seasonal behavior is not the main factor affecting the weakening of the occurrence frequency. According to de Paula et al. (2015) and Yu et al. (2020), the decreased PRE vertical drift during the 2012–2013 SSW event plays an important role in the suppression of EFI development and hence in ionospheric F-layer scintillation. Additionally, the change in meridional wind also has a potential influence on the field line integrated conductivity of an unstable flux tube, leading to the suppression of EFIs/ionospheric scintillation during SSW periods (de Jesus, Batista, Jonah, et al., 2017; de Paula et al., 2015; Huba & Krall, 2013).

3.5. Combined Analysis

The four-year results reveal that the different types of SSW events (major warming or minor warming) have similar suppression effects on the activity of ionospheric F-layer scintillation. Combining multiyear results and their average together is beneficial for distinguishing the controlling factors of ionospheric scintillation behavior. To further investigate the ionospheric scintillation behavior during these four SSW events, the variation in ionospheric scintillation altitude and occurrence rate with the pre-SSW, SSW, and post-SSW periods is presented in Figure 9. The salient features observed in Figure 9 are described as follows:

1. The prominent feature was the consistent suppression of the occurrence altitudes and rates of ionospheric F-layer scintillation during the SSW periods. Figure 9 shows that both occurrence altitudes and rates evidently decreased from the pre-SSW period to the SSW period, while during the post-SSW period, they recovered to a similar level during the pre-SSW period, excluding the occurrence rate during the post-SSW period of 2009, which may still be influenced by the SSW event, as mentioned before. Thus, the SSW-induced inhibitory effect rather than the seasonal factor should be the main factors during SSW periods.

2. Figure 9 clearly shows that there is a positive correlation between the ionospheric scintillation parameters and the intensity of solar activity, which agrees with previous results (e.g., Carter et al., 2013; Yu
et al., 2018). The year 2013, with the highest levels of solar activity, has the highest altitude and rate of occurrence, which may partly contribute to the largest decrease in magnitude during the SSW period of this year. Correspondingly, 2009, under the lowest levels of solar activity, had the lowest occurrence altitude and rate. The years 2008 and 2010 are in the middle. Overall, the trend observed under different solar activities does not show very notable differences, so we do not have to consider it as an influencing factor for the observed variations.

3. Figure 9a suggests that the SSW types may influence the decrease in altitude. The descent of the occurrence altitude are highest during two major SSW events (2009 and 2013), followed by the 2010 moderate SSW event and then the 2008 minor SSW event. This finding suggests that the strength of the SSW event possibly affects the occurrence altitude of ionospheric F-layer scintillation. The detailed mechanism needs to be studied by simulation. For the occurrence rate, there is no clear correlation between the variation in the occurrence rate and the SSW types. Figure 9b shows that the 2008 minor SSW event has the lowest decreased magnitude during the SSW period. Notably, the occurrence rate during the duration of the first peak warming is decreased by ∼15%, which is comparable to the 2009 and 2010 SSW events. Thus, no well-organized behavior of the variation in the occurrence rate is related to the SSW types. Similarly, Gupta and Upadhayaya (2017) found no marked differences in the trend of electron density enhancement observed during the major and minor SSW events. Thus, more work needs to be done to understand the relationship between scintillation behavior and SSW types.

4. Summary and Conclusion

In this study, we use the COSMIC RO data set to analyze how ionospheric F-layer scintillation/EFIs over the American sector responds to various SSW events (i.e., the SSW events of 2007–2008, 2008–2009, 2009–2010, and 2012–2013). These SSW events are distinguished from each other in some aspects, such as the SSW types, event duration, number of peak warmings, planetary wave forcing, solar and geomagnetic activities, and so on. However, despite the diversities shown in each event, the ionospheric F-layer scintillation over the American sector exhibits a similar response to all of them. The main conclusions of this study can be summarized as follows:

1. The occurrence altitude and rate of ionospheric F-layer scintillation over the American sector decrease by 13.48 km and 17% on average, respectively, during the SSW periods when compared with the pre-SSW periods, as shown in Table 1. The results reveal that the different types of SSW events (major warming or minor warming) have similar suppression effects on the development of EFIs and hence on the activity of ionospheric F-layer scintillation, although ionospheric scintillation during minor warming has a relatively small response magnitude. In previous studies (de Jesus, Batista, Jonah, et al., 2017; de Paula et al., 2015; Yu et al., 2020), the SSW-induced suppression of the generation of ionospheric irregularities was investigated under high solar activity. To our knowledge, this study is the first in the literature that suggests an SSW event under low solar activity, including the minor warming event type, can also affect the generation of ionospheric irregularities/scintillation. Furthermore, for the first time, we reported an obvious decrease in the average occurrence altitude of ionospheric F-layer scintillation during SSW events. In addition, we found that the SSW types may have an influence on the decrease in altitude. The decreased altitudes are highest during two major SSW events (2009 and 2013), followed by the 2010 moderate SSW event and then the 2008 minor SSW event.

2. The occurrence altitude and rate of ionospheric F-layer scintillation over the American sector eventually recovered to the pre-SSW or relatively comparable level during the post-SSW period, as displayed in Table 1 and Figure 9. Therefore, the inhibitory effects on ionospheric F-layer scintillation during the SSW periods cannot be explained merely as seasonal behavior over the American sector. The decrease in vertical drift and/or related TEC parameters around the afternoon/early-evening hours was obviously observed during most of the SSW events in previous works (Chau et al., 2010; de Paula et al., 2015; Fang et al., 2012; Goncharenko, Coster, et al., 2010; Paes et al., 2014). Additionally, significant changes in meridional wind have been widely reported during SSW events (de Paula et al., 2015; Goncharenko et al., 2018; Jonah et al., 2014; Zhang et al., 2020). Compared with the seasonal effects, the SSW-induced effects mentioned above should be more pronounced in the weakening of ionospheric scintillation
activities during those periods. The mechanism controlling irregularity development during SSW periods is very complicated and needs to be further investigated in future research.

3. One intriguing feature that occurred in a period before the 2009–2010 SSW event is the decreased occurrence rate of ionospheric F-layer scintillation, without a declining trend in the average occurrence altitude. We infer that the long-lasting enhancement of both planetary wave 1 and the lunar semidiurnal tide (see J. Liu et al. [2019] of Figure 5) during this period, resulting in the change in the E region dynamics, may be responsible for the low occurrence frequency of ionospheric scintillation associated with EFIs (Abdu et al., 2006; Goncharenko, Chau, Liu, et al., 2010; Jase et al., 2017), which deserves further study. Another analogous decrease in the occurrence rate of ionospheric F-layer scintillation is observed several days before the peak warming of the 2008–2009 SSW event. Coincidentally, enhanced planetary wave 2 and lunar semidiurnal tide activities are also clearly presented during the same period in Figure 2 of J. Liu et al. (2019). The possible mechanisms should be further studied.

Data Availability Statement

The F10.7 and Kp indices are downloaded from the Center for Space Standards and Innovation (http://www.celestrak.com//SpaceData/). The authors sincerely acknowledge the COSMIC Data Analysis and Archive Center (CDAAC) team for the access to the COSMIC data (http://www.cosmic.ucar.edu/). The authors are grateful to NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, for the NCEP/NCAR Reanalysis data on the web site at http://www.esrl.noaa.gov/psd/

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