Ionospheric Signatures Associated with Sudden Stratospheric Warming (SSW) Episodes Over Okinawa

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***Abstract*— Sudden stratospheric warmings (SSWs) are large and rapid temperature increases in the winter polar stratosphere associated with reversal of the climatological wintertime westerly winds. A comparative study of Major and Minor SSW events which occurred in the Northern Hemisphere has been carried out in this work. We have considered one major SSW and one minor SSW of 2012-2013 and 2015-2016 winters respectively. MERRA2 reanalysis data for Zonal Mean Zonal Wind (ZMZW) and Temperature have been used to characterize the SSW events. The temperature profiles for altitude range 30-90 km have been obtained from Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) onboard Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED). Among various ionospheric parameters, we have used critical frequency of F_2 layer (f_oF_2) and base height of ionosphere (h'F) to study the ionospheric response to these events over Okinawa (26.21ºN, 127.68ºE). Ionospheric parameters have different response to both the events. Significant ionospheric perturbations are observed during minor warming also, although we expect it during major SSW.**

Keywords—Sudden stratospheric warming, ionosphere, mesospheric temperature inversion, zonal mean zonal wind

I. INTRODUCTION

Sudden stratospheric warming (SSW) is a large meteorological feature of the high latitude middle atmosphere during winter season caused by the interaction of enhanced planetary wave activities with stratospheric zonal mean flow and associated changes in the polar region dynamics. It was discovered by Scherhag [1] who first noted a sudden increase of temperature in the radiosonde over Berlin. After that a number of investigations have been carried out by observations and modeling to find out the complex structure and formation of the incident. In connection with SSW, there is a breakdown of the polar vortex, which extends to abrupt increase of the meridional temperature and slow down or reversal of the westerly zonal wind at high latitude [2, 3, 4, 5]. If there is an increase in poleward stratospheric temperature at 60° latitude and an associated circulation change from zonal mean eastward flow to westward flow at 10 hPa level, such warming is categorized as Major SSW. While, if there is no reversal at 10 hPa level, such warming is termed Minor SSW [3, 6, 7]. The transition phase of the winter stratosphere into summer mode, when the easterlies are developed, is called as Final warming. Then the easterlies persist until the following winter. SSWs in late February or March often turn directly into final warmings. An early and abrupt final warming is known as Major Final Warming (MFW) [3, 8, 9, 10]. Depending on the conditions of the polar vortex, such warming events can be classified into vortex displacement events and vortex splitting events [11, 12]. A warming is known as Vortex displacement event when the vortex is shifted off the pole; while it is a vortex splitting event when the vortex splits into two or more daughter vortices.

The layer of ionized gas in the upper atmosphere is the ionosphere. It is a complex and dynamic layer that is significantly affected not only by the solar activity and geomagnetic disturbances, but also by the neutral atmospheric processes. About 20% of the ionospheric variabilities are due to meteorological processes [13]. SSW events are the strongest manifestation of both vertical coupling [14, 15, 16] and lateral coupling [17] of the atmosphere. Although the effect of SSW on the upper atmosphere was hypothesized several decades ago [18], considerable research has been done during the last decade only. Many observations have shown the perturbations in various ionospheric parameters, which mostly include the total electron content (TEC) and equatorial electrojet (EEJ), and a few include F2 layer maximum electron density and vertical plasma drift [19, 20, 21, 22, 23, 24, 25, 26].

In our present work, a comparative study of Major and Minor SSW events which occurred in the Northern Hemisphere has been carried out. Then we have investigated the effects of such SSWs on the ionosphere. We have mainly considered critical frequency of F_2 layer (f_oF_2) and base height of F layer (h'F) over Okinawa.

II. DATA AND METHODOLOGY

The stratospheric zonal mean zonal wind (ZMZW) and temperature reanalysis data are taken from Modern-Era Retrospective analysis for Research and Applications (MERRA2), which can be downloaded from http://acdbext.gsfc.nasa.gov/Data services/met/ann data.html. It has been developed by NASA's Global Modeling and Assimilation Office, focusing mainly on the satellite era from

1979 to the present. Ref [27] provides an overview of the system and the observations used in the dataset. Temperature data are taken at 10 hPa and 80°N, while the ZMZW data are taken at 10 hPa and 60°N. The ionospheric parameters used in this work are obtained from Ionosonde located at Okinawa (26.21˚N, 127.68˚E). We have been mainly dealing with critical frequency of F_2 layer (f_oF_2) and base height of F layer (h'F). The critical frequency f_oF_2 is related to peak electron density N_mF_2 as

$$N_mF_2 = 1.24\,(f_oF_2)^2 \times 10^{10}\ \text{el.m}^{-3}$$

In this work, we have used deviations of foF2 and h'F by taking the difference from winter mean as stated below

$$d(f_oF_2)_i = (f_oF_2)_i - \overline{f_oF_2}$$
$$d(h'F)_i = (h'F)_i - \overline{h'F}$$

where, $\overline{f_oF_2}$ and $\overline{h'F}$ are winter average of f_oF_2 and h'F respectively. Ionospheric data are downloaded from https://wdc.nict.go.jp/IONO/HP2009/ISDJ/index-E.html.

The altitude profiles of temperature over Okinawa have been taken from the Sounding of the Atmosphere using Broadband Emission Radiometry (SABER) onboard Thermosphere-Ionosphere-Mesosphere Energetics and Dynamics (TIMED) satellite, which is a limb scanning and a 10-channel broadband infrared radiometer. These data can be downloaded from http://saber.gats-inc.com/data.php. For the study we have used version 2.0 of temperature. We have considered SABER passes over a range of latitudes (26.21˚N ±2) and longitudes (127.68˚E ±2). Dst index is taken from OMNIWeb, from the website https://omniweb.gsfc.nasa.gov/form/dx1.html.

III. RESULTS AND DISCUSSION

Firstly, we have figured out SSW events from Temperature and ZMZW data from MERRA2 reanalysis data. If there is an abrupt increase of temperature at 80°N and a slow-down of the ZMZW at 60°N, then we consider it to be a minor event; and the day of maximum temperature is taken as the central date for the event. If the ZMZW reverses along with the increase in temperature for more than four days continuously, then we consider it as a major event. The first day of wind reversal is considered as the central date of a major event. For the study we have considered major SSW of 2012-2013 winter, which has the central date on January 6, and the minor SSW of 2015-2016 with central date on February 8.

We have plotted stratospheric parameters for winter (from November to March) of the above-mentioned years in Fig. 1. The upper panel shows temperature profiles at 80°N and the lower panel shows ZMZW at 60°N, both at 10 hPa. Both the parameters are shown by blue curves for 2012-2013 winter and grey curves for 2015-2016 winter. The dotted curve shows climatological mean of 40 years (1981-2020) for both the parameters in both the panels. The temperature curve for 2012-2013 winter clearly shows abrupt increase in temperature after December 31, with peak stratospheric temperature ~241K on January 12. The temperature increases remarkably than the climatological mean for almost 20 days. ZMZW slows down from mid-December and reverses on January 6. It remains easterly for almost 20 days. Overall, ZMZW remains disturbed for more than two months and comes back to climatological value by the end of February.

The minor event of 2015-2016 winter is observed during early February with peak polar temperature on February 8. 2015-2016 winter is an exception with a MFW when ZMZW finally turns easterly on March 5 for rest of the time of the year until the next winter.

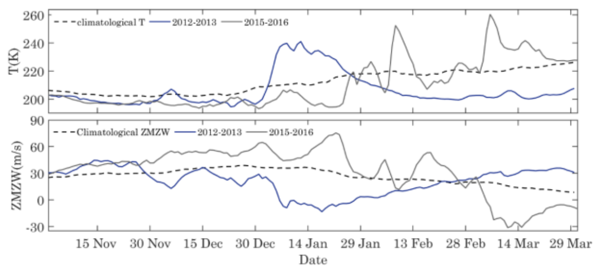

Fig. 1. Stratospheric fluctuations during 2012-2013 (blue curves) and 2015-2016 (grey curves) winter. The upper panel shows temperature profiles and the lower panel shows zonal mean zonal wind (ZMZW) profile. The dotted curve in both the panels denote the climatological mean of 40 years (1981-2020).

If we observe altitude profiles of temperature and ionospheric profiles over Okinawa during the events, we can see clear perturbations during both SSWs. Fig. 2 shows SABER temperature profile during the 2012-2013 major SSW. Maximum temperature deviation is seen on January 17 (red curve), when the easterly wind has maximum velocity. Mesospheric cooling is observed within an altitude range of ~70-80 km on the same day. The temperature deviation gradually decreases after January 21. Mesospheric temperature inversion (MTI) is observed above almost 75 km for both days. Fig.3 shows ionospheric and geomagnetic fluctuations during this event. The upper panel shows the variation of df_oF_2, while the middle panel shows that of dh'F and the lower panel shows the Dst index during a period from mid-December till February. Before the temperature enhancement, we observe a decrease of f_oF_2 with maximum negative deviation of ~5 MHz. As the polar stratospheric temperature and ZMZW get disturbed, f_oF_2 increases during evening till night for first few days. Immediately after the peak polar temperature, the easterly wind attains maximum velocity, and simultaneously f_oF_2 significantly increases in the afternoon hours which gradually extends till midnight. A maximum deviation upto ~5 MHz has been noted. The base height also increases during the period of disturbed temperature and ZMZW. A maximum positive deviation of more than 120 km is noted during this disturbed period. The geomagnetic condition as inferred from the Dst index of the lower panel shows that there is no any intense storm during this period, hence we can refer the ionospheric changes to the 2012-2013 major SSW.

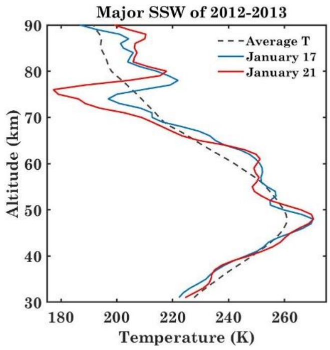

Fig. 2. SABER temperature profile over Okinawa during major SSW of 2012-2013 winter

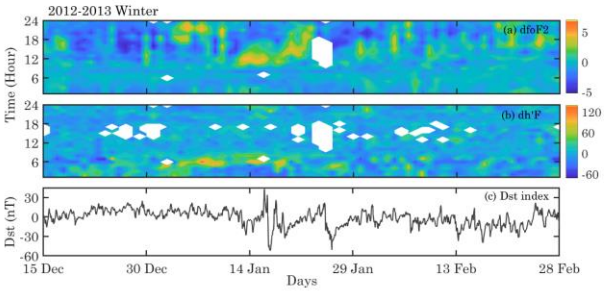

Fig. 3. Ionospheric profile over Okinawa during 2012-2013 major SSW. Deviations of (a) foF2 and (b) h'F, and (c) Dst index variations during December 15 to February 28.

Fig. 4 shows the SABER temperature profile during minor SSW of 2015-2016 winter. As the polar temperature starts increasing, we notice changes in temperature profile over Okinawa. Two stratopause and relatively a colder mesopause is noted on February 5 (blue curve). Stratospheric temperature deviation is observed till February 10. During this event clear Mesospheric Temperature Inversion (MTI) is noticed. Significant ionospheric fluctuations have also been observed during the minor SSW (fig. 5). Dst index has depicted geomagnetic disturbances during this period and associated ionospheric changes can be seen. After the central date of the minor SSW, f_oF_2 enhances during noon with a maximum positive deviation of ~5.5 MHz. In the recovery phase, just before the MFW, f_oF_2 starts increasing from noon till mid-night with a maximum deviation ~8 MHz. During the minor warming, h'F also increases and the maximum deviation reaches up to ~130 km. Later, during the MFW, significant enhancement of f_oF_2 is noted from afternoon till midnight with a maximum positive deviation ~7.7 MHz.

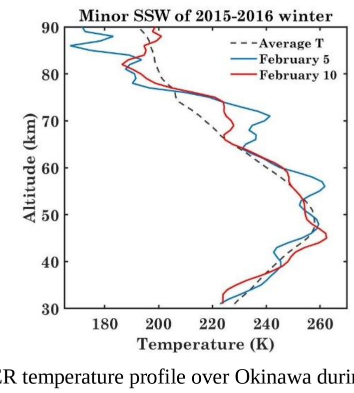

Fig. 4. SABER temperature profile over Okinawa during minor SSW of 2015-2016 winter

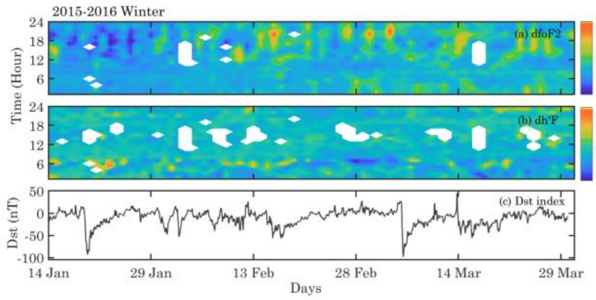

Fig. 5. Ionospheric profile over Okinawa during 2015-2016 minor SSW. Deviations of (a) foF2 and (b) h'F, and (c) Dst index variations during December 15 to February 28.

The fluctuations in mesospheric temperature are mainly caused by GW drag [28]. When westerly stratospheric winds slow down or reverses during SSW, it leads to reversal of the mesospheric winds as well, and also alternate the residual circulation from downward to upward, which eventually results in adiabatic cooling of the mesosphere [29, 30]. The double stratopause is again mainly due to GWs, PWs as well as combined wave activities. The disturbed E region dynamo mainly cause perturbations in the ionospheric profile during SSW. It is also considered to be caused by altering the vertical propagation of PW [31]. PWs interact with the tides and GWs, and this combined wave activities can affect the atmosphere upto the ionospheric height [32, 33]. In both the cases, we have observed prominent night time peak electron density enhancements rather than the expected increase during morning and decrease during evening hours. We can attribute this behavior to F region dynamo due to higher F region Pederson conductivity [4, 34].

IV. CONCLUSION

The stratospheric parameters vary significantly from the climatological mean during the major SSW, and the deviation is relatively more in major event than in minor. ZMZW remains disturbed for almost two months during the major SSW. The SABER temperature profiles show fluctuations over Okinawa during both the events, although stratospheric temperature deviation is more prominent during major SSW. MTI is clearly visible over an altitude range 65-75 km during the minor SSW, while during the major warming, mesospheric cooling is observed at that height and positive deviation is seen above 75 km up to 90 km. Although we expect that the ionospheric fluctuations will be less during the minor warming, here in both the cases the maximum positive deviation of both the ionospheric parameters reaches almost the same amount. To make a clear conclusion on this topic, we need more analysis of data on vertical drift and that of GWs and PWs.

ACKNOWLEDGMENT

The authors are thankful to NASA/GSFC's ACDL for providing the stratospheric data, NICT's WDC for ionospheric data, and OMNIWeb for Dst index data. The authors would also like to thank the SABER team for providing access to the online temperature data.

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