Published by The College of Science & Information Technology (COSIT), TASUED, Vol. 18, No. 1, pp. 87-108.

COSIT, TASUED

Journal of Science and Information Technology (JOSIT)

The Influence of Solar Activity Level on Sudden Stratospheric Warming Events During Solar Cycle 23 (1998-2008)

***[1]Kotoye, A.A., [2]Bamidele, K. J., [3]Ajose, A. S., [2]Falayi, E. O.**

[1]Science Laboratory Technology Department, Abraham Adesanya Polytechnic, Ijebu-Igbo, Nigeria.

[2]Department of Physics, Tai Solarin University of Education, Ijagun, Nigeria.

[3]Department of Physics, Lagos State University of Technology. Oto/ Ijanikin, Nigeria.

**Corresponding Author: afobuddy@gmail.com*

ABSTRACT

The Sudden Stratospheric Warming (SSW) events which occurred during solar cycle 23 (1998-2008) were investigated using daily stratospheric data (temperature, planetary wave, and zonal mean wind). A total of 10 events that occurred in the period were investigated, and they were all major events. The Wavelet Power Spectrum approach was also used to analyze the stratospheric parameters. It provides more details about the transient variabilities in stratospheric parameters. The analysis of the effect of the solar activity level on sudden stratospheric warming and the direction or phase of the Quasi-Biennial Oscillation (QBO) were also considered. The planetary wave (PW) amplification was observed to precede the rise in temperature and the reduction in speed of the zonal mean wind. It was noted that planetary wave amplification drives SSW. When the QBO was westerly, the stratospheric temperature shows a positive correlation with solar activity level, PW-1 showed a weak positive correlation (0.21), while PW-2 showed a negative correlation (-0.55). In the easterly phase, temperature and solar activity level show an inverse relationship, while both PW-1 and 2 showed a positive correlation with solar activity level. The result suggested that in the westerly phase, the solar activity level drives stratospheric temperature via adiabatic energy transfer but has no influence on the strength of the PW. In the easterly phase, the solar activity level does not influence stratospheric temperature, but it influences the generation of stronger PWs which drive intense SSW events. These results clearly show the influence of solar activity level on SSW and the coupling mechanism between the equatorial troposphere and the polar stratosphere.

Keywords: Sudden Stratospheric Warming, Quasi-Biennial Oscillation, Planetary wave, Wavelet Power Spectrum, Amplification

INTRODUCTION

The atmosphere, being made up of gases that surround the Earth is made up of four layers, namely- the troposphere, the stratosphere, the mesosphere, and the thermosphere. The stratosphere extends from the top of the troposphere to a height of about 50km to 55 km. The atmospheric pressure at the top of the stratosphere is far lower than the pressure at sea level, and it houses the Ozone layer, which is the part of Earth's atmosphere where Ozone gas is majorly found. In the stratosphere, temperature increases with height because the Ozone layer absorbs ultraviolet (UV) radiation from the Sun. This restricts turbulence and mixing in the stratosphere. Although the temperature at the tropopause may be about −60 °C (−76 °F; 210 K),

---

Cite as:

Kotoye A.A., Bamidele K.J., Ajose A. S. and Falayi, E. O. (2024). The Influence of Solar Activity Level on Sudden Stratospheric Warming Events During Solar Cycle 23 (1998-2008). *Journal of Science and Information Technology (JOSIT),* Vol. 18 No. 1, pp. 87-108.

the top of the stratosphere is much warmer and may be near 0 °C (Zhang et al., 2021; Scaife, 2022).

Due to the the variation of temperature with height in the stratosphere, there exists a very stable atmospheric condition, so the stratosphere lacks the air turbulence and mixing which produces weather effects. These weather effects are commonly found in the troposphere. (Matthias & Kretschmer, 2020).

Consequently, the stratosphere is almost completely free of clouds and other forms of weather-related structures and phenomena. However, at the poles, clouds are occasionally seen in the lower part of the stratosphere where the air is coldest (Scaife, 2022; Haynes et al., 2021).

RELATED WORKS

An SSW is a large-scale disturbance in the stratospheric polar vortex which causes a major variability in the winter stratosphere, especially in the Northern Hemisphere. In the polar winter stratosphere, the wintertime eastward winds that surround the polar vortex are maintained radiatively by cold polar night conditions (Hocke et al., 2024). It is an event that is important to understanding the winter-time variation of the dynamics in the polar stratosphere (Goncharenko et al., 2021c; Zhang et al., 2020). It features a sharp increase in air temperature of the stratosphere by about tens of degrees, accompanied by a weakening or a total change in the direction of zonal wind. As planetary waves (PW) propagate upwards from the troposphere, they are amplified and break in the stratosphere thereby weakening the zonal wind (Zhang et al., 2020). The process of weakening the polar vortex makes it easy for SSW to occur (Domeisen & Butler, 2020). If the zonal mean wind is weakened, the SSW is said to be a minor event. The Coriolis force makes up for the deceleration of the eastward zonal mean wind by causing a pole-ward meridional circulation. This pole-ward circulation causes a down-welling at the poles and an up-welling at the equator causing adiabatic heating and cooling respectively in these regions. Conversely, if the direction is reversed, it is a major SSW event (Hocke et al., 2024; Goncharenko et al., 2021c & Zhang et al., 2020). During SSW, the normal polar vortex changes its shape and position, therefore, based on the mode of development, SSW events are often classified as either vortex split or vortex displacement events (Pedatella, 2022).

Although it occurs in both hemispheres, the fact that planetary waves have more energy in the Northern Hemisphere due to its topography, SSW is more frequent in the Northern Hemisphere (Ma et al, 2020; Wang et al., 2020). However, observations have shown a global response of ionospheric parameters to SSW. The deceleration or change in the direction of the zonal mean zonal wind (i.e., whether major or minor warming) does not seem to have any effect on the ionospheric parameters since large responses have been reported in the ionosphere during minor warming events (Pedatella, 2018; Mosna, 2021; Goncharenko et al., 2021c). Studies have shown that SSW events have a significant relationship with TEC, geomagnetic storm, and lunar tides. A huge portion of the observed daily variations in ionospheric parameters are not completely due to ionizing flux and geomagnetic activities. It has been observed that lower atmospheric processes accouont for about 20% and 33% of the maximum electron density in the F region at day time and night respectively Goncharenko et al., 2020; Bojilova & Mukhtarov, 2023; Goncharenko et al., 2021b). A strong daytime response to SSW which is characterized by a semi-diurnal variation. At low latitudes, ionospheric perturbations commence a few days after the stratospheric air temperature reaches its peak, and they are observed as an enhancement and reduction of the EIA in the morning and afternoon respectively (Goncharenko et al., 2020).

METHODOLOGY

In this investigation, SSW data comprising stratospheric temperature, stratospheric wind speed, and gravity wave data between the years 1998 and 2008 were used during solar cycle 23. Stratospheric parameter data were obtained from https://acdext.gsfc.nasa.gov/Data_services/met/nn_data.html. The Wavelet Power Spectrum (WPS) approach which provides more details about the transient variabilities in stratospheric parameters was also used to analyze the stratospheric parameters. WPS is a very effective mathematical tool for evaluating time series with different scales. This analysis technique offers information about the frequency of the event relative to its locality in the time series (Falayi et al., 2020).

The WPS is created by the amplification, ψ(t)→ψ(t), and translations, ψ(t)→ψ(t+ 1), with reference to time t. The mother wavelet is presented in Equation (1).

$$\Psi_{a,y}(t) = a^{\frac{1}{2}}\Psi(\frac{t-y}{a}) \quad (1)$$

$$\Psi(t) = \frac{e^{iw_0 t}}{\sqrt[4]{\pi e^{\frac{i^2}{2}}}} \quad (2)$$

$$WPS(a,y) = \int_{-\Psi}^{\Psi} x(t)\,\Psi_{a,y}^{*}(t)dt \quad (3)$$

Where:

$\Psi_{a,y}(t)$ is the wavelength function

w_0 is the dimensionless frequency

$\Psi_{a,y}^{*}(t)$ is the conjugate of the wavelength function $\Psi_{a,y}(t)$

t is the time

The expression of the wavelength coefficient at time index ‘n’ and scale ‘a’ is given as

$$WPS_n(a) = \Psi\,?_{n'=0}^{N-1}\,x(n)'\,\Psi * [\frac{(n'-n)dt}{a}] \quad (4)$$

where N is the length of the data time series and dt represents the time interval. The scale-averaged WPS is used to examine variation in power over a band of scales as shown in equation (5)

$$\overline{W_n^2} = \frac{\Psi j \Psi t}{0.776}\int_{j1}^{j2} \frac{|W(a_j)^2|}{a_j} \quad (5)$$

(Falayi et al., 2020).

The stratospheric parameter data set was processed using the wavelet power spectrum to describe the variance of stratospheric temperature, zonal mean wind, and planetary wave. A considerable energy distribution was perceived in the data set. It is an enhanced performance to study the inconsistency of the mode that dominates with time-frequency during its variation. Equations (1) - (5) were used to obtain the wavelet power spectrum analysis to estimate the time-frequency characteristics of polar stratospheric parameters as shown in Figures 11 - 20.

RESULT AND DISCUSSION

Result

Variation of Stratospheric Parameters

Figures 1 to 10 below show the variation of winter stratospheric parameters during SSW events from 1998 to 2008. Major SSW events are those in which the zonal mean wind reverses direction from eastward to westward as depicted by a reduction below the zero line. Minor events are those in which there is no reversal in direction.

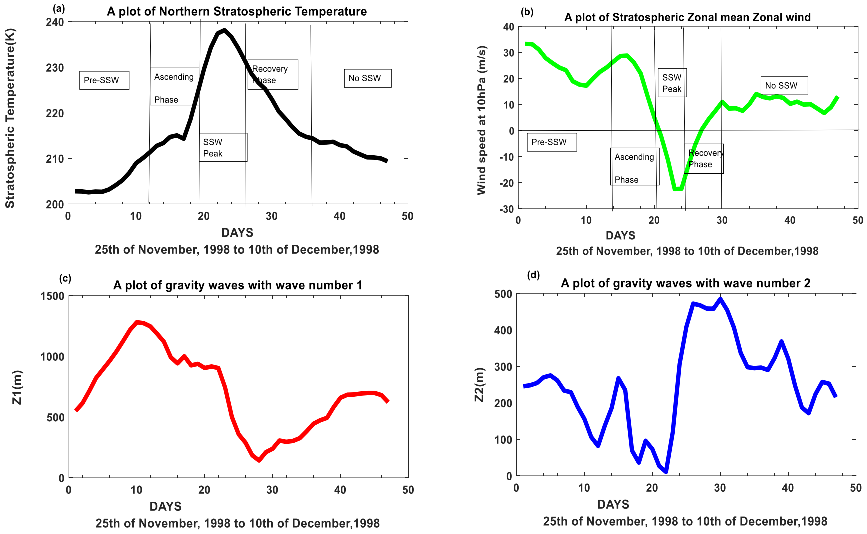


Figure 1. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during 1998 SSW event.

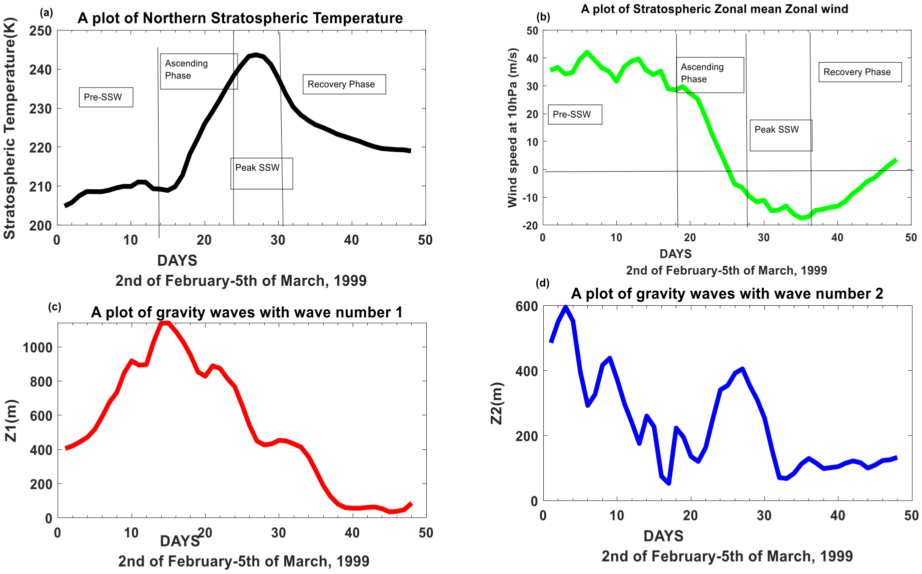


Figure 2. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during 1999 SSW event.

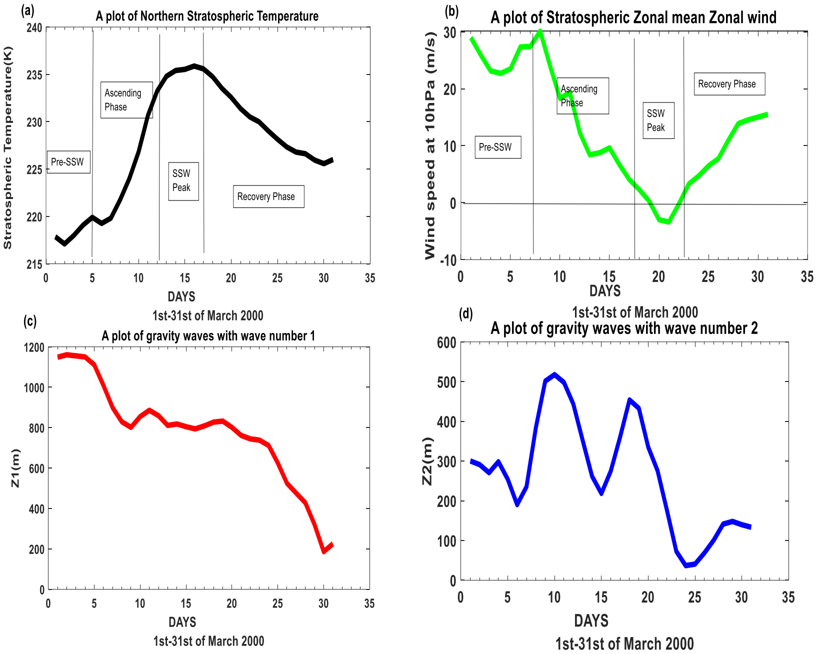


Figure 3. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during 2000 SSW event.

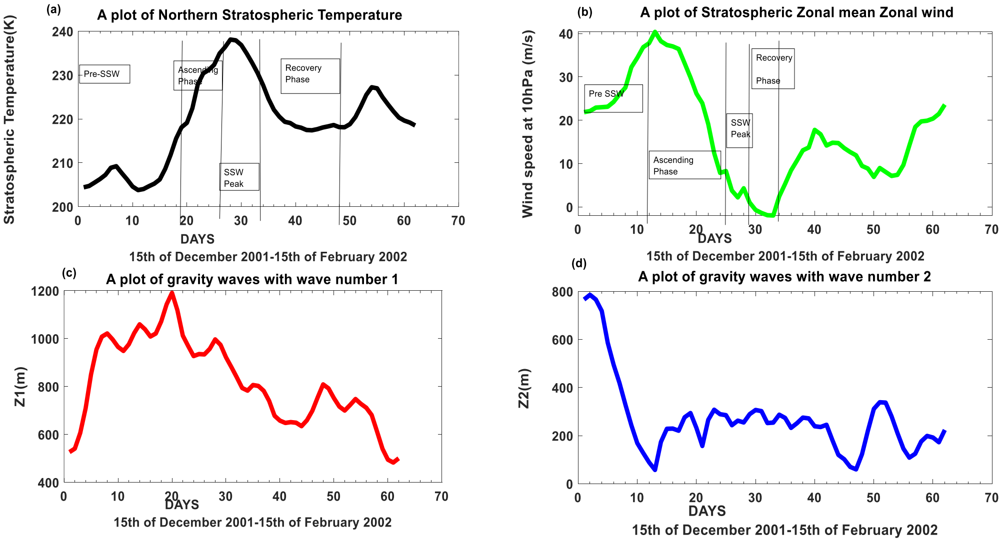


Figure 4. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during 2001-2002 SSW event

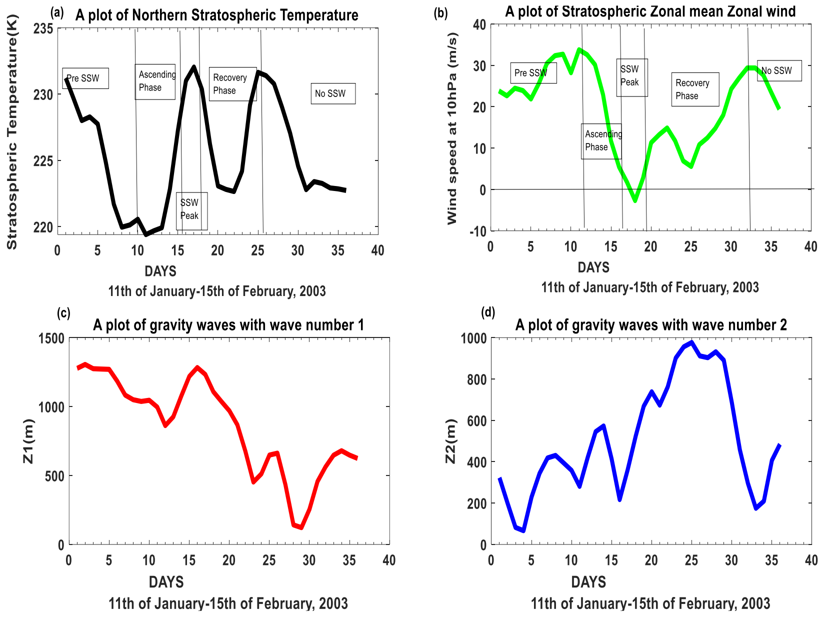


Figure 5. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during 2003 SSW event.

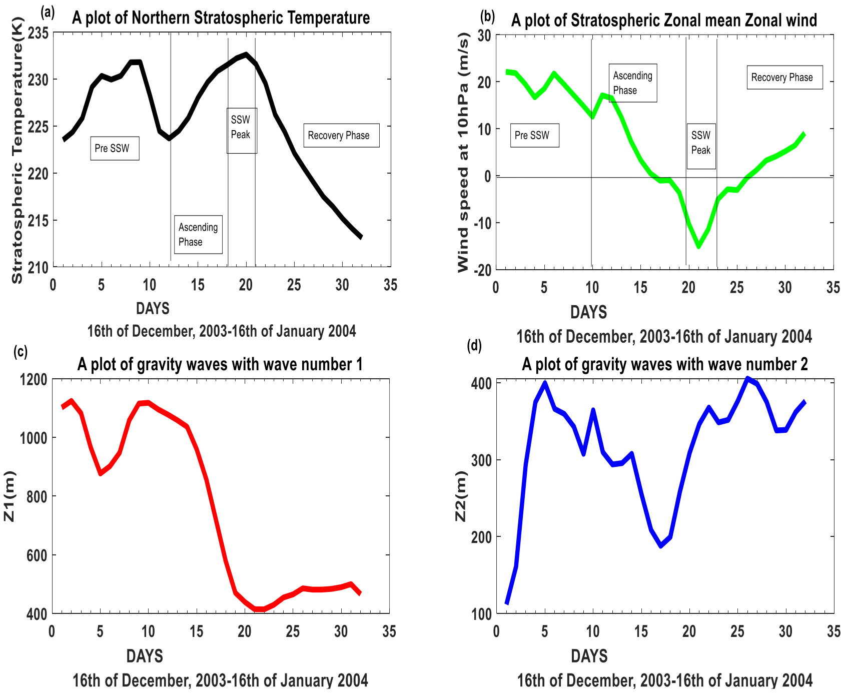


Figure 6. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during the 2004 SSW event

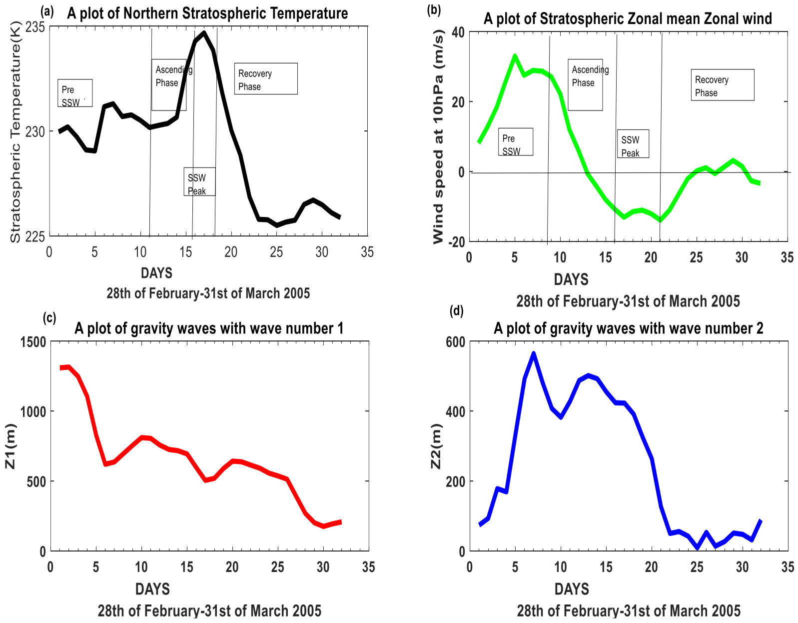


Figure 7. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during 2005 SSW event.

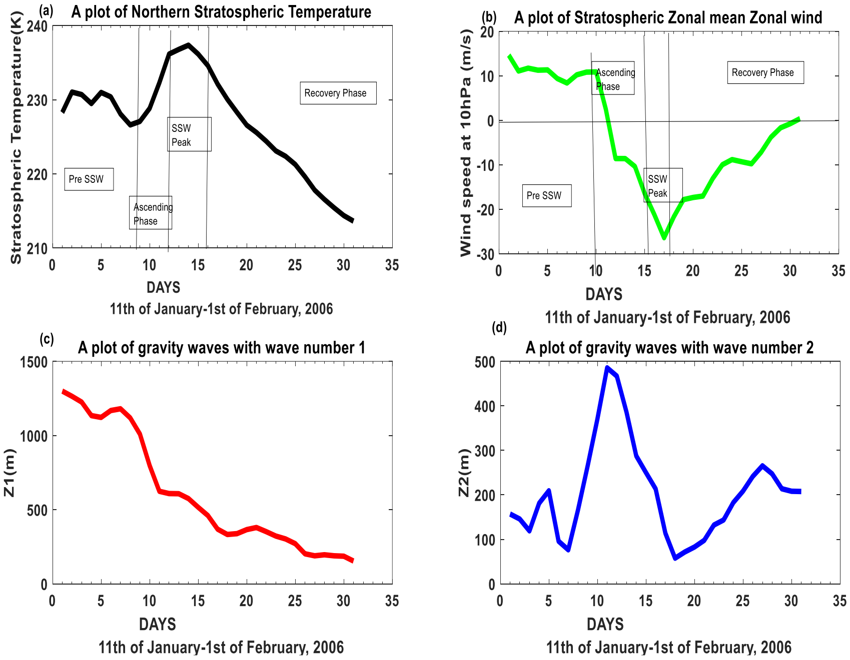


Figure 8. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during 2006 SSW event.

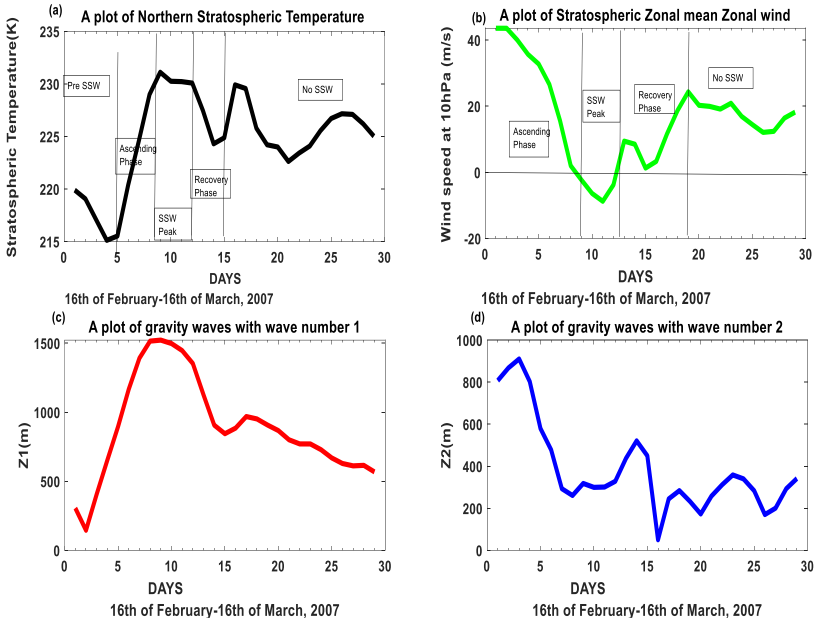


Figure 9. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during the 2007 SSW event.

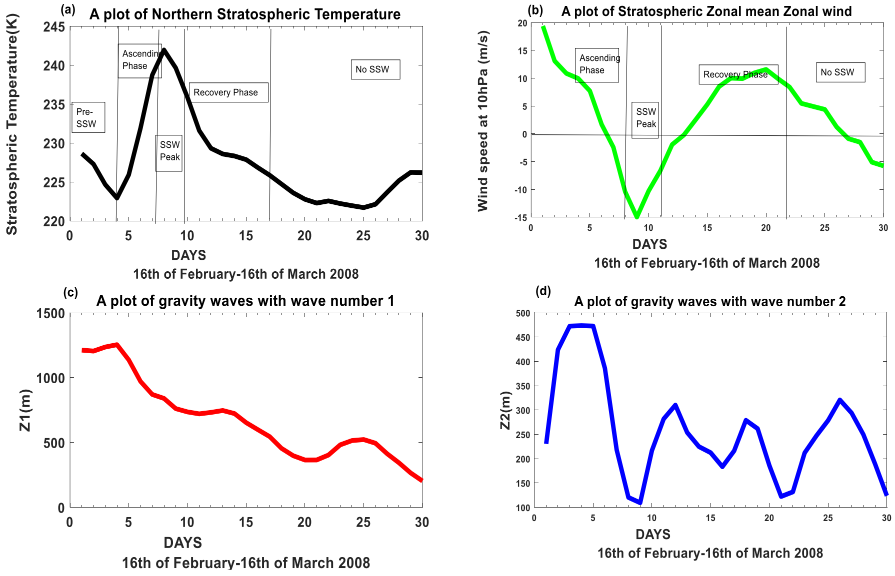


Figure 10. Stratospheric temperature, zonal mean zonal wind speed, planetary waves 1&2 during 2008 SSW event.

Figures 1 to 10 show the plots of polar stratospheric parameters during SSW periods from the year 1998 to 2008. Each Figure is composed of 4 plots, namely- stratospheric temperature, zonal mean zonal wind (ZMZW), and planetary waves 1 and 2. In all the years considered, stratospheric temperature exhibited the same pattern: it is seen to increase rapidly to a maximum value which ranges from about 235 K-238 K after which it then begins to reduce sharply until it returns to pre-SSW values. The zonal mean wind and the planetary waves however show remarkable variation across the years. The zonal mean wind exhibited a reversal in direction in all the years considered, indicating a major warming event. Planetary wave 1 triggered the event in 1998,1999 and 2001-2002, while planetary wave 2 was responsible in 2000, 2004- 2006, and 2008.

In 2003 and 2007, 2 SSW events occurred in quick succession. In both cases, the first event was a vortex displacement (PW-1) event while the second event was a vortex split (PW-2) event. It can also be seen that the first event was a major SSW event while the second one was a minor SSW event.

Wavelet Power Spectrum Analysis (WPS)

The WPS analysis adopted in this study has been used to examine the fluctuation in the power of the polar stratospheric parameters between 1998 and 2008, observed over an average period of about fifty days. Figures 11 - 20 show the WPS plot for the polar stratospheric parameters (temperature, zonal mean wind, planetary waves 1 and 2) across all the years considered. The wavelet power is plotted against both time on the horizontal axis and the corresponding frequency on the vertical axis. Therefore, reading across the graph at any frequency shows the variation of the power with time, while reading up the graph at any time shows variation of power with the frequency (Negash & Raju, 2024; Guo et al., 2022). The wavelet power is usually depicted on contour plots, where the colors are used to depict the amount of energy at a specific frequency and time. This shows that the time series is a very good indicator for polar stratospheric temperature, zonal mean wind speed, and planetary waves 1 and 2. In all the figures, there are periods of high concentration of power for temperature, planetary wave, and zonal mean wind as shown. All the variations were observed to have a signature of the spectral exponent which was computed by using the linear regression method for the SSW period. Also, it was noted that periods of polar disturbance are shown by high wavelet coefficients of stratospheric parameters while low wavelet coefficients indicate the absence of polar disturbance. Wavelet coefficients with higher energy are more prevalent at low frequency. This can be attributed to the fact that the PW enhancement that causes the polar disturbance is a low-frequency phenomenon. The increase in the amplitude of the planetary wave (PW) depends largely on the temporal and spatial structure of the troposphere and the lower stratosphere.

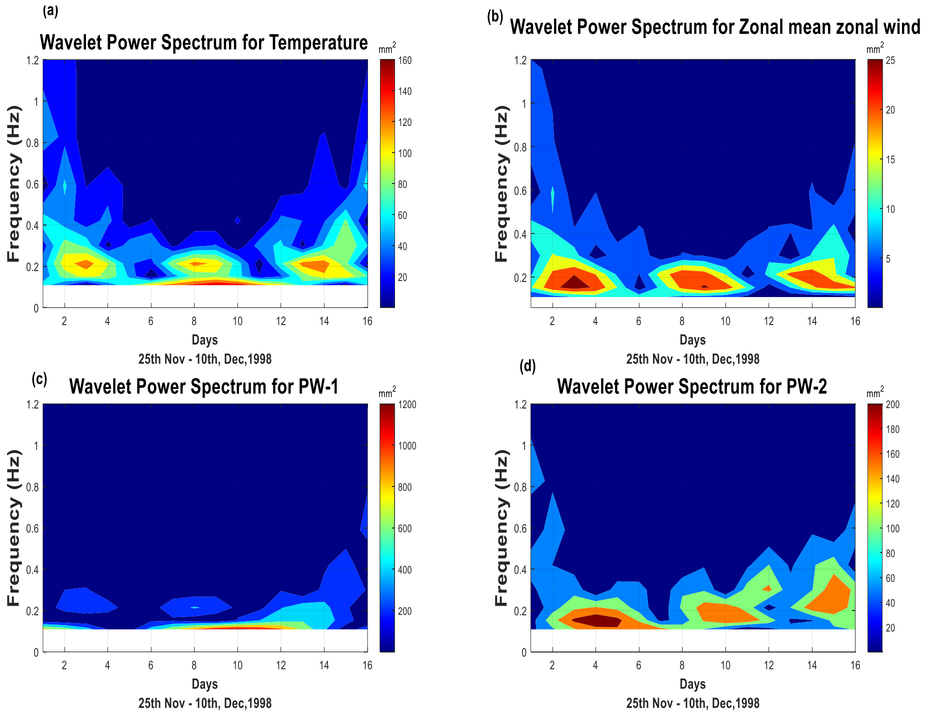


Figure 11. Wavelet power spectrum plot for 1998 SSW event.

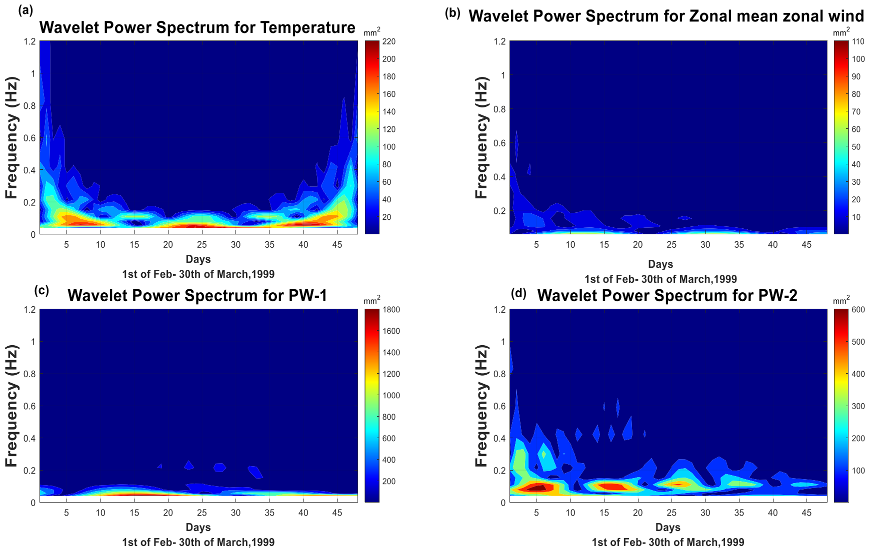


Figure 12. Wavelet power spectrum plot for 1999 SSW event.

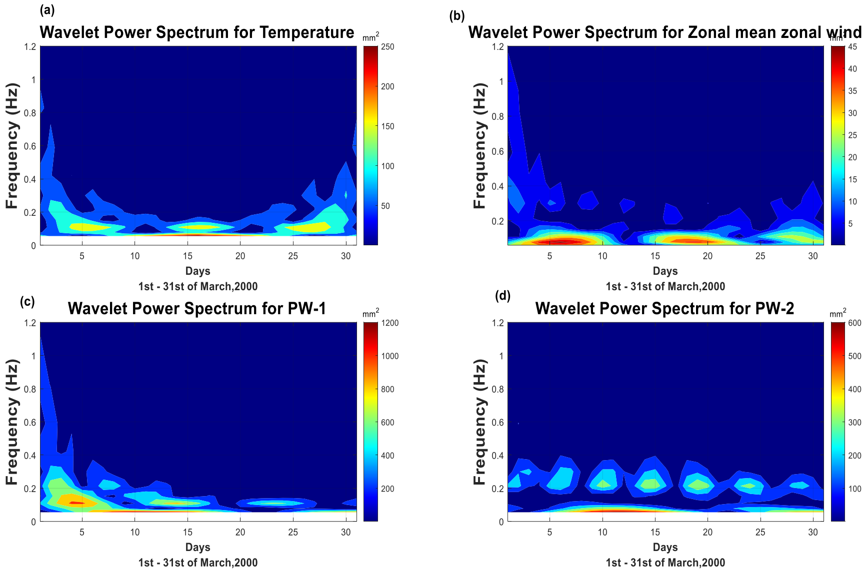


Figure 13. Wavelet power spectrum plot for 2000 SSW event.

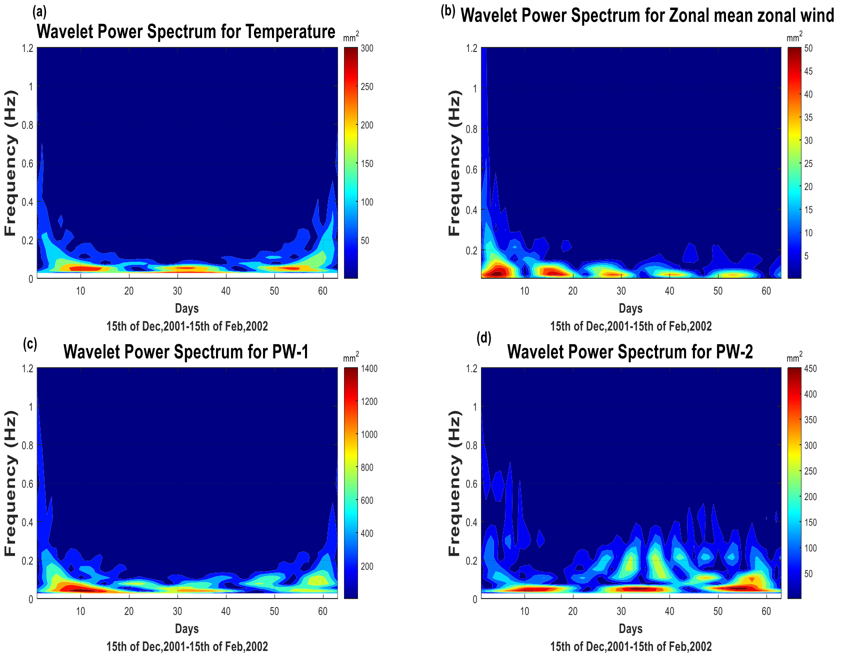


Figure 14. Wavelet power spectrum plot for 2001-2002 SSW event.

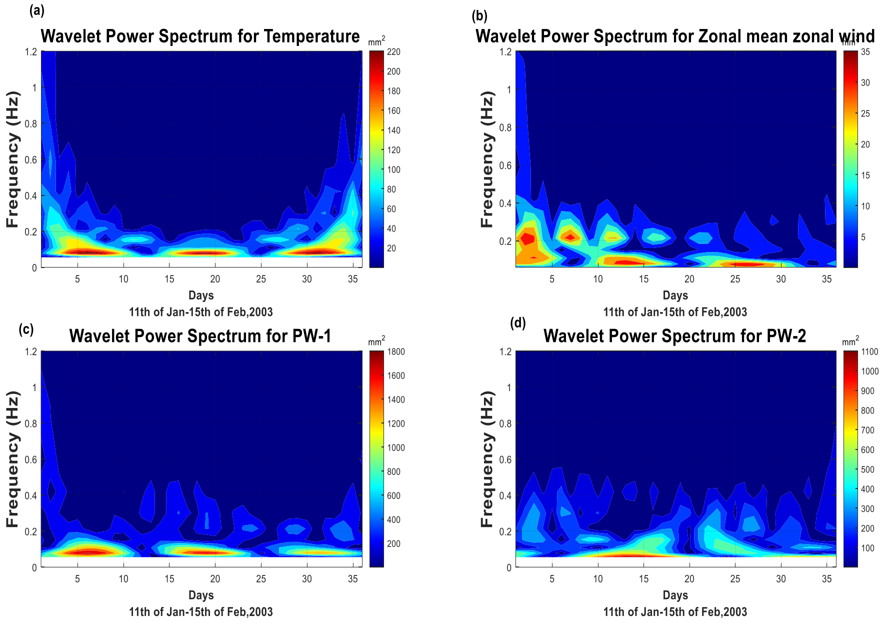


Figure 15. Wavelet power spectrum plot for 2003 SSW event.

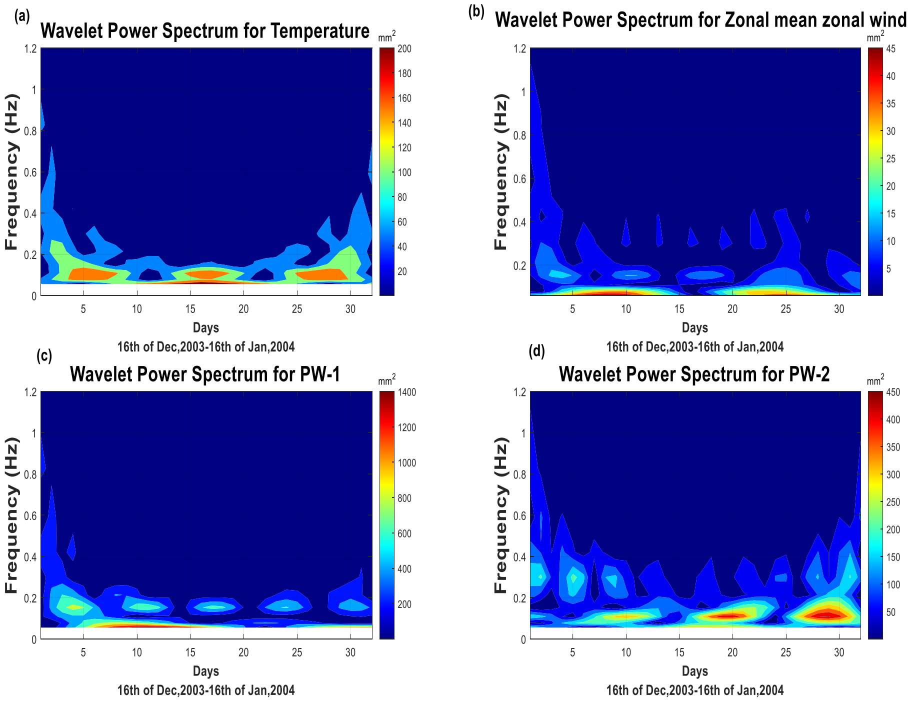


Figure 16. Wavelet power spectrum plot for 2004 SSW event.

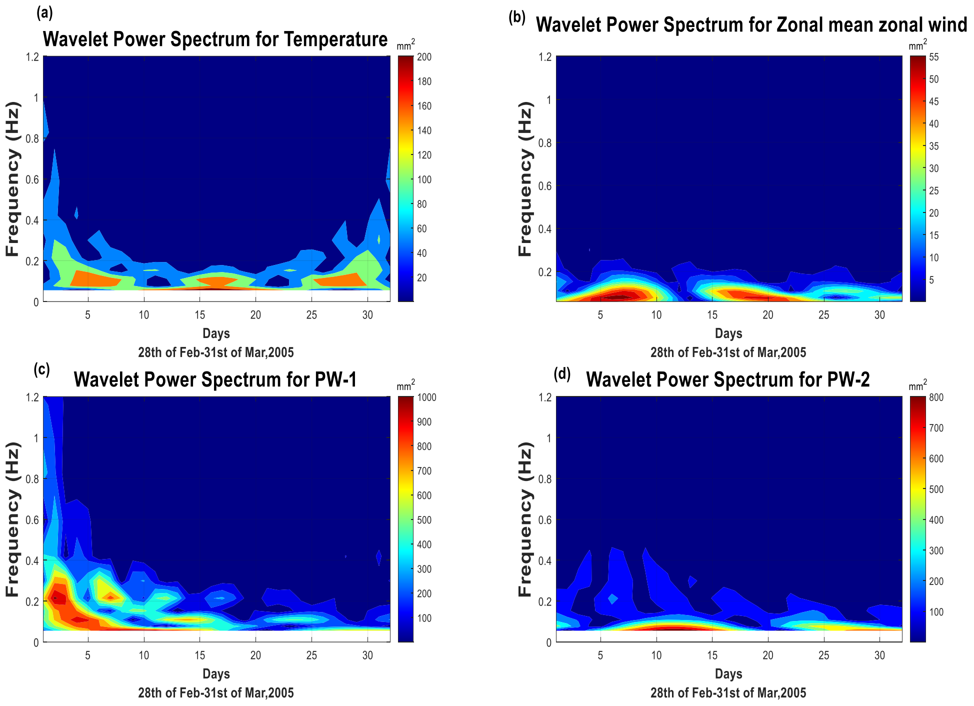


Figure 17. Wavelet power spectrum plot for 2005 SSW event.

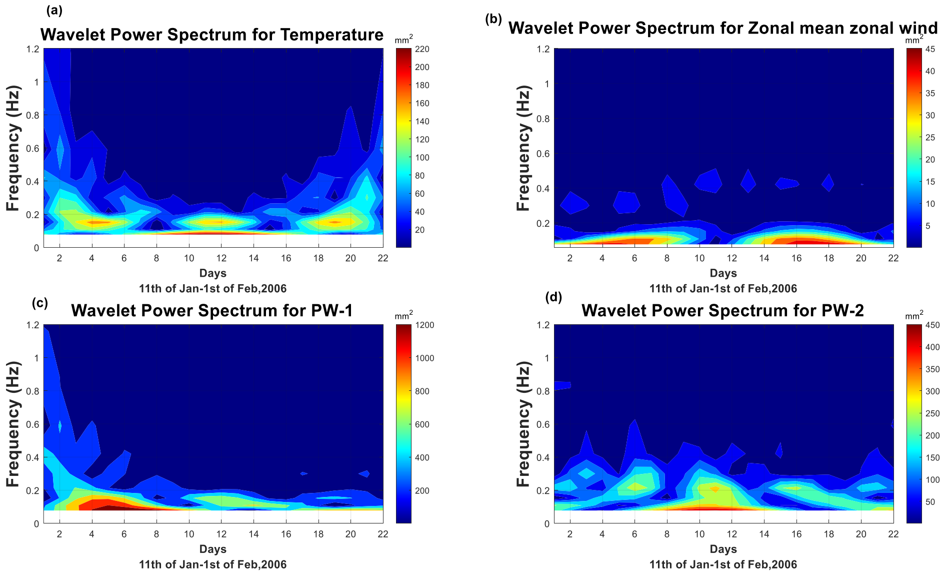


Figure 18. Wavelet power spectrum plot for 2006 SSW event.

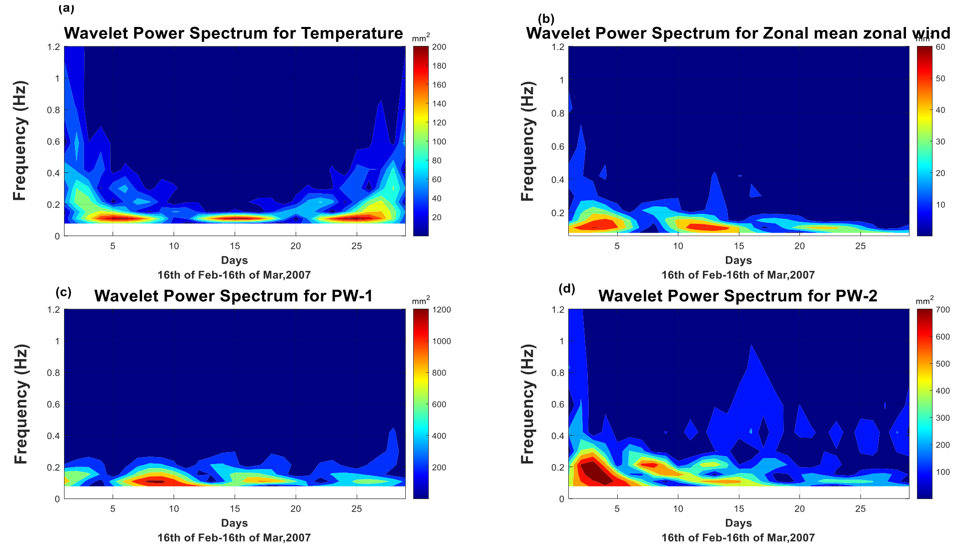


Figure 19. Wavelet power spectrum plot for 2007 SSW event.

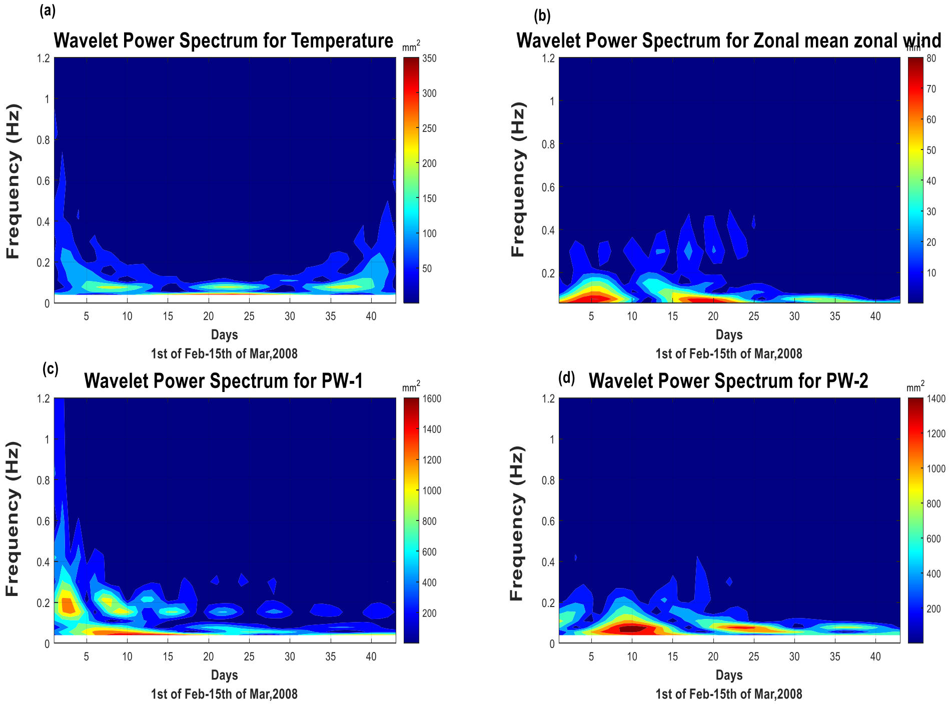


Figure 20. Wavelet power spectrum plot for 2008 SSW event.

Figures 11 to 20 show the power spectrum for the stratospheric parameters earlier shown in Figures 1 to 10. Signals like those of stratospheric temperature, zonal wind speed, and planetary wave amplitude can be decomposed into different frequency variations to form wavelets to study their variations. In a general sense, the wavelet analysis is a method of analyzing data which gives a detailed view of a signal or time series and a good assessment of the inherent modes of variability of such a time series. This method shows how the different parts of one signal change over time, giving a more complete picture than other data analysis tools. It is a powerful mathematical tool for studying localized power variations within a time series and is used by breaking down the time series into time and frequency components, thus, making it possible to determine the dominant modes of variability and how those modes vary over time (Guo et al., 2022; Falayi et. al., 2020). This method is the result of applying wavelet analysis techniques to a signal. It reveals how much power (variance) exists at different scales (frequencies) and time points and gives a visual representation of how the frequency content of the signal evolves. The main benefit of the WPS investigation technique is that it gives facts about the frequency of the occurrence about its locality in the time series. Unlike standard frequency (e.g. 100Hz), the frequencies in the wavelet power spectrum are relative to the chosen wavelet and the scale used. They represent the range of variations the wavelet can capture at a particular scale. The WPS is produced by the solution of equation 1-5 above.

Relationship Between Polar Stratospheric Parameters and Solar Activity Level

The plots in Figures 21-26 show the relationship between polar stratospheric parameters (temperature and planetary waves) and solar activity level. This relationship is not readily visible if the data sets are treated as a whole; but when they are divided according to the phases of the QBO, the relationships and correlations become obvious (Hitchman et al., 2021; Gray et al., 2022).

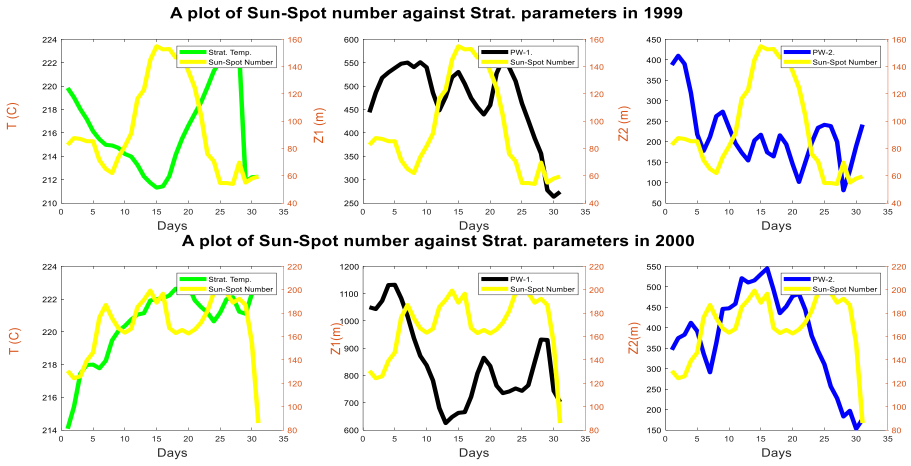
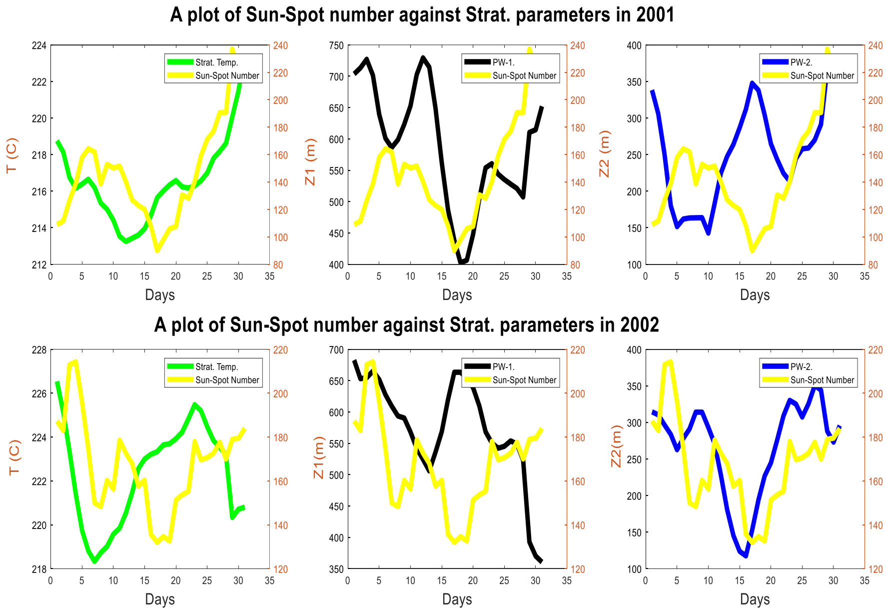
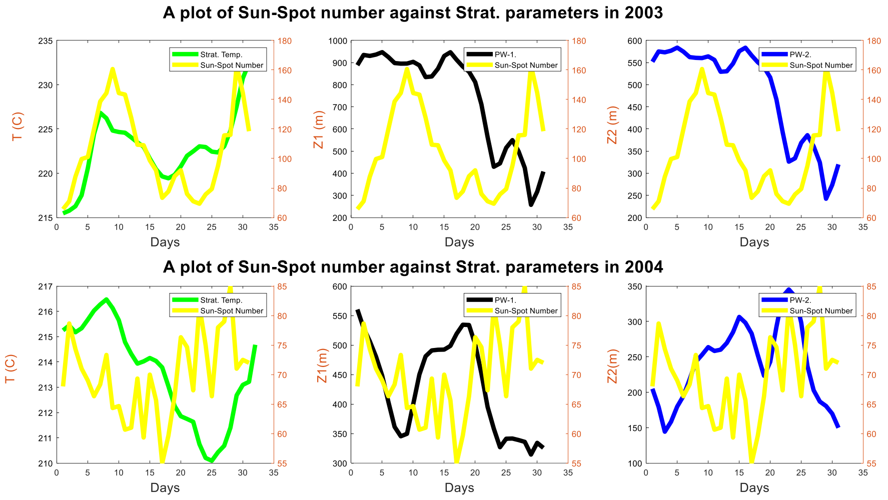


Figure 21. A plot showing the relationship between Sun-spot number and stratospheric parameters for 1999 and 2000 SSW events.


A plot of Sun-Spot number against Strat. parameters in 2001

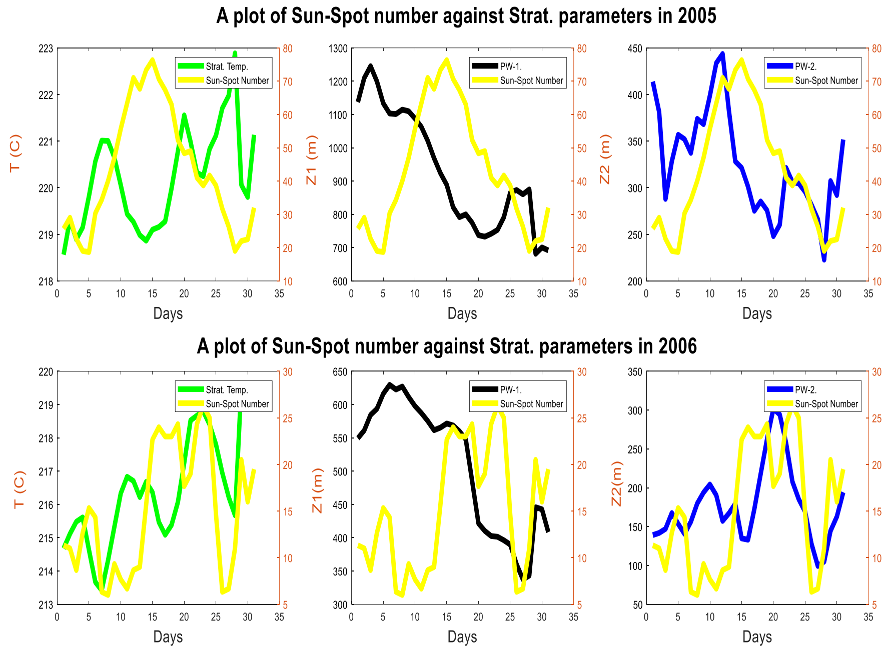
A plot of Sun-Spot number against Strat. parameters in 2002

Figure 22. A plot showing the relationship between Sun-spot number and stratospheric parameters for 2001 and 2002 SSW events.


A plot of Sun-Spot number against Strat. parameters in 2003

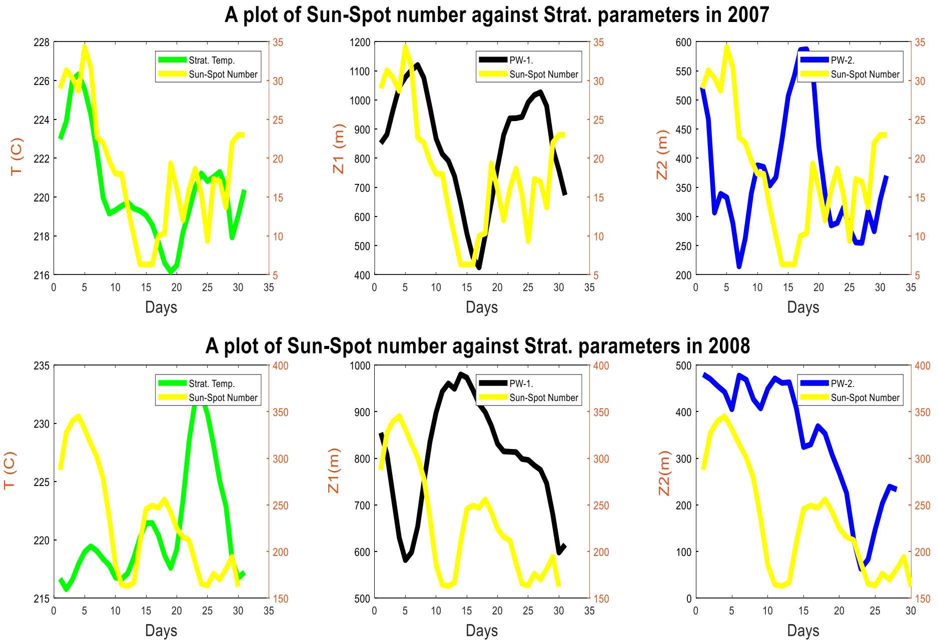
A plot of Sun-Spot number against Strat. parameters in 2004

Figure 23. A plot showing the relationship between Sun-spot number and stratospheric parameters for 2003 and 2004 SSW events.


A plot of Sun-Spot number against Strat. parameters in 2005

A plot of Sun-Spot number against Strat. parameters in 2006

Figure 24. A plot showing the relationship between Sun-spot number and stratospheric parameters for 2005 and 2006 SSW events.


A plot of Sun-Spot number against Strat. parameters in 2007

A plot of Sun-Spot number against Strat. parameters in 2008

Figure 25. A plot showing the relationship between Sun-spot number and stratospheric parameters for 2007 and 2008 SSW events.

The QBO is a wind regime in the low-latitude stratosphere whose direction changes from eastward to westward with a period of about 28 months (Gray, 2018; Bushell et al., 2022; Cai et al., 2022). Its phase has been shown to affect the polar stratospheric temperature. In the easterly phase, temperature is generally higher than in the westerly phase regardless of the solar activity level (Cai et al., 2022). Also, a positive correlation exists between polar stratospheric temperature and solar activity level when the QBO is westerly phase as against when it is in the easterly phase (Soukharev & Hood, 2001). Following the grouping from the works of Holton and Tan in 1980, the years 2000, 2001-2002, 2003, 2006, and 2007 were years in which the QBO was in the westerly phase (Elsbury et al., 2021). Therefore, in Figures 21b, 22a, 23a., 24b, and 25a, the polar stratospheric temperature shows a good correlation with solar activity level with a correlation coefficient of 0.64. This shows that stratospheric temperature increased as solar activity level increases and vice versa. Also, the QBO was in the easterly phase in the years 1999 (Fig 21 a), 2002 (Fig. 22b), 2004 (Fig. 24 b), 2005 (Fig. 23b), and 2008 (Fig. 25b), hence, the polar stratospheric temperature shows a negative correlation with solar activity level with correlation coefficient -0.22. This shows a weak inverse relationship between stratospheric temperature and solar activity level. In the westerly phase, temperature increases with solar activity level, while for the easterly phase, temperature and solar activity level show an inverse relationship. The planetary waves 1 and 2 were also investigated during both the westerly and easterly phases. In the westerly phase, PW-1 showed a weak positive correlation with solar activity level with a correlation coefficient of 0.21, while PW-2 showed a negative correlation with a correlation coefficient of -0.55. This result implies that even though solar activity level does not exhibit a strong influence on the amplitude of PW-1, it appears to exhibit an inverse relationship with PW-2 amplitude. In the easterly phase, both PW-1&2 showed a positive correlation with solar activity level with correlation coefficients 0.48 and 0.15 respectively. However, PW-1 is seen to show a stronger correlation than PW-2. This implies that solar activity level significantly influences the amplitude of PW-1 compared to the amplitude of PW-2.

DISCUSSION

In all the results obtained, only stratospheric properties in the polar region of the northern hemisphere have been considered. This is because SSW events occur more frequently in the northern hemisphere compared to the southern hemisphere. The northern hemisphere has a higher land-to-sea ratio compared to the southern hemisphere, and so, has more mountain ranges and more prominent land-sea contrasts. These features help to increase the amplitudes of tropospheric winds over the northern hemisphere compared to the southern hemisphere (Goncharenko et. al., 2021; Eswaraiah et. al., 2020). In effect, planetary waves are amplified more, and this increases the possibility of the occurrence of an SSW event. The energy released from the interaction of PW with zonal flow drives SSW. The energy of a wind pattern is determined by its speed and amplitude. Since winds are generated by the combination of the irregular solar heating of the atmosphere and air motion over the uneven earth's surface, PW speed is expected to vary. Also, since it has been established that the movement of the PW over different land features increases its amplitude, it is expected that at high speed, the amplitude will be enhanced more than at low speed, thus, PW energy will also vary. It is therefore clear that high-energy PWs will trigger a major SSW, while PWs with low energy will trigger minor events (Zhang et. al., 2020; Lindgren et. al., 2018). At the onset of an SSW event, PWs weaken the zonal wind considerably, causing the polar vortex to either shift its position (vortex displacement) or be split into daughter vortices (vortex split) (Yamazaki et al., 2020; Goncharenko et. al., 2021). As this happens, air within the zonal mean wind slows down and converges at the center of the polar vortex. The converged air then descends and is compressed adiabatically. This makes the polar vortex a high-pressure region and causes the stratospheric temperature to increase sharply in a matter of days (Yamazaki et al., 2020; Goncharenko et. al., 2021).

Various research works have shown the effect of the quasi-biennial oscillation (QBO) on global atmospheric circulation patterns. Changes in the direction of its propagation from eastward to westward and vice versa have been shown to significantly impact the polar stratosphere (Anstey et al., 2023; Cai et al., 2022). Both the kelvinwave is responsible for the eastward direction of the QBO, while the Rossby-gravity wave is responsible for the westward phase (Yamazaki et al., 2020). Typically, planetary waves in the troposphere propagate both upward and towards the equator. This is determined by the structure of the zonal-mean wind which also depends on latitude and height. The phase of the QBO determines the latitude of the zero-wind line which functions as a wave-guide for stationary planetary wave propagation. The zero-wind line is the boundary between eastward and westward propagating tides and a very important surface for stationary planetary waves (Kim et al., 2024; Bushell et al., 2022). In the easterly phase of the QBO, it is displaced poleward, forming a narrower wave-guide that restricts planetary waves to the extratropical region. This results in more intense wave activity in the polar region which is evident in a greater impact on the polar mean flow, and hence a warmer polar stratosphere. Conversely, in the westerly phase, the zero wind line shifts equatorward, and planetary waves can penetrate the tropics and even across the equator without encountering a waveguide (Bushell et al., 2022).

From figures 21-25 above, it is seen that the effect of the solar activity level on stratospheric temperature is revealed by the direction of flow of the QBO. This result is in agreement with observations from previous works such as Zuev et al., (2023), Haji, (2022), and Rongzhong & Dingzhu, (2024). The asymmetry in the period of variation between the westerly and easterly phases is not entirely random but, rather systematic. These variations change the phase of the QBO with respect to the annual cycle especially during winter months, when the polar circulation is sensitive to the equatorial wind (Kim et al., 2024; Yamazaki et al., 2020).

Near the equator, the observed variation of equatorial wind needs a change in temperature of just about 1–2 K. This is in sharp contrast to the much greater temperature change observed over the poles. Such a polar temperature change could be introduced through a change in the energy balance of the stratosphere, which is associated with Ozone heating. For this to explain the observed temperature changes, it must be in agreement with the solar irradiance, which changes by only a small amount at wavelengths that control Ozone at these altitudes (l,200 nm). It must also be in agreement with the adiabatic mean circulation, which strongly influences temperature structure and would be modified by a change of Ozone heating. The mechanism described above is not likely to influence polar temperature directly since direct short-wave heating at high latitudes is already negligible during winter. The influence of solar activity level on polar stratospheric temperature must therefore be transferred poleward indirectly, for example, through planetary waves and the adiabatic mean circulation that their absorption drives. Energy in the equatorial stratosphere is due to Ozone heating, which is attributed to solar ultra-violet absorption by the Ozone (Silverman et al., 2018). This varies with solar activity level. As mentioned earlier, planetary wave propagation is both upward and equator-ward. During the westerly phase of the QBO, planetary waves do not encounter the critical line and so, they can propagate into the equatorial region from where they transport energy adiabatically from the equator to the polar region. The energy transported has signatures of the solar activity level, which is seen on the polar stratospheric temperature by transfer. This makes the temperature and solar activity level vary in phase with each other. On the contrary, during the easterly phase of the QBO, the planetary waves encounter the critical line and are restricted from the equatorial region. Even though this restriction leads to the propagation of a stronger planetary wave, it also means that there will be no adiabatic energy transfer from the equator to the poles. Therefore, the polar temperature will not exhibit variations with solar activity level and they will be out of phase with each other.

All the SSW events observed in this study are major events. However, there is a remarkable variation in their intensity if the phase of the QBO is considered. In the easterly phase (years 1998, 1999, 2004, 2005, and 2008), the zonal mean wind speed reaches up to -28 m/s. On the other hand, in the westerly phase (years 2000, 2001-2002, 2003, 2006, and 2007), the zonal mean wind speed reaches up to just about -9 m/s. This result shows that the phase of the QBO affects the intensity of the SSW event. In the easterly phase, the critical line acts as a waveguide which produces a strong PW at the polar region. The amplitude of the strong PW is then amplified by the topographical features. This produces a very strong PW which is capable of both reversing the direction of the zonal mean flow and also driving it in the westward direction. In the westerly phase, there is no waveguide, however, the PW carries energy adiabatically from the equatorial region, and its amplitude is also enhanced by the topographical features. This also reverses the direction of the mean zonal flow and drives it slightly. It is therefore evident that PWs are stronger in the easterly phase compared to the westerly phase. This result suggests that the position of the critical line has a stronger effect on the strength of the PW compared to the temperature due to energy transport from the equatorial region to the polar region.

CONCLUSION AND RECOMMENDATION

This study has revealed that the direction of the QBO clearly shows the relationship between solar activity level and wintertime polar stratospheric parameters. This relationship is however not straightforward. In the westerly phase, solar activity level influences temperature positively, but not PW. In the easterly phase, solar activity level strongly influences PW amplification, but not on temperature. This feature should be investigated in future research with a larger data set to see if the pattern is repeated across multiple solar cycles.

REFERENCES

Anstey, J. A., Osprey, S. M., Alexander, J., Baldwin, M. P., Butchart, N., Gray, L.& Richter, J. H. (2022). Impacts, processes, and projections of the quasi-biennial oscillation. *Nature Reviews Earth & Environment*, *3*(9), 588-603.

Bojilova, R., & Mukhtarov, P. (2023). Analysis of the Ionospheric Response to Sudden Stratospheric Warming and Geomagnetic Forcing over Europe during February and March 2023. *Universe*, *9*(8), 351.

Bushell, A. C., Anstey, J. A., Butchart, N., Kawatani, Y., Osprey, S. M., Richter, J. H. & Yukimoto, S. (2022). Evaluation of the quasi-biennial oscillation in global climate models for the SPARC QBO initiative. *Quarterly Journal of the Royal Meteorological Society*, *148*(744), 1459-1489.

Cai, Q., Chen, W., Chen, S., Ma, T., & Garfinkel, C. I. (2022). Influence of the Quasi-Biennial Oscillation on the spatial structure of the wintertime Arctic Oscillation. *Journal of Geophysical Research: Atmospheres*, *127*(8), e2021JD035564.

Domeisen, D. I., & Butler, A. H. (2020). Stratospheric drivers of extreme events at the Earth's surface. *Communications Earth & Environment*, *1*(1), 59.

Elsbury, D., Peings, Y., & Magnusdottir, G. (2021). Variation in the Holton–Tan effect by longitude. *Quarterly Journal of the Royal Meteorological Society*, *147*(736), 1767-1787.

Eswaraiah, E., Kumar, K.N., Kim, Y. H., Chalapathi, G. V., Lee, W., Jiang, G., Yan, C., Yang, G., Ratnam, M. V., Prasanth, P.V., Rao, S.V.B., Thyagarajan, K. (2020), Low-latitude mesospheric signatures observed during the 2017 sudden stratospheric warming using the fuke meteor radar and ERA-5, *Journal of Atmospheric and Solar-Terrestrial Physics*, doi: https:// doi.org/10.1016/j.jastp.2020.105352.

Falayi, E. O., Adewole, A. T., Adelaja, A. D., Ogundile, O. O., & Roy-Layinde, T. O. (2020). Study of nonlinear time series and wavelet power spectrum analysis using solar wind parameters and geomagnetic indices. *NRIAG Journal of Astronomy and Geophysics*, *9*(1), 226–237. https://doi.org/10.1080/20909977.2020.1728866

Goncharenko, L. P., Harvey, V. L., Greer, K. R., Zhang, S. R., & Coster, A. J. (2020). Longitudinally dependent low-latitude ionospheric disturbances linked to the Antarctic sudden stratospheric warming of September

2019. *Journal of Geophysical Research: Space Physics*, *125*(8), e2020JA028199.

Goncharenko, L. P., Harvey, V. L., Greer, K. R., Zhang, S. R., Coster, A. J., & Paxton, L. J. (2021b). Impact of September 2019 Antarctic Sudden Stratospheric Warming on Mid-Latitude Ionosphere and Thermosphere Over North America and Europe. *Geophysical Research Letters, 48*(15). https://doi.org/10.1029/2021GL094517

Goncharenko, L. P., Harvey, V. L., Liu, H., & Pedatella, N. M. (2021c). Sudden Stratospheric Warming Impacts on the Ionosphere-Thermosphere System: A Review of Recent Progress. In *Ionosphere Dynamics and Applications* (pp. 369–400). wiley. https://doi.org/10.1002/9781119815617.ch16

Gray, L. J., Lu, H., Brown, M. J., Knight, J. R., & Andrews, M. B. (2022). Mechanisms of influence of the Semi-Annual Oscillation on stratospheric sudden warmings. *Quarterly Journal of the Royal Meteorological Society*, *148*(744), 1223-1241.

Guo, T., Zhang, T., Lim, E., Lopez-Benitez, M., Ma, F., & Yu, L. (2022). A review of wavelet analysis and its applications: Challenges and opportunities. *IEEE Access*, *10*, 58869-58903.

Haji Mohamadi, H. (2022). Investigating role of the Quasi-Biennial Oscillation in the variability of the Stratospheric-Tropospheric circulation of the Polar Vortex in relation to the atmospheric circulation changes over Southwest Asia and Iran. *Journal of Meteorology and Atmospheric Science*, *4*(4), 308-325.

Haynes, P., Hitchcock, P., Hitchman, M., Yoden, S., Hendon, H., Kiladis, G. & Simpson, I. (2021). The influence of the stratosphere on the tropical troposphere. *Journal of the Meteorological Society of Japan. Ser. II*, *99*(4), 803-845.

Hocke, K., Wang, W., & Ma, G. (2024). Influences of sudden stratospheric warmings on the ionosphere above Okinawa. *Atmospheric Chemistry and Physics*, *24*(10), 5837-5846.

Hitchman, M. H., Yoden, S., Haynes, P. H., Kumar, V., & Tegtmeier, S. (2021). An observational history of the direct influence of the stratospheric quasi-biennial oscillation on the tropical and subtropical upper troposphere and lower stratosphere. *Journal of the Meteorological Society of Japan. Ser. II*, *99*(2), 239-267.

Kim, Y. H., Voelker, G. S., Bölöni, G., Zängl, G., & Achatz, U. (2024). Crucial role of obliquely propagating gravity waves in the quasi-biennial oscillation dynamics. *Atmospheric Chemistry and Physics*, *24*(5), 3297-3308.

Lindgren, E. A., Sheshadri, A., & Plumb, R. A. (2018). Sudden stratospheric warming formation in an idealized general circulation model using three types of tropospheric forcing. *Journal of Geophysical Research: Atmospheres,* 123, (10), 125–139. https://doi.org/10.1029/ 2018JD028537.

Ma, H., He, M., Liu, L., Li, W., Yang, Y., Zhang, R. & Li, G. (2022). Solar tide-like signatures in the ionospheric total electron content during the 2018 sudden stratospheric warming event. *Space Weather*, *20*(9), e2022SW003042.

Matthias, V., & Kretschmer, M. (2020). The influence of stratospheric wave reflection on North American cold spells. *Monthly Weather Review*, *148*(4), 1675-1690.

Mosna, Z., Edemskiy, I., Laštovička, J., Kozubek, M., Koucká Knížová, P., Kouba, D., & Siddiqui, T. A. (2021). Observation of the ionosphere in middle latitudes during 2009, 2018, and 2018/2019 sudden stratospheric warming events. *Atmosphere*, *12*(5), 602.

Negash, T., & Raju, U. P. (2024). Study on long-term troposphere lower stratosphere temperature (TLST) trend in tropical and subtropical northern hemisphere using ground-based and COSMIC satellite data. *Journal of Atmospheric and Solar-Terrestrial Physics*, 106306.

Pedatella, N. M., Chau, J. L., Schmidt, H., Goncharenko, L P., Stolle, C., Hocke, K., et al. (2018). Sudden Stratospheric Warming Impacts on the Whole Atmosphere, *Radio Sci*, doi:10.1020/2017ES005448.

Pedatella, N. (2022). Ionospheric variability during the 2020–2021 SSW: COSMIC-2 observations and WACCM-X simulations. *Atmosphere, 13*(3), 368.

Rongzhong, M., & Dingzhu, H. (2024). Modulation of QBO on the relationship between stratospheric polar vortex and surface air temperature over Eurasia during early winter. *Climate Dynamics*, 1-20.

Scaife, A. A., Baldwin, M. P., Butler, A. H., Charlton-Perez, A. J., Domeisen, D. I. V., Garfinkel, C. I., Hardiman, S. C., Haynes, P., Karpechko, A. Y., Lim, E.-P., Noguchi, S., Perlwitz, J., Polvani, L., Richter, J. H., Scinocca, J., Sigmond, M., Shepherd, T. G., Son, S.-W., and Thompson, D. W. J.: Long-range prediction and the stratosphere, Atmos. Chem. Phys., 22, 2601–2623, https://doi.org/10.5194/acp-22-2601-2022, 2022.

Silverman, V., Harnik, N., Matthes, K., Lubis, S. W., & Wahl, S. (2018). Radiative effects of ozone waves on the Northern Hemisphere polar vortex and its modulation by the QBO. *Atmospheric Chemistry and Physics*, *18*(9), 6637-6659.

Wang, L., Hardiman, S. C., Bett, P. E., Comer, R. E., Kent, C., & Scaife, A. A. (2020). What chance of a sudden stratospheric warming in the southern hemisphere? *Environmental Research Letters*, *15*(10), 104038.

Zhang, R., Liu, L., Liu, H., Le, H., Chen, Y., & Zhang, H. (2020). Interhemispheric Transport of the Ionospheric F Region Plasma During the 2009 Sudden Stratosphere Warming. *Geophysical Research Letters, 47*(6). https://doi.org/10.1029/2020GL087078

Zhang, X., Zhang, Y., Lu, X., Bai, L., Chen, L., Tao, J. & Zhu, L. (2021). Estimation of lower-stratosphere-to-troposphere ozone profile using long short-term memory (LSTM). *Remote Sensing*, *13*(7), 1374.

Zuev, V. V., Maslennikova, E. A., & Savelieva, E. S. (2023). Influence of Quasi-Biennial Oscillation on the Dynamics of Stratospheric Polar Vortices According to Data of Satellite Observations. *Izvestiya, Atmospheric and Oceanic Physics*, *59*(10), 1307-1313.