Postprint: Study of Atmospheric Quasi-16-Day Planetary Waves in Sudden Stratospheric Warming Events

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Abstract

In early to mid-January 2014, a weak warming event occurred in the high-latitude stratosphere with a warming amplitude of approximately 25 K, during which the zonal westerly winds weakened and reversed direction in early February. Planetary waves are considered to play an important role in the generation of Sudden Stratospheric Warming (SSW) events. Therefore, using wind field data detected by five meteor radars at low and middle latitudes along the near-120°E meridian chain in the Northern Hemisphere, this study investigated the planetary wave conditions in the atmospheric wind field of the Mesosphere and Lower Thermosphere (MLT) region before and during the warming event. The results show that prior to the polar stratospheric warming, the MLT region atmosphere exhibited significantly enhanced quasi-16-day waves, and when the warming reached its maximum, the 16-day wave was also strongest. This indicates that there exists a certain coupling relationship between planetary wave variations in the low- and middle-latitude MLT region and SSW events. Furthermore, using stratospheric reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) to analyze the wave and zero-wind-line conditions in the Northern Hemisphere stratosphere during the SSW, it was found that the stratospheric quasi-16-day wave and the zero wind line moved temporally from low latitudes to high latitudes, suggesting a certain dynamical link between the 16-day wave and SSW.

Full Text

A Study of Quasi-16-Day Planetary Waves During Sudden Stratospheric Warming Events

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Abstract

A minor sudden stratospheric warming (SSW) event occurred in early to mid-January 2014, with a temperature increase amplitude of approximately 25 K and zonal eastward wind that weakened and reversed direction by early February. Planetary waves (PWs) are believed to play a significant role in SSW events. Using wind data from five meteor radars at low and middle latitudes in the Northern Hemisphere near 120°E longitude, we investigated planetary wave conditions in the mesosphere and lower thermosphere (MLT) region before and during this event. Results show that enhanced quasi-16-day planetary waves were present in the MLT region, with the enhancement occurring prior to the warming and reaching maximum amplitude when polar temperatures peaked. This demonstrates coupling between the low- and middle-latitude MLT region and the SSW event. Furthermore, using reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF), we analyzed stratospheric wave conditions and zero-wind lines in the Northern Hemisphere during the SSW. The stratospheric quasi-16-day wave and zero-wind line moved from low to high latitudes over time, suggesting a dynamical connection between the 16-day wave and the SSW.

Keywords: quasi-16-day planetary waves, sudden stratospheric warming, mesosphere-lower thermosphere

0 Introduction

Sudden stratospheric warming (SSW) is a phenomenon in which the polar stratospheric atmosphere experiences a rapid temperature increase during winter, accompanied by abrupt changes in circulation structure. During SSW events, the stratospheric polar vortex undergoes strong disturbances or collapse, and the prevailing westerly circulation decelerates and may even reverse to easterly. Matsuno [1] first explained SSW from a dynamical perspective, proposing that it results from the upward propagation of tropospheric planetary waves into the stratosphere. Matsuno and Nakamura [2] later reinterpreted the mechanism using the concept of Lagrangian-mean meridional circulation. Enhanced planetary waves propagate upward from the troposphere, and transient planetary waves interact with the basic flow during vertical propagation. This interaction decelerates and may reverse the winter stratospheric westerly jet, while generating upward and downward air motions in the upper stratosphere at high latitudes that lead to anomalous warming at the stratospheric base and anomalous cooling in the mesosphere. Liu and Roble [3] clearly demonstrated through simulation the growth and decay processes of planetary waves during stratospheric warming events, their interaction with the mean flow, and changes in the mean circulation and transport throughout the stratosphere-mesosphere-thermosphere system.

Although SSW primarily occurs in the winter polar stratosphere, numerous observational and modeling studies have confirmed its influence on the global atmosphere and ionosphere, including effects on tropospheric weather systems, stratospheric trace gas distribution, anomalous ionospheric absorption, and close relationships with mesospheric cooling and lower thermospheric warming [4-7]. Enhanced planetary wave activity and anomalous temperature changes during SSW events demonstrate unique coupling processes between atmospheric layers in the vertical direction, while latitude-dependent anomalies in atmospheric parameters also reflect SSW' s impact on latitudinal coupling in the global atmosphere. Fritz and Soules [8] first showed that stratospheric disturbances during high-latitude SSW events are related to cooling in the tropical stratosphere. Mukhtarov et al. [9] used UKMO data to study the zonal structure of stratospheric anomalies during the strong 2003/2004 Arctic winter SSW, finding that high-latitude warming is associated with cooling at low and middle latitudes, while high-latitude zonal wind negative anomalies correspond to positive anomalies at low and middle latitudes, particularly strong in the upper stratosphere. Singh et al. [10] studied 11 SSW events and found that during major stratospheric warmings, the mesospheric temperature exhibits a bimodal latitudinal distribution: cooling in the Northern Hemisphere polar mesosphere, warming at low and middle latitudes in the Northern Hemisphere, cooling near the equator, and then warming at middle latitudes and cooling at high latitudes in the Southern Hemisphere. Some studies [11] have reported similar temperature anomalies in the low-latitude stratosphere and mesosphere during SSW. Hoffmann et al. [12] used continuous medium-frequency and meteor radar observations of MLT winds during SSW and found strong winter variations in the MLT region due to enhanced planetary wave activity, indicating clear coupling between the lower, middle, and upper atmosphere.

Atmospheric waves serve as important mediators for coupling between different atmospheric layers. Many SSW studies have shown that SSW events are accompanied by enhanced planetary wave activity. Planetary waves are global-scale waves that can be classified as quasi-stationary or traveling waves, with zonal wavenumber-1 quasi-stationary waves being important factors causing stratospheric sudden warming. Labitzke et al. [13] studied the relationship between

SSW and winter planetary wave amplitude variations, noting that SSW often occurs when wave-1 amplitude reaches its maximum and wave-2 amplitude is minimum, with enhanced wave-1 amplitude being a prerequisite for warming outbreaks. Traveling planetary waves associated with SSW are typically related to atmospheric normal modes. Pogoreltsev et al. [14] used numerical simulation to study the influence of normal modes on SSW, finding that normal modes improve the transmission environment for quasi-stationary wave-1 and enhance its interaction with the mean flow. Pancheva et al. [15] used UKMO zonal wind data and wind data from 11 radars to study zonal coupling between the stratosphere and mesosphere during strong warming events, concluding that the opposite relationship between high- and low-latitude stratospheric zonal flows is caused by global-scale zonal symmetric waves.

Common periods of atmospheric planetary waves include 2-day, 5-day, 10-day, and 16-day waves, with quasi-16-day waves being particularly prominent during SSW. Koermer et al. [16] discussed kinetic and thermal energy changes associated with strong and weak SSW events in the winters of 1976/1977 and 1975/1976, finding that ultra-long waves with periods of 10-20 days dominated in the stratosphere. Vineeth et al. [17] studied stratospheric wave structures during SSW and found that the tropics and polar regions are connected through quasi-16-day waves, which gradually propagate from the tropics to the polar region during SSW years but do not show this pattern in non-SSW years. In the MLT region, 16-day waves are most active in winter. Some studies [18] have detected 12-19 day period oscillations in the MLT height range using MST radar. Laskar et al. [19] studied the influence of SSW and solar activity on vertical coupling of the neutral and ionized atmosphere, finding strong quasi-16-day wave activity in three strong SSW events and relatively weak activity in weak SSW events. Analysis of TIMED-SABER temperature wavelet power spectra [20] showed enhanced quasi-16-day wave activity in the mesosphere during SSW.

To better understand the relationship between quasi-16-day waves in the mesosphere and lower thermosphere and SSW, this study uses meteor radar wind data from five stations along the near-120°E longitude chain at low and middle latitudes in the Northern Hemisphere to investigate atmospheric wave conditions in the MLT region during SSW, combined with European Centre reanalysis data to further analyze middle atmospheric coupling in the Northern Hemisphere during the January 2013/2014 SSW event.

1 Data and Analysis Methods

This study uses ECMWF ERA-interim reanalysis data, which provides global atmospheric reanalysis data since 1979 and is updated in real time. The analysis employs wind and temperature field data at 2-10 hPa heights with a latitude-longitude resolution of [missing in original] and four data points per day. To observe wave conditions in the stratosphere and MLT region near the observation station longitudes (selecting 113.2°E), a Butterworth bandpass filter with bandwidth [missing in original] is applied to extract daily mean temperature and wind field fluctuations at 10° latitude intervals, with filter order [21] set to 10.

Meteor radars determine the radial velocity of atmospheric motion at meteor trail locations based on Doppler shifts of reflected echo signals from meteor trails that drift with the atmospheric wind field [22]. This study uses meteor radar data from five stations: Fuke (FK), Qujing (QJ), Wuhan (WH), Beijing (BJ), and Mohe (MH). The main operational parameters of the meteor radars are shown in Table 1. Considering that observed meteor counts follow a Gaussian distribution centered at 90 km, wind field data in the height range of 80-100 km are used to ensure data quality, covering the period from December 2013 to March 2014. Wavelet analysis is employed to obtain wave characteristics of the radar-observed wind field. Wavelet analysis transforms time series of physical quantities into two-dimensional time-frequency distributions. The Morlet wavelet, a complex sinusoid modulated by a Gaussian envelope, is particularly convenient for analyzing wave-like events in MLT neutral winds and related large-scale disturbance propagation from lower layers. This study applies Morlet wavelet analysis [23] to daily mean wind and temperature field data, using linear interpolation to fill occasional data gaps to ensure continuity.

2 Analysis Results

[Figure 1: see original paper] shows the day-to-day variability of ECMWF zonal mean temperature at 10 hPa, 80°N (solid line, left axis) and zonal mean zonal wind at 10 hPa, 60°N (dashed line, right axis) during the 2013/2014 winter. The figure reveals three SSW events occurring in January-March. According to the National Centers for Environmental Prediction (NCEP) criterion, the number of days when temperature remains at its peak value defines the SSW event duration [24]. From this perspective, the January SSW is the focus of this study, as the latter two events were brief in duration. The January warming amplitude was approximately 25 K, with zonal wind weakening but not reversing until February, thus classifying this as a minor warming event.

[Figure 2: see original paper] presents wavelet power spectra of daily mean zonal wind from the five stations, arranged from low to high latitude (left to right: FK, QJ, WH, BJ, MH) and from high to low altitude (top to bottom). For the 2013/2014 SSW event, atmospheric conditions at 80-100 km altitude were analyzed at five low- and middle-latitude stations. The figure shows that during SSW, the MLT region generally exhibits long-period fluctuations of 8-20 days, though wave characteristics vary slightly with latitude. The two low-latitude stations (FK and QJ) show stable 10-20 day fluctuations at all heights in January. The two mid-latitude stations (WH and BJ) exhibit similar wave patterns at high altitudes (above 90 km) as at low latitudes, but show fluctuations with periods greater than 16 days beginning in early December at lower altitudes. The high-latitude station (MH) displays 8-12 day period fluctuations in January, with wave intensity decreasing with altitude.

[Figure 3: see original paper] shows the same analysis but for meridional wind. Meridional wave intensity is significantly weaker than zonal, though the MLT region also exhibits 8-20 day long-period fluctuations during SSW. At the two low-latitude stations, wave intensity decreases with altitude above 88 km, while below 88 km the fluctuation periods are smaller than those above. At mid-latitude stations, wave patterns are relatively less clear. WH station shows 8-16 day fluctuations dominating from 90 km in January, weakening near the detection boundary. BJ observations reveal both 6-20 day period fluctuations in December and January, with relatively stronger 16-20 day fluctuations. MH results are similar to low-latitude stations but with smaller periods at all heights.

[Figure 4: see original paper] shows 12-20 day bandpass-filtered wind fields at 82 km (bottom), 88 km (middle), and 100 km (top) for the five stations, with zonal wind in the left column and meridional wind in the right column. The MLT region wavelet analysis shows 8-20 day long-period fluctuations, with 12-20 day fluctuations being more prominent at most heights and stations. To clarify the timing and intensity of these periodic fluctuations, radar-observed wind fields were bandpass-filtered for 12-20 day periods. The filtered zonal winds (left column) show enhanced 12-20 day fluctuations beginning in late December, peaking in early-to-mid January. At 100 km, fluctuations occur nearly simultaneously across stations, but at lower altitudes, fluctuations at BJ and MH lag sequentially. In terms of intensity, WH is strongest, followed by QJ, with BJ and FK showing similar magnitude and MH being weakest. Meridional fluctuations (right column) are generally weaker than zonal, with relatively strong activity in early-to-mid January. Unlike zonal winds, fluctuations occur nearly simultaneously at low altitude (82 km) but appear more chaotic at high altitude (100 km). Intensity-wise, MH is strongest, followed by BJ, with QJ and FK showing similar magnitude and WH being weakest, though overall differences between stations are small.

[Figure 5: see original paper] shows 12-20 day stratospheric temperature fluctuations (left) and time variation of zonal mean zonal wind (right) at 10 hPa over the Northern Hemisphere at 113.2°E longitude. The enhancement of mean wave amplitude in the MLT region occurs when stratospheric wave amplitude increases, indicating vertical coupling during SSW events. To further investigate this coupling, stratospheric temperature and wind fields were analyzed. The left panel shows that fluctuations are relatively weak at low latitudes, stronger at middle latitudes in early-to-mid December, and enhanced at middle-to-high latitudes from late December to early-to-mid January, with polar temperature fluctuations becoming strong from late January to early February. This temporal distribution indicates wave propagation from relatively low latitudes toward the pole. Similar patterns are found in wind field analysis. The right panel shows time variation of zonal mean zonal wind at 10 hPa from equator to North Pole, with westerlies prevailing in the mid-to-high latitude stratosphere and easterlies at low latitudes. During SSW, high-latitude westerlies weaken. The zero-wind line in the high stratosphere moves from the equator in early December to its northernmost position near 40°N in early January.

Wavelet analysis of the five stations shows that during SSW, the Northern Hemisphere low- and middle-latitude MLT region exhibits significantly enhanced quasi-16-day wave activity. Laskar [19] found strong 16-day wave activity in three strong SSW events, but this study shows strong quasi-16-day waves even in a minor warming event, with zonal wave amplitudes up to 20 m/s and weaker meridional amplitudes up to 13 m/s. This amplitude range is consistent with the 10-20 m/s range observed by Kingsley et al. [25] using early meteor radar versions.

Many scholars believe that transient planetary waves with periods of several to ten days, propagating westward in the MLT region, have spatial structures similar to normal modes of an isothermal atmosphere and may represent resonant responses to certain forcings. Alternatively, they may be unstable wave modes generated by atmospheric instability. Forbes [26] detected oscillations with periods near 16 days using 52°N medium-frequency radar data from January-March 1979. Smith and Avery [27] studied resonant wave enhancement during the 1979 strong warming event using linear models and observations. Liu et al. [3] simulated a self-generated SSW and its MLT impacts using coupled TIME-GCM/CCM3, finding that planetary wave-1 dominated during warming, with its enhancement possibly due to wave resonance. Many studies have identified these observed waves as the second symmetric westward-propagating wavenumber-1 Rossby wave, corresponding to the (1,-4) normal mode [28]. Comparing 16-day wave intensities across stations in this event, WH station (30.5°N) shows the strongest zonal wave amplitude, which decreases toward both higher and lower latitudes, with the northernmost MH station showing the weakest amplitude. Meridionally, MH shows the strongest fluctuation intensity while WH is weakest. As shown in [Figure 6: see original paper], this intensity variation resembles the atmospheric 16-day Rossby normal mode (1,-4). Based on Liu' s research on the relationship between wave enhancement and resonance during warming, the 16-day wave resembling an atmospheric normal mode in this event may be related to atmospheric resonance enhancement.

[Figure 6: see original paper] shows the theoretical atmospheric Rossby (1,-4) normal mode, representing the "16-day wave."

Furthermore, the 16-day wave enhancement in the MLT region began in late December, while polar stratospheric temperature began increasing in early December and peaked in early January, with 16-day wave amplitude also reaching its maximum when temperature peaked. Many studies indicate that dynamical changes in the high-latitude stratosphere precede SSW onset, considered as preconditioning of the polar stratosphere. Hoffmann et al. [12] also found that mesospheric cooling and MLT zonal wind reversal precede SSW, suggesting that circulation disturbances propagate downward from the MLT region to the stratosphere during SSW. Liu and Roble [29] used models to explore dynamical coupling between the stratosphere and mesosphere during a strong Southern Hemisphere SSW, finding that strong planetary wave forcing before the warming altered the mesospheric mean state, reversing the polar mesospheric and stratospheric jets and creating a planetary wave breaking zone. With subsequent wave activity, the critical layer and wave breaking zone descended from the mesosphere to lower altitudes, affecting the wave transmission environment and creating conditions favorable for wave breaking, which facilitated the establishment of strong stratospheric warming and its extension throughout the polar stratosphere and mesosphere. This study also found early dynamical changes in the low- and middle-latitude MLT region, suggesting a possible connection between planetary wave variations in this region and stratospheric SSW events, though the interaction mechanism remains unclear.

Stratospheric analysis results show that the 16-day wave moved from relatively low latitudes toward high latitudes over time, while the zonal mean zonal wind also moved from equator to high latitudes. This matches Vineeth' s findings on stratospheric quasi-16-day wave enhancement and zero-wind line movement. Dunkerton et al. [30] suggested through numerical simulation that the dynamical connection between SSW and tropical regions may be caused by critical layers (zero-wind lines) in the wind field that first appear in the tropical stratosphere and subsequently move poleward. The presence of zero-wind lines during stratospheric warming events represents a dynamical precondition that provides a refractive index channel favorable for planetary wave reflection toward the pole. In this SSW event, the zero-wind line moved in the high stratosphere but apparently lacked sufficient dynamical forcing, retreating equatorward after reaching 40°N. This may be related to the insufficient intensity of this event.

This SSW event also reveals different behaviors in zonal and meridional fluctuations. Zonally, the 16-day wave shows strong intensity at all observed heights, while meridionally, the 16-day wave is less prominent at high altitudes, and zonal fluctuation periods are relatively shorter than meridional periods. Many studies indicate that the westerly driving force in the winter stratosphere induces a residual circulation directed poleward and downward, causing stratospheric warming. In the MLT region, Laskar [31] established a new meridional circulation from pole to equator by studying temperature gradients in the lower thermosphere during SSW, equatorward winds in the MLT region, and dayglow emissions of oxygen atoms at low latitudes. Such changes in the background meridional circulation may cause the different zonal and meridional wave behaviors during SSW events.

Mid-latitude wave conditions appear more complex in the analysis. During winter, forced stationary planetary waves at mid-latitudes cannot directly propagate to the stratosphere but instead propagate northward to the stratosphere and to the upper tropical troposphere through two wave guides [32]. One path involves vertical propagation from the troposphere to the stratosphere at high latitudes, followed by equatorward propagation in the stratosphere, known as the polar waveguide. The other involves propagation from the mid-latitude troposphere to the tropical tropopause, known as the low-latitude waveguide. Since stationary planetary waves are the primary waves triggering SSW, the complexity of mid-latitude wave conditions may be related to these propagation characteristics of forced stationary planetary waves in winter mid-latitudes.

Conclusion

This study used meteor radar wind data from five stations at different latitudes in the Northern Hemisphere to analyze atmospheric wave conditions in the MLT region during the 2013/2014 SSW. Results show that enhanced long-period planetary waves, primarily manifesting as quasi-16-day waves, existed in the MLT region before and during this minor warming event. The spatial structure of these quasi-16-day waves resembles the atmospheric normal mode (1,-4) in the middle and upper atmosphere, while being modulated by complex changes in the background atmosphere. Early dynamical changes were also found in the low- and middle-latitude MLT region, indicating a possible connection between planetary wave variations in this region and stratospheric SSW events, though the interaction mechanism remains unclear. Additionally, different zonal and meridional wave behaviors were observed in the low- and middle-latitude MLT region during SSW, possibly related to changes in the background meridional circulation. Stratospheric analysis using European Centre reanalysis data revealed that despite this being a minor warming event, the stratospheric quasi-16-day wave and zero-wind line moved from low to high latitudes, indicating latitudinal coupling during stratospheric sudden warming. In summary, stratospheric sudden warming implies close coupling among various atmospheric layers and regions, and better understanding of this coupling process will require further effort.

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