

Article

Intraseasonal Variation in the Mesosphere Observed by the Mengcheng Meteor Radar from 2015 to 2020

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Abstract: The intraseasonal oscillations (30–100 days, ISO) in the MLT (mesosphere and lower thermosphere) horizontal wind are investigated based on observations from the Mengcheng meteor radar. There is a clear seasonal variation in ISO in the horizontal wind at 80 km, which is strongest during the winter and weakest during the summer. At 100 km, ISO occurs throughout most of the year except winter, and there are significant differences in periods and amplitudes from year to year. From 2015 to 2016, ISOs with periods of 40–60 days were present in the 100 km horizontal wind, whereas none were simultaneously observed in the 80 km horizontal wind. Cross wavelets were used to study the relationship between ISO in the MLT region and ISO in the lower atmosphere. Some of the ISO activity is linked to tropospheric tropical convective activity, but the ISO connections with that in tropospheric convection are not consistent in the upper mesosphere and in the lower thermosphere.

Keywords: intraseasonal oscillation; mesosphere and lower thermosphere; meteor radar observation



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1. Introduction

The mesosphere and lower thermosphere (MLT) are regions that connect the lower and upper layers of the atmosphere, with an altitude range of approximately 60 to 120 km. The general circulation of the mesosphere is connected to the perturbation of the atmosphere below via upward propagating atmospheric waves [1–3]. The coupling between the mesosphere and the lower atmosphere is the key to understanding the mean state and variability of the middle and upper atmospheres. The different types of atmospheric fluctuations play a key role in the coupling between the lower atmosphere and the upper atmosphere through their ability to transport momentum, energy, and atmospheric composition between different altitudes and different latitudes [4–7], which results in atmospheric perturbations with a variety of spatial and temporal characteristics. The perturbation in the hydrostatic and geostrophic balance could trigger waves, including buoyancy or gravity waves (GWs), Rossby or planetary waves (PWs), Kelvin waves (KW), and tides [8–11].

Small-scale gravity waves induced by the perturbation in the lower atmosphere propagate upwards into the MLT region, leading to acceleration/deceleration of background winds and variations in the thermal structure and general circulation by breaking or dissipation of GWs. Interannual variations such as the SAO [12,13], QBO [14], short-period oscillations of 3 to 15 days [15–18], and ISO variations with periods between 30 and

100 days [19–23] have been suggested to be able to impact atmospheric variability in the MLT region. The QBO in the lower stratosphere is modulated by convectively generated waves such as gravity waves, Rossby gravity, and Kelvin [24–26], whereas KW and GW are considered to be important for driving the SAO [27,28].

The early evidence for intraseasonal oscillations in the MLT region comes primarily from low-latitude radar observations [29,30]. Since previous studies have placed greater emphasis on impact factors on variations in temperature, circulation, or average flow in the MLT region over shorter (e.g., from a few hours to a few days) and longer time scales (e.g., >100 days), the mechanisms of intraseasonal variability (~30–100 days) in the MLT region have not been well established [31]. Evidence for intraseasonal oscillations in the MLT region can be found in several different ground-based radar observations. Intraseasonal oscillations in the zonal winds, gravity waves, and tides of the MLT with periods of approximately 60, 35 to 40 and 22 to 25 days are observed by radar in the equatorial central Pacific [19,20].

Pancheva et al. [32] suggest that the observed 75-day ISO in the MLT region may result from in situ perturbations in the upper atmosphere rather than the tropospheric activities below [33]. In other studies, lower atmospheric intraseasonal activity, such as the Madden and Julian Oscillation [34], has been suggested to modulate upwards propagating tides and GWs and thus may cause similar cyclical variations in the upper atmosphere [20,29,35,36]. Recent studies [37–39] have demonstrated the existence of global-scale 90-day oscillations in the thermospheric zonal mean flow and diurnal eastward wavenumber three tidal wind from 2009 to 2010 based on cross-track wind measurements from the Challenging Minisatellite Payload [40] and the Gravity field and steady-state Ocean Circulation Explorer (GOCE) satellite [41]. In addition to the observational evidence of intraseasonal oscillations in the MLT close to the equator, recent radar observations have also demonstrated the presence of intraseasonal oscillations in different areas, e.g., Yi et al. [42,43] have provided evidence for oscillations near 90 days in southern China based on temperatures and winds obtained from the Kunming Meteor Radar.

The primary objective of this study is to characterize and quantify the intraseasonal variability of the upper atmosphere in eastern China based on the observed horizontal wind of the mesosphere and lower thermosphere from 2015 to 2020 by meteor radar located at Mengcheng and to investigate its relation to the intraseasonal oscillatory activity of the lower atmosphere.

The remainder of the paper is organized as follows: Section 2 describes the adopted meteor radar observations and intraseasonal activity data from the lower atmosphere and the analysis methods. In Section 3, we discuss the main features of intraseasonal activity in the upper atmosphere from meteor radar observations. Section 4 describes the relationship between the intraseasonal activity of the upper atmosphere and the intraseasonal activity of tropical convection in the lower atmosphere. The main results and conclusions are summarized in Section 5.

2. Data and Methods

The Mengcheng All-Sky Interferometric Meteor Radar (MCMR) was installed in 2014 at Mengcheng (33.4° N, 116.5° E) in Anhui Province, China, and has been in operation by the University of Science and Technology of China (USTC) since April 2014 to the present day. The MCMR radar is an enhanced meteor detection radar series (EMDR) manufactured by ATRAD Ltd., which is similar to the Buckland Park meteor radar system proposed by Holdsworth et al. [44]. The MCMR transmits a 38.9 MHz pulsed coherent radio signal with a wavelength of 7.71 m and a peak power output of 20 kW with a 4-bit code and a pulse repetition rate (PRF) of 430 Hz with 4 samples.

The daily Outgoing Longwave Radiation (OLR), version 1.2, from NOAA Climate Data Record (CDR), is adopted to represent the intraseasonal variation in the tropical troposphere [45].

Following the wind inversion technique described in [44], the temporal and altitude resolutions of the horizontal winds from 70 to 110 km observed by the Moncheng meteor radar are 1 h (time) and 2 km (altitude), respectively. For the most part, the residual RMS (root mean square) of the hourly horizontal velocity provided by the Moncheng meteor radar system is less than 10 m/s. A joint measurement campaign was carried out by Reid et al. [46] and Zeng et al. [47] to assess the performance and uncertainty of the winds observed by the meteor radar based on the observation from Davis Station in the Antarctic and from Kunming Station at low latitudes, respectively. The uncertainty of zonal and meridional wind observed by the meteor radar for the 1 h average is less than 4 m s^{-1} near 90 km.

Daily mean horizontal winds at the MLT used in this study were obtained by averaging latitudinal and meridional winds from hourly measurements of MR winds. The amplitudes of the fluctuations from 20 to 100 days at Moncheng were then extracted using daily zonal and meridional mean winds to investigate the characteristics of the ISO wind field in the northern midlatitude MLT region.

Continuous radar observations of meteors have been carried out all over the world since 1947 [48–51]. In the MLT (~70–110 km) region, the signal reflected from the meteor orbit is Gaussian in shape, with the peak situated at ~90 km altitude and 40 km full width [42,52,53]. Hourly horizontal wind values are obtained by least-squares fitting of the meteor radar observations at hourly time steps, which is based on the assumption of low vertical wind speeds [54]. The daily mean horizontal winds are then used to calculate the characteristics of intraseasonal variation for the period ranging from 20 to 100 days. Since there are few meteors at certain time intervals, especially at high and low altitudes during the afternoon, the MR observations are typically heterogeneous; thus, we applied Lomb-Scargle periodograms to analyze the period characteristics of the ISO based on the daily zonal wind speed. The characteristics of ISO are obtained by harmonic fitting at the selected period, which was defined where the amplitude reaches its maximum between 20 and 100 days for the analyzed 200-day period. Since the ISO amplitude is significantly stronger in the zonal component compared to the meridional counterpart in the regional MLT radar observations, the calculation of the periodogram is based on the zonal component. The calculation of “anomalies” in this study was achieved by removing the climatologically averaged variation in the seasonal cycle from the dataset.

Morlet wavelet and cross-wavelet analyses were applied [55,56] to determine the variability of interest in the time series.

3. Results

Figure 1 shows the amplitude variation corresponding to the 30- to 100-day period of the zonal wind at altitudes of 100 km (upper panel) and 80 km (upper panel) observed by Moncheng Meteor Radar from January 2015 to December 2020. The intraseasonal zonal wind oscillation is strongest in boreal winter at 80 km between 2015 and 2020, and most of the power is concentrated in the period range of 60 to 100 days. Despite the lack of data measurement in 2019 for technical reasons, the ISO in the mesopause region (80 km) showed a significant increase in amplitude during each winter from 2015 to 2020, and the ISO periods of the zonal wind showed a gradual increase from January (50 to 60 days) to March (80 to 90 days). At 100 km, there is a salient component in 2015 with periods from 60 to 90 days. However, the amplitude of the ISO in the zonal wind did not vary significantly as a function of the seasonal variation, and the power distribution was a wide range between 30 and 80 days. Between 2015 and 2017, there was significant ISO activity within a period of 40 to 70 days in the zonal wind observed by the meteor radar at 100 km. The period for the ISO at 100 km is larger in 2015 and 2017 (50 to 70 days) and smaller in 2016 (approximately 40 days). Moreover, during the summer of 2020, the intraseasonal oscillation was observed with a period of approximately 50 to 80 days at 100 km. In general, the amplitude of the ISO in the zonal wind is stronger at 80 km with a peak in excess of 15 m s^{-1} , whereas the amplitude is lower at 100 km with a peak at approximately 10 m s^{-1} .

This result implies that the intraseasonal oscillations in the upper mesosphere and lower thermosphere do not match one another. Since relatively low-period ISOs are prominent at 100 km but not at 80 km, it is possible that these low-period ISOs are generated locally in the lower thermosphere rather than propagating from the lower atmosphere.

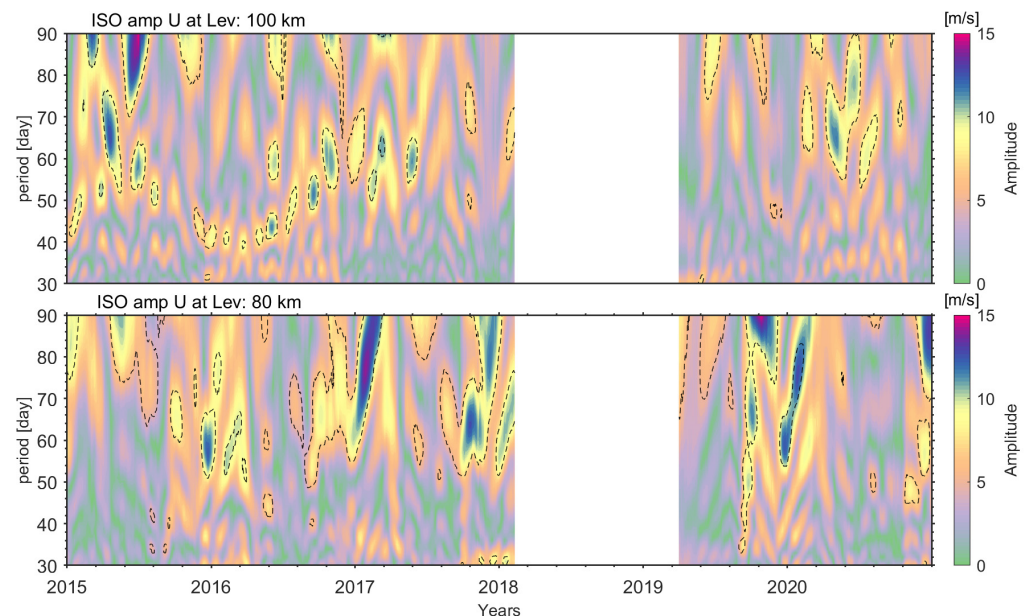


Figure 1. Lomb Scargle Spectral of zonal wind at 100 km (**upper panel**) and 80 km (**lower panel**) wind observed by the meteor radar between January 2015 and December 2020. The area surrounded by the dashed lines indicates significant power according to the false alarm probability.

The periodogram of the Lomb-Scargle of the zonal wind as observed by the 100 km Moncheng meteor radar from 2015 to 2020 is shown in Figure 2, with the green dots indicating the period corresponding to the maximum amplitude in the range of 30 to 90 days. The zonal wind oscillations at 100 km altitude can be divided into two categories, quasi40-day variation and 50–90-day variation, based on the period. A clear intraseasonal oscillation signal was observed in the zonal wind at 100 km for the largest period from 2015 to the beginning of 2018, with the exception of the winters of 2017 and 2018. In 2015 and 2016, there was clear ISO activity with an amplitude of approximately 10 m s^{-1} at a quasi40-day period, while the quasi-40-day oscillation was less evident in 2017, 2018, 2019, and 2020. Although the seasonal variation in the oscillations with a period of approximately 40 days is not significant, the amplitudes of the quasi40-day oscillations vary from year to year.

In contrast, there is a more pronounced seasonal variation for ISOs with periods in the range of 50 to 90 days, with stronger oscillations of 60 to 90 days occurring from February to March and June to July each year, while an oscillation of nearly 60 days was observed from April to May in 2015, 2017, and 2020. In the winters of 2016 to 2017, a clear oscillation with a period of 50 to 60 days can be detected in the 100 km zonal wind observations, but the oscillation from 50 days to 90 days is relatively weak with an amplitude of less than 4 m s^{-1} in the other winters, with the exception of the winters of 2016 to 2017.

At 80 km, the zonal wind oscillations do not have a clear signal at the quasi40-day period but mostly show variability with periods ranging from 50 to 90 days (Figure 3). The zonal wind ISO at 80 km altitude is characterized by clear seasonal variability, with a representative enhancement of the ISO activity within periods from 50 to 90 days from November to February each year, which is, on average, approximately ten times larger than the minimum during the months from June to August. The period of strongest ISO of the 80 km zonal wind is slightly lower in December (approximately 60 days) and January than in November and February (approximately 80 days).

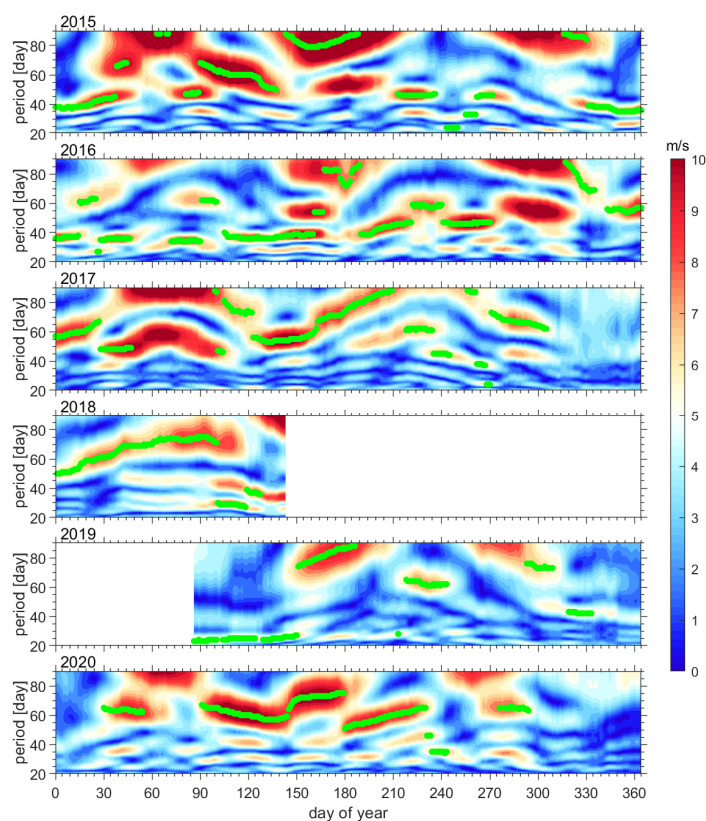


Figure 2. Periodograms of zonal amplitudes for 2014–2022 at 100 km. The date represents the center day of a 200-day window. The cyan points denote the period with the largest amplitude between 20 days and 100 days for wave amplitudes greater than 6 m s^{-1} .

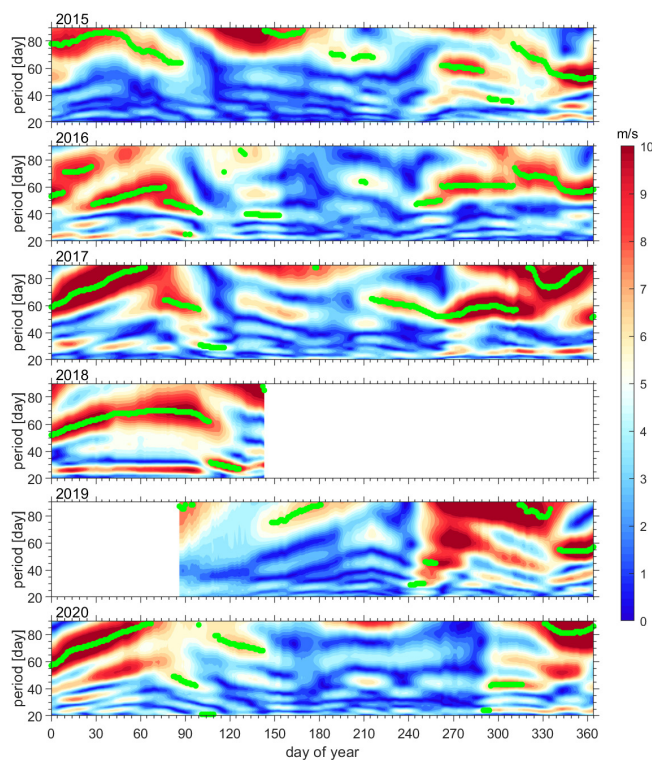


Figure 3. Same as Figure 2 but for Periodograms of zonal amplitudes at 80 km. The date represents the center day of a 200-day window. The cyan points denote the period with the largest amplitude between 20 days and 100 days for wave amplitudes greater than 6 m s^{-1} .

The characteristics of the amplitude and period variation of the ISO in the zonal wind at 80 km are similar to those at 100 km during the months of November and December, respectively, as shown in Figure 2. However, similar features at 80 km were not seen in the 100 km zonal wind during the months of January and February. It is implied that the zonal wind is dominated by the 60–90-day ISO from the upper mesosphere to the lower thermosphere in November and December, while similar ISO activity in January and February only occurs in the upper mesosphere but does not affect the lower thermosphere region. In the summer (from June to August), the amplitude of the ISO zonal wind at 80 km is much smaller (less than 2 m s^{-1}) than in the winter at most periods. In general, there is a distinct seasonal difference in the ISO zonal wind at 80 km, even though there is barely a seasonal dependence in the zonal ISO wind at 100 km. Thus, we further investigated the zonal wind ISO characteristics during different seasons.

Because the 80 km ISO zonal wind activity is strongest in winter, we focus first on the characteristics of the 80 km ISO during winter (November to March) and compare it with the 100 km zonal wind ISO. To investigate the relationship between the periods and amplitudes of the ISO oscillations at 80 km and 100 km, period histograms for different amplitude ranges in boreal winter are presented in Figure 4. To focus on the intraseasonal timescale, we ignore all periods beyond the boundaries that are shorter than 30 days or longer than 100 days. The dark blue bar indicates cases with maximum amplitude ($>12 \text{ m/s}$), blue indicates cases with moderate amplitude (amplitude between 8 and 12 m/s), and the light cyan bar encompasses all cases with amplitudes greater than 3 m/s . Intraseasonal oscillations at 100 km are typically strong during the extended boreal winter, with only a few cases of amplitude lower than 8 m s^{-1} . At 100 km, the counts of strong intraseasonal oscillation events (dark blue, amplitudes greater than 12 m s^{-1}) are mostly concentrated in the quasi-40-day and 60–80-day ranges. However, the counts of weaker oscillation events (light blue, amplitudes smaller than 12 m s^{-1}) are distributed over all periods with no apparent preference. Considering the large number of ISOs with total amplitudes between 8 m s^{-1} and 12 m s^{-1} , ISOs with total amplitudes greater than 8 m s^{-1} are considered “active ISO” cases in the remainder of this paper.

At 80 km, strong ISOs mostly occur with periods longer than 60 d (the median of the periods is 68 days and 65 days for those with amplitudes greater than 12 m s^{-1} and between 8 and 20 m s^{-1} , respectively).

During the extended boreal summer (May–September), the amplitude of the 100 km ISO occurs mainly in the range between 8 and 12 m s^{-1} (Figure 5). The median and mean periods are 64 and 63.7 days for the 100 km ISO in summer, respectively, and the occurrence of ISO is seen near several different ranges of periods near 40, 60, and 80 to 90 days. Most of the ISOs occurring at 80 km are strong activities with amplitudes in excess of 12 m s^{-1} . At 80 km, the median and average periods of the ISO cycles are 64 days and 59.8 days, respectively. ISO occurs not only near the 60-day period but also near the 35-day and 80–90-day periods.

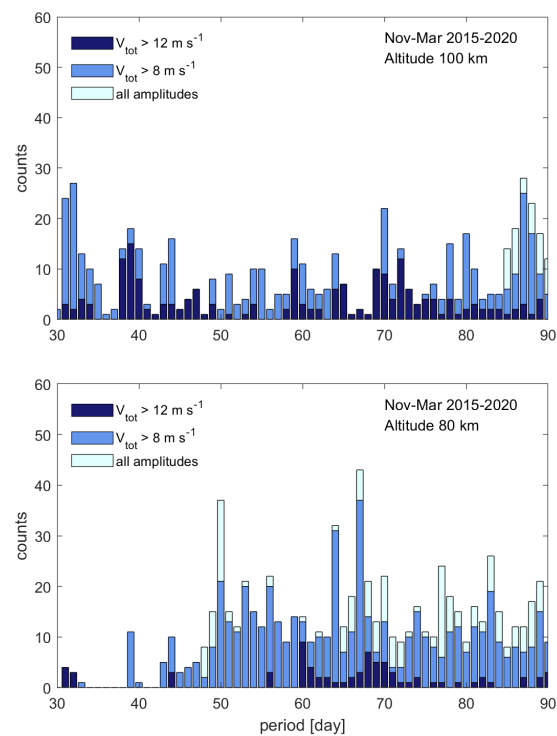


Figure 4. Distribution of periods for different wind speed ranges in the boreal winter (November–March) for 2015–2020. Dark blue: amplitudes larger than 12 m s^{-1} only. Light blue: amplitudes between 8 and 12 m s^{-1} . Light cyan: amplitudes smaller than 8 m s^{-1} .

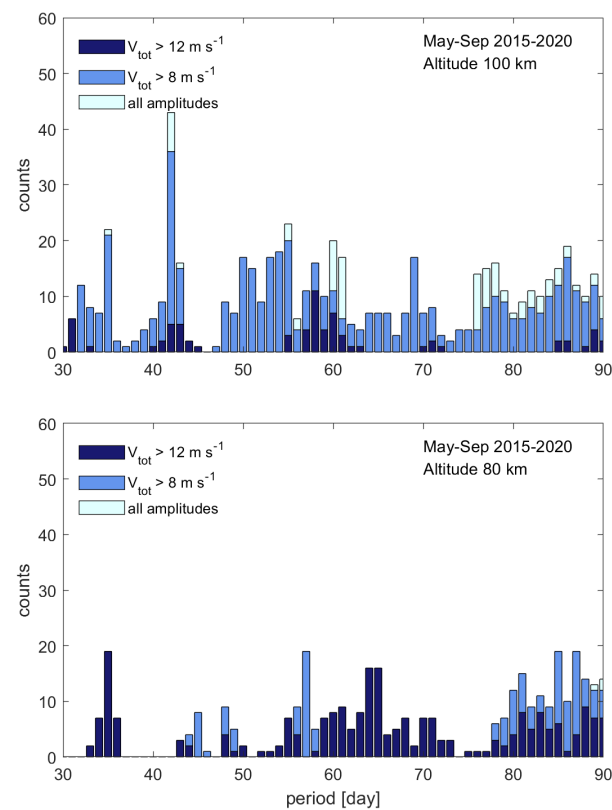


Figure 5. Same as Figure 4 but for the distribution of periods during the boreal summer (from May to September). Dark blue: amplitudes larger than 12 m s^{-1} only. Light blue: amplitudes between 8 and 12 m s^{-1} . Light cyan: amplitudes smaller than 8 m s^{-1} .

To assess the difference in amplitude between the zonal and meridional components of the ISO, the relative differences in amplitude Δv are defined as

$$\Delta v = 2 \cdot \frac{v_z - v_m}{v_z + v_m} \cdot 100\% \quad (1)$$

where v_z (v_m) refers to the zonal (meridional) component of the amplitude of the ISO in the meteor radar-observed horizontal wind. The dominant component of the intraseasonal oscillation is clearly visible in Δv , the positive (negative) value of which represents the dominance of the zonal (meridional) wind (Figure 6).

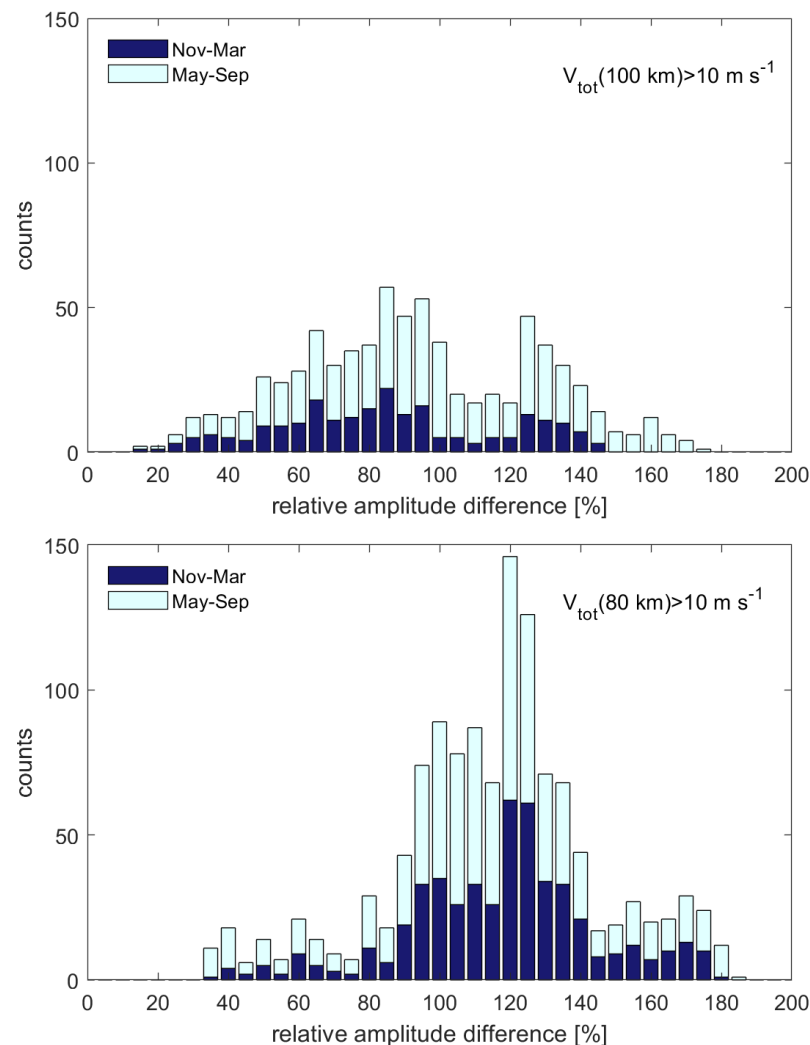


Figure 6. Histogram of the relative amplitude differences (Δv) between the zonal and meridional components of the ISO amplitudes at 100 km (**upper panel**) and 80 km (**lower panel**). Only oscillations with amplitudes in excess of 10 m s^{-1} are considered. There are 738 days considered for winter (indicated by the dark blue bars, November–March), whereas 285 days are considered for the remainder of the year (Light cyan bars, April–October).

The mean of the relative difference at 100 km is 83.9%, while the median is 85% among 228 “active ISO” days of winter. The 5% and 95% percentiles of the difference amount to 30% and 135%, respectively. For the extended boreal summer (May to September), the mean of the relative difference is 106.7%, whereas the median is 100% among 285 “active ISO” days at 100 km. The 5% and 95% percentiles of the difference for the summer amount to 50% and 160%, respectively.

At 80 km (the lower panel in Figure 6), the mean of the relative difference is 117.5%, whereas the median is 120% among 503 “active ISO” days of winter. The 5% and 95% percentiles of the difference amount to 65% and 165%, respectively. For the extended boreal summer (May to September), the mean of the relative difference is 105.1%, whereas the median is 105% among 285 “active ISO” days at 80 km. The 5% and 95% percentiles of the difference for the summer amount to 40% and 175%, respectively.

Thus, the zonal component tends to be greater than the meridional component. Although the zonal amplitudes tend to be slightly larger because the ISO periods have been selected based on the amplitude peaks in the zonal waves, the effect is not large.

4. Discussion

Above, we show the characteristics of the amplitudes and periods in the ISO of the horizontal MLT wind observed by the MCMR with respect to different seasons and altitudes. Previous studies have suggested that there may be a correlation between ISO activity in the MLT region and intraseasonal variation in the lower atmosphere [21,22,37]. The tropical tropospheric atmosphere is characterized by periodic intraseasonal oscillatory activity [36]. The atmospheric gravity wave excited by large-scale atmospheric convections could propagate vertically into the upper atmosphere and then release energy and momentum into the upper atmosphere through the process of wave breaking and dissipation.

The outgoing longwave radiation (OLR) is an estimate of the low-energy infrared radiation emitted from the Earth and its atmosphere to outer space, which is measured by radiometers onboard National Oceanic and Atmospheric Administration (NOAA) polar-orbiting satellites. OLR is considered a proxy for tropospheric convective activity, along with GW and tidal sources. Tropical convection can modulate planetary wave activity at the middle and high latitudes, which in turn impacts the middle and upper atmosphere at the middle and high latitudes through wave-mean flow and wave-wave interactions. Tropical convection could influence the atmospheric thermal tide by modulating the distribution of water vapor and the absorption of radiation in the troposphere.

In this study, the OLR averaged over the tropics (20° S– 20° N) was adopted to represent the ISO in the tropical troposphere. Figure 7 shows the cross-wavelet transform of the MCMR-observed zonal wind at 100 km and daily mean outgoing longwave radiation averaged over the tropics (20° S– 20° N) from January 2015 to December 2020.

The cross wavelet analysis in Figure 7 shows that the 60-day variabilities in MCMR zonal wind in the MLT region and tropical tropospheric convection (OLR) are correlated, with approximately 3–4 cycles from winter to summer for 2015 and 2018, but the correlation is absent in 2016, 2019 and 2020. Huang KM et al. (2015) [57] reported that short-period oscillations excited by perturbations in the troposphere are able to propagate directly into the MLT region. On the other hand, the long-period oscillation, which cannot propagate to the MLT directly, is believed to be modulated by diurnal tidal variations influenced by tropospheric perturbations such as latent heat release in the convections [42]. During 2015, the quasi-60-day zonal wind ISO is in phase with the OLR in the tropical troposphere, while the tropical tropospheric convection leads the MLT zonal wind by approximately 90° (i.e., 15 days) during 2017.

The correlation between tropical convective activity and the ISO of the zonal MLT wind at 100 km in 2015 and 2017 is consistent with the relatively stronger amplitude of the quasi-60-day ISO in the MLT region (Figure 2), suggesting that the stronger winter-to-summer ISO in the horizontal wind in these two years could be due to lower atmospheric perturbations, such as convective-induced small-scale gravity waves, internal gravity waves, inertial gravity waves or Rossby-gravity waves.

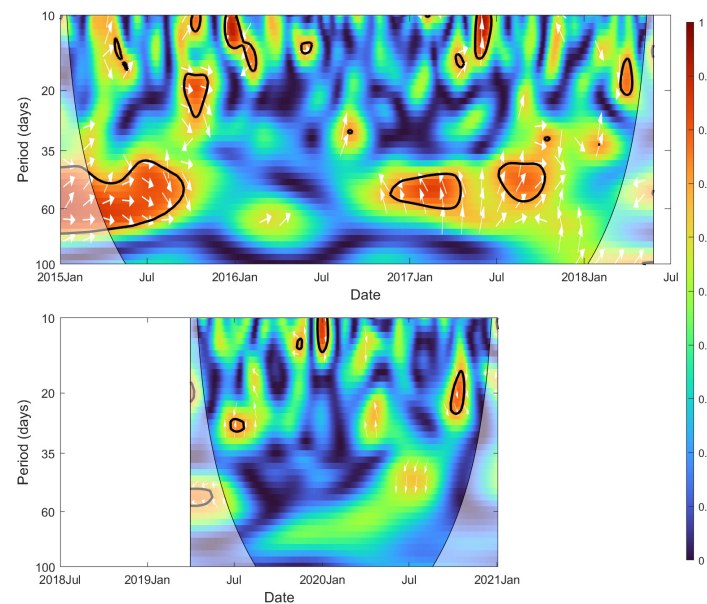


Figure 7. Cross wavelet transform of the MCMR observed zonal wind at 100 km and daily outgoing longwave radiation between 20° S and 20° N) obtained from the NOAA Climate Data Record (CDR) from January 2015 to December 2020. The 95% significance level is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left, and temperature leading ozone by 90° pointing straight up).

The cross-wavelets in the second half of 2016 indicate that the 40–60-day ISO in 80 km horizontal winds over Mengcheng is correlated with the global tropical convective ISO for two cycles (Figure 8). However, the ISO with similar periods in 100 km horizontal winds in other years is not correlated with the tropical convective ISO. The quasi-30-day oscillation at 80 km is correlated with tropospheric convective activity that occurred in early 2020 and lasted for approximately two cycles.

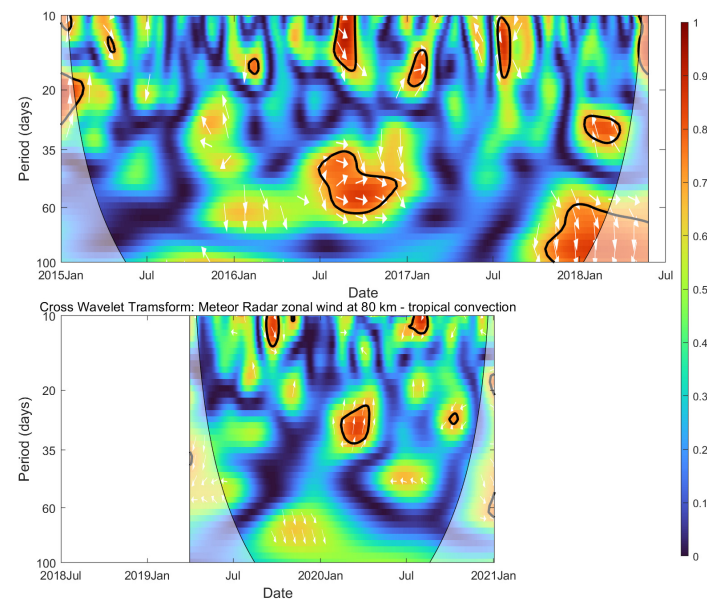


Figure 8. Cross wavelet transform of the MCMR observed zonal wind at 800 km and daily outgoing longwave radiation between 20° S and 20° N) obtained from the NOAA Climate Data Record (CDR) from January 2015 to December 2020. The 95% significance level is shown as a thick contour. The relative phase relationship is shown as arrows (with in-phase pointing right, anti-phase pointing left, and temperature leading ozone by 90° pointing straight up).

5. Conclusions

In this paper, we present observations of intraseasonal oscillations (30–100 days) in the MLT horizontal wind from January 2015 to December 2020 and investigate the relationship between the ISO in the MLT and tropical tropospheric convective variations. The intraseasonal oscillation in zonal and meridional wind obtained from the Mengcheng meteor radar (33.4° N, 116.5° E) has different characteristics of periods and amplitudes at different altitudes. At 80 km, there is a clear seasonal variation in ISO in the horizontal wind observed by the meteor radar system, which is strongest during the winter and weakest during the summer, with the maximum of the periods mostly occurring between 50 and 90 days. In contrast, at 100 km, ISO occurs throughout most of the year except winter. There are significant differences in the periods and amplitudes of the 100 km ISO from year to year. From 2015 to 2016, ISOs with periods of 40–60 days were present in the 100 km horizontal wind, whereas no ISO within similar variation was simultaneously observed in the 80 km horizontal wind. In general, ISO in horizontal winds of 80 km has a longer period of 50 days or longer, while ISO in horizontal winds at 100 km has a broader distribution in periods. The ISO amplitude in the zonal wind is approximately twice as high as that in the meridional wind at both 80 km and 100 km, either in winter or summer.

Cross wavelets were used to study the relationship between ISO in the MLT region and ISO in the lower atmosphere. There is a difference between the correlation of ISO in the lower atmosphere and ISO in the upper mesosphere (80 km) and the correlation with that in the lower thermosphere (100 km). It is suggested that the winter-to-summer quasi-60-day ISO in the horizontal wind in the lower thermosphere could be due to the lower atmospheric perturbations in 2015 and 2017. The correlation between the 40 and 60-day ISO in 80 km horizontal winds and the global tropical convective ISO in the second half of 2016 is not observed in connection with 100 km wind.

In general, there is clear intraseasonal oscillation activity in the horizontal wind obtained from the Mengcheng meteor radar multiyear observations. However, there are distinctly different characteristics of ISO activity in the upper mesosphere and low thermosphere regions, suggesting that ISO activity is independent of each other at different altitudes. In the MLT region, part of the ISO activity is linked to tropospheric tropical convective activity, but the ISO connections in the upper mesosphere and regions of the lower thermosphere with the lower atmosphere are also inconsistent with one another.

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Data Availability Statement: The data presented in this study are available on request from the author (C.Y., cyyang@ustc.edu.cn). The data are not publicly available due to institutional restrictions. High-quality Climate Data Records (CDR) of daily Outgoing Longwave Radiation (OLR) are downloaded at <https://www.ncei.noaa.gov/data/outgoing-longwave-radiation-daily/access/> accessed on 1 May 2023.

Conflicts of Interest: The authors declare no conflict of interest.

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