Statistical characteristics of atmospheric gravity wave in the mesopause region observed with a sodium lidar at Beijing, China

Shohua Gong\textsuperscript{a,b}, Guotao Yang\textsuperscript{a,e}, Jiyao Xu\textsuperscript{a}, Jihong Wang\textsuperscript{a}, Sai Guan\textsuperscript{a}, Wei Gong\textsuperscript{c}, Jun Fu\textsuperscript{b}

\textsuperscript{a} State Key Laboratory of Space Weather, National Space Science Center, Chinese Academy of Sciences, Beijing 100190, China
\textsuperscript{b} School of Physics and Electronics Engineering, Hainan Normal University, Haikou 571158, China
\textsuperscript{c} State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan 430072, China

1. Introduction

Atmospheric gravity waves (AGWs) are now believed to play a central role in establishing the large-scale circulation and structure of the middle and upper atmosphere. Our understanding of AGWs on many fronts has been advanced by numerous theoretical, numerical, and observational studies since the pioneering works of Hines (1960). Those fronts include AGW sources, parameters, propagation dynamics, variations with altitude, seasonal and geographic variability, and implications of various parameterizations for atmospheric circulation and structure (Nappo, 2002; Wright and Gille, 2011). Several important models and theories have been derived, such as Dewan and Good's (1986) linear instability theory, Hines' (1991) Doppler-spreading theory, Dewan's (1994) saturated-cascade theory, and Gardner's (1994) diffusive filtering theory. These have provided some explanations to the vertical wave number spectrum, based on different physical mechanisms for dissipating wave energy (including shear and convective instabilities, cascade process, wave-induced Doppler effects and wave-induced diffusion).

As an effective method for investigating AGW activities, sodium lidar observations can provide good understanding of AGW phenomena in the mesopause region, owing to their high temporal and spatial resolutions. The sodium layer is an excellent tracer of gravity wave perturbations because steep sodium density gradients at the bottom and top of the layer can enhance these perturbations. Many studies of AGW intensities, spectra and wave field characteristics in the mesopause region have been made with sodium lidars in the United States, South pole and Brazil [e.g., Senft and Gardner, 1991; Gardner and Voelz., 1987; Collins et al., 1994; Yang et al., 2006, 2008b]. However, since AGW characteristics generally vary with location, more detailed observational evidence is needed. Further, detailed understanding of generation mechanisms and resulting wave characteristics is still lacking for accurate description of AGW effects within global models.

Since early 2010, 253 nightly observations of sodium lidar at Beijing have been done with support from the Chinese Meridian Project (Wang, 2010). After analysis of these observation data, we present the first lidar study of AGW activity in the mesopause region above Beijing. We address nightly, monthly and seasonal variabilities of this activity in this paper. Reasons behind the evolution of these characteristics are discussed, based on qualitative analyses of AGW sources and background atmospheric winds.

2. Instrumentation and data analysis methodology

Beijing lidar station locates at the suburb of Yanqing county (40.3°N, 116.2°E), and its sodium lidar mainly consists of three parts: the laser system, optical receiving system and signal processing system. The probing beam is generated by a Nd:YAG laser-pumped dye laser, and its wavelength is precisely controlled by employing a Na fluorescence cell to excite the resonance transition of Na atoms in sodium layer. The beam is set to pointing at zenith, and its typical energy and divergence are about 30 mJ
and 1 mrad. The repetition rate of Nd:YAG laser is 30 Hz. Back-scattered fluorescence photons from sodium layer are collected with a receiving telescope (diameter is $\varnothing 950$ mm). The field-of-view of telescope is set to about 3 mrad. An optical filter with 1 nm bandwidth, a cooled PMT, a fast amplifier and a time-resolved photon counter are used for optical signal detection. Data are finally collected and saved in a computer. For an individual lidar profile, the photon counts are accumulated for every 5000 laser pulses in 3 min. The time resolution is 3 min, and the altitude resolution is 96 m (0.64 $\mu$s photon counting gates).

From April 2010 to September 2011, lidar observation has been constantly done in 253 suitable nights. A database of 2208 h was obtained under the efforts of our group members. Monthly distributions of observing nights and hours are respectively plotted in Fig. 1. The observing hours are significantly longer in winter than in summer because summer is the rainy season of Northern China. As a nightly measurement, more observations are during the middle of night and least during the hours just sunset and just before sunrise.

All data are selected in this work except those data during the periods of sodium burst ($N_a$) in 46 nights. The sodium density profiles are spatially and temporally low-pass filtered with a cutoff of about 2 km and 15 min. The criterion described by Beatty et al. (1992) is applied, and only those waveletike perturbations that occur in several successive density profiles and exhibit coherent downward phase progression are considered to be quasi-monochromatic AGWs. (In general, the sodium density profile perturbed by an AGW presents a monochromatic waveike, and the ridge and trough are evenly distributed on the both sides of the each note.) The technique developed by Yang et al. (2008a) is employed to extract the parameter values of each AGW.

Based on the fundamental theory developed by Gardner and Voelz (1985, 1987), when the steady state profile of sodium layer is horizontally homogeneous, the layer density response to a monochromatic AGW can be written as

\[ n_s(r,t) = n_0(z) - \gamma H n_0(z) + [Ae^{iz}/(\gamma - 1)] \cos(\omega t - kr) \]  

(1)

where $n_s(r,t)$ is the density of sodium layer, and $n_0(z)$ is the density of unperturbed sodium layer; $Ae^{iz}$, $\gamma$, $k$, $\beta$ are the wave amplitude, wave frequency, wave number vector and amplitude growth factor of AGW respectively; $\gamma$ is the ratio of specific heats ($\sim 1.4$), $H$ is the atmospheric scale height ($\sim 6$ km), and $r = xk + z\beta$ is the position vector.

When the wave amplitude is not large, the linear perturbation can only be taken into account, and formula (1) will be transformed into as follows:

\[ n_s(r,t) \approx n_0(z) - [n_0(z) - \gamma H n_0(z)/dz] Ae^{iz} \frac{\gamma - 1}{\gamma} \cos(\omega t - kr) \]  

(2)

Because the sodium density perturbations caused by AGWs are directly related to the associated atmospheric density fluctuations ($r_{\text{Atmosphere}}$), the relative sodium density fluctuations ($r_{\text{Sodium}}$) can be expressed in terms of the atmospheric density fluctuations ($r_{\text{Atmosphere}}$) as follows (Gardner and Voelz, 1985):

\[ r_{\text{Sodium}} \approx \frac{1 + (\gamma H / n_0)(dn_0/dz)}{\gamma - 1} r_{\text{Atmosphere}} \approx \frac{1 + (\gamma H / n_0)(dn_0/dz)}{\gamma - 1} Ae^{iz} \cos(\omega t - kr) \]  

(3)

One may calculate the sodium variation with $\Delta n = n_s - n_0$, and obtain the atmospheric density fluctuations ($r_{\text{Atmosphere}}$) using Eq. (3). Then, the linear wave perturbation of atmospheric density ($\Delta N / N \approx Ae^{iz} \cos(\omega t - kr)$) can be calculated, and the value of vertical wavelength $\lambda_z$ can be obtained by measuring the average distance between each pair of adjacent antinodes in wave perturbation. The vertical phase velocity $c_z$ can be measured by calculating

![Fig. 1. Histograms of observing nights (blue column) and observing hours (green column) in different months. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)](image)

![Fig. 2. Density profile sequence of sodium layer observed on September 28, 2010.](image)
the downward moving velocity of wave peaks in density profile sequence. The observed period $T_{ob}$ can be calculated with $c_z = \lambda c / T_{ob}$.

The following is an example of this data analysis methodology. The density profiles of sodium layer presenting in Fig. 2 were obtained on September 28, 2010. According to the criterion introduced above, it is easy to find from the density profile sequence that a quasi-monochromatic AGW is propagating in sodium layer. Its vertical phase velocity $c_z = 0.261$ m s$^{-1}$ can be obtained by measuring the moving downward speed of those wave peaks.

To extract the values of other wave parameters from this sodium density profile sequence, the density profiles observed by lidar are firstly averaged in time to form an average density profile in Fig. 3(a) (the blue curve). Then a connection layer (the dot green curve) is constructed by connecting the midpoints between each ridge and trough of the average density profile. And an approximated background layer (the dash red curve) can be obtained after the connection layer is smoothed using a three-point moving average.

Since the density profile of unperturbed sodium layer generally distributes in Gaussian, $n_0(z) = (c/\sqrt{2\pi}\sigma_0)\exp\left[-(z-z_0)^2/2\sigma_0^2\right]$, the

![Diagram](image-url)

**Fig. 3.** Processes of extracting parameter values of AGW: (a) to obtain an approximated background layer, (b) to get the reasonable background layer with the Levenberg-Marquardt fit, (c) to get the sodium density fluctuation and atmosphere density fluctuation, and (d) measurement of the wavelength. (For interpretation of the references to color in this figure, the reader is referred to the web version of this article.)
approximated background layer can be improved by fitting it with two Gaussians in Fig. 3(b) employing Levenberg–Marquardt method. And the improved background layer (the dash red curve) is regarded as the reasonable background layer (steady sodium layer). For this Levenberg–Marquardt fit, its correlation coefficient is $R = 0.99952$, and the parameter values of two Gaussians respectively are $c_1 = 1.933 \times 10^5$, $z_{0,1} = 92.95$ km, $\sigma_1 = 2.95$ km; $c_2 = 1.903 \times 10^5$, $z_{0,2} = 87.08$ km, and $\sigma_2 = 3.05$ km.

According to Eq. (3), the relative sodium density perturbation ($r_{\text{dium}}$) and the atmospheric density fluctuations ($r_{\text{Atmosphere}}$) are calculated and plotted in Fig. 3(c). The linear AGW perturbation of atmospheric density is calculated and plotted in Fig. 3(d). After the wave perturbation curve is spatially high-pass filtered with a cutoff of 4.5 km, a vertical wavelength $\lambda_v = 3.59$ km is finally obtained by measuring the average distance between each pair of adjacent antinodes in Fig. 3(d). (The corresponding leakage in this high-pass filtering process is also plotted in Fig. 3(d) with dash–dot line.) And the period is calculated to be $T_{\text{ab}} = 3.82$ h with $T_{\text{ab}} = \lambda_v/c_2$.

Taking this approach, both vertical wavelengths and observed periods of quasi-monochromatic waves can be accurately obtained from those sequences of wave-like Na density profiles in different nights. The estimates of vertical wavelengths are limited by the results of the Levenberg–Marquardt fitting, and the biases are generally less than 2%. Because the observed period is calculated with $T_{\text{ab}} = \lambda_v/c_2$, the uncertainty is determined by the errors in vertical wavelength measurements and vertical phase velocity measurements. For the resultant errors in $c_2$ measurement are typically 5–8%, the errors in measurement of observed periods are generally less than 10%.

In fact, because of the influence of mean wind field in the Na layer, the observed period should be the Doppler shifted wave period rather than the intrinsic period, and the former should be generally larger than the latter (Gardner and Voelz, 1987, Eq. (20)). Moreover, for the case that the wind speed varies much at different sodium layer altitudes along the wave propagation direction, the coherent phase progression in density profiles will be distorted, and those waves will not be considered as monochromatic gravity waves in terms of the employed criterion. So our statistics are also biased toward waves that experienced a uniform Doppler shift or which propagated approximately normal to the mean flow.

3. Results and discussion

3.1. Observation results

From April 2010 to September 2011, there were 162 quasi-monochromatic waves observed in different nights, and their vertical wavelengths and observed periods are respectively plotted versus month in Fig. 5. Statistics show that their vertical wavelengths ($\lambda_v$) ranged from 2 km to 12.88 km, with average vertical wavelength 3.80 km. The corresponding observed periods ($T_{\text{ab}}$) were from 1.03 h to 16.48 h, with annual mean 3.56 h. Histograms of these observations are also plotted in Fig. 6. The number of AGWs clearly decreases with increasing wavelength and observed period, and typical values of AGW parameters are vertical wavelength $\lambda_v = 2$–4 km, observed period $T_{\text{ab}} = 1$–4 h, vertical phase velocity $c_2 = 0.2$–0.5 m s$^{-1}$. Those observation results reveal that the lidar-observed quasi-monochromatic AGWs in the mesopause region above Beijing are usually dominated by short-period waves and the waves with a longer period than 4 h are less common.

Following the data analysis method of Section 2, parameter values of the AGWs were precisely extracted. There were $N = 162$ quasi-monochromatic AGWs observed on different nights, and their vertical wavelengths and observed periods are respectively plotted versus month in Fig. 5. Statistics show that their vertical wavelengths ($\lambda_v$) ranged from 2 km to 12.88 km, with average vertical wavelength 3.80 km. The corresponding observed periods ($T_{\text{ab}}$) were from 1.03 h to 16.48 h, with annual mean 3.56 h. Histograms of these observations are also plotted in Fig. 6. The number of AGWs clearly decreases with increasing wavelength and observed period, and typical values of AGW parameters are vertical wavelength $\lambda_v = 2$–4 km, observed period $T_{\text{ab}} = 1$–4 h, vertical phase velocity $c_2 = 0.2$–0.5 m s$^{-1}$. Those observation results reveal that the lidar-observed quasi-monochromatic AGWs in the mesopause region above Beijing are usually dominated by short-period waves and the waves with a longer period than 4 h are less common.

Relationships between $\lambda_v$ and $T_{\text{ab}}$ have been analyzed and plotted on a log–log scale in Fig. 7. It is evident that there is a strong systematic relationship between $\lambda_v$ and $T_{\text{ab}}$. After a power-law maximum likelihood (ML) algorithm is used to fit the data points of the figure in the form $\lambda_v = C T_{\text{ab}}^{\alpha}$, a relationship $\lambda_v = \lambda_0 T_{\text{ab}}^{\alpha}$ is obtained for all observations. The correlation coefficient from this fit is $r^2 = 0.881$ even though some large Doppler

![Fig. 4.](image-url)
errors in $T_{ob}$ are expected. This systematic relationship ($\lambda_{c} \propto T_{ob}^{0.544}$) derived at Beijing agrees well with the prediction of Gardner's diffusive filtering theory (Gardner, 1994), and it means only those waves which have the largest amplitudes and roughly fall along the diffusive damping limit ($\lambda_{c} = (2\pi DT_{0})^{1/2}$) are easily observed by lidar in the mesopause region.

Relationships between $\lambda_{c}$ and $T_{ob}$ in the summer (March through August) and winter (September through February) are also analyzed with the same method in Fig. 7. They are respectively $\lambda_{c} = 0.23T_{ob}^{0.49}$ in the summer and $\lambda_{c} = 0.16T_{ob}^{0.56}$ in the winter. It is found that the value of slope $p$ and coefficient $C$ change considerably from summer to winter. That means, at Beijing, the seasonal variation of AGW activities is very obvious.

Nearly all previous lidar observations indicate a strong systematic relationship between $\lambda_{c}$ and $T_{ob}$, and the values of slope are similar to the result derived by us ($p=1/2$). At Illinois (40°10'N, 88°10'W), an observation $\lambda_{c} = 0.40T_{ob}^{0.55}$ is reported by Gardner and Voelz (1987). Later, a similar relationship $\lambda_{c} = 0.24T_{ob}^{0.57}$ is presented by Collins et al. (1996) in their study of AGW activity using Na Wind/Temperature lidar. At São José dos Campos (23°S, 46°W), a low-latitude location, a relationship $\lambda_{c} = 0.42T_{ob}^{0.53}$ is reported by Yang et al. (2008a). However, it should be noticed that there are still slight variations in observed $p$ and $C$ values at different locations. For example, for a given wave with a typical period of 3 h, its wavelength will be observed to be about 4.6 km at Illinois (about 6.9 km for Gardner and Voelz’s observations), about 3.9 km at São José dos Campos, and about 3.6 km at our observation site. This suggests that AGW activity has its own regional characteristics at different locations.

In addition, the associated rms errors in coefficient $C$ and slope $p$ of this ML fit have been calculated and listed in Table 1. The errors are dominated by the scatter in data due to Doppler effects. (Note that the correlation coefficient $r^2$ is calculated from the raw data and does not depend on the curve fitting algorithm.)

3.2. Analysis of main sources

To our knowledge, AGWs can be produced by mesoscale meteorological and irregular motions, and the main contributing factors may be from hydrodynamic sources of momentum, mass, and heat. Generally, at a specific location, convection and topography are the most obvious sources, although other sources may be significant at certain sites or be associated with specific large-scale dynamics (Fritts and Alexander, 2003). The intensities of waves generated below 20 km altitude are usually much stronger than those generated above this altitude, because of the growth of AGW amplitudes associated with the decrease in atmospheric density (Gavrilov and Fukao, 1999). Hence, for the typical AGWs observed with sodium lidar, the main contribution may come from topography and convection in troposphere and stratosphere below 20 km.

Following the method of Senft and Gardner (1991), the distance between the observation site and tropospheric source can be estimated by multiplying $T_{ob}/T_{B}$ by the height of the sodium layer. Where $T_{B}$ is the Brunt–Väisälä period and it is approximately 5 min near the mesopause. The annual mean of $T_{ob}$ is 3.56 h (Fig. 5). That suggests that tropospheric sources are about 3750 km away from Beijing, on average. Since those observed periods are typically 1–4 h (in Fig. 6(b)), it can be estimated that AGW sources are principally 1050–4300 km away from the observation site. At these distances, orographic forcing and convective heating over the Qinghai–Tibet Plateau may be the most probable sources of the typical AGWs observed at Beijing. This plateau is the highest in the world, and is situated in the southwestern Chinese mainland. It constitutes about one quarter of the area of China, and numerous AGWs may be generated above it (Alexander et al., 2008). Basing on the observations of HF Doppler arrays, Wan et al. (1998) and Xu et al. (2008) report that the topography and convection above this plateau are the primary sources of medium-scale AGWs above...
A similar conclusion is also made by Ding et al. (2011) when they investigated the traveling ionospheric disturbances over China with GPS network. Therefore, it may be reasonable to regard the topography and convection above this plateau as the primary sources of AGWs observed by our lidar.

For the 162 AGWs observed at Beijing, the wave event rate (WER) in different period intervals has been calculated in different seasons and it is plotted in Fig. 8. The WER is calculated as the total number of wave events divided by the total observation hours over one season. The figure shows that the WER of AGWs with $T_{ob}$ between 1 h and 4 h is greater than those with other periods. This means that the AGW activities are dominated by components of these typical waves ($T_{ob} \in [1, 4]$ h in Fig. 6(b)). By contrasting the WER of waves across different seasons, one can find that AGW activity has an apparent minimum in winter and these typical AGWs are more active in spring and summer. This seasonal variation is similar to that of tropospheric temperature, and it suggests that seasonal variation of AGW activity is mainly related to the seasonal temperature variation in the troposphere. As is known, convection is a dominant gravity wave source in the troposphere, and the frequency and intensity of AGW source are related to temperature (Beres et al., 2005). When temperature increases, convection that involves thermal forcing associated with latent heat release becomes stronger and more frequent, thereby generating more AGWs during its interaction with overlying stable layers (McLandress et al., 2000).

Based on the above qualitative analyses, it is reasonable to think that AGW activities observed in the mesopause region above Beijing are mainly related to the topography and convection over Qinghai–Tibet Plateau. To those typical AGWs ($T_{ob} \in [1, 4]$ h in Fig. 6(b)), they could be mainly generated by the convections, and their activity may be dominantly influenced by the seasonal variations of convections.

Central China. A similar conclusion is also made by Ding et al. (2011) when they investigated the traveling ionospheric disturbances over China with GPS network. Therefore, it may be reasonable to regard the topography and convection above this plateau as the primary sources of AGWs observed by our lidar.

For the 162 AGWs observed at Beijing, the wave event rate (WER) in different period intervals has been calculated in different seasons and it is plotted in Fig. 8. The WER is calculated as the total number of wave events divided by the total observation hours over one season. The figure shows that the WER of AGWs with $T_{ob}$ between 1 h and 4 h is greater than those with other periods. This means that the AGW activities are dominated by components of these typical waves ($T_{ob} \in [1, 4]$ h in Fig. 6(b)). By contrasting the WER of waves across different seasons, one can find that AGW activity has an apparent minimum in winter and these typical AGWs are more active in spring and summer. This seasonal variation is similar to that of tropospheric temperature, and it suggests that seasonal variation of AGW activity is mainly related to the seasonal temperature variation in the troposphere. As is known, convection is a dominant gravity wave source in the troposphere, and the frequency and intensity of AGW source are related to temperature (Beres et al., 2005). When temperature increases, convection that involves thermal forcing associated with latent heat release becomes stronger and more frequent, thereby generating more AGWs during its interaction with overlying stable layers (McLandress et al., 2000).

Based on the above qualitative analyses, it is reasonable to think that AGW activities observed in the mesopause region above Beijing are mainly related to the topography and convection over Qinghai–Tibet Plateau. To those typical AGWs ($T_{ob} \in [1, 4]$ h in Fig. 6(b)), they could be mainly generated by the convections, and their activity may be dominantly influenced by the seasonal variations of convections.

Here, we need to address that the above mentioned is a qualitative analysis on the AGW sources and the quantitative studies are beyond the scope of this paper.

### 3.3. Nightly and seasonal variation characteristics

To investigate the nightly variation of AGW activity, histograms of nightly WER are plotted versus local standard time (LST) in Fig. 9, and an average wave event rate (WER) of 0.222 h$^{-1}$ is found. The WER for one local time interval is computed by using the total number of wave events observed during this time interval to divide with the times of observation experiment we carried out in this time interval. (The number of experiments carried out in each LST interval is correspondingly given in Fig. 9.) In Fig. 9, the WER roughly increases from 17 to 24 LST and decreases from 24 to 07 LST, having maximum from 22 to 24 LST. It means, in the mesopause region over Beijing, AGW is most active near midnight and passive in dusk and dawn.

In contrast with lidar observation results reported elsewhere, it is found that the nightly variation of AGW activity commonly varies with observation sites. Gardner and Voelz (1987) indicated...
that the period of greatest AGW activity at Illinois was from 2100 to 2200 LST, and the corresponding WER was more than twice that of any other hour. Yang et al. (2008b) stated that the nightly distribution of the quasi-monochromatic WER was irregular at Campos (23°S, 46°W). Both these observations of nighttime AGW activity are different from ours. The discrepancy may be ascribed to different properties of AGW sources in the troposphere, or a lower stratosphere at the observation sites. However, Gardner and Voelz (1987) asserted that it is difficult to postulate that a source mechanism in the lower atmosphere is important to nightly distributions of WER, because AGW propagation to the sodium layer requires more than 20 h. Perhaps it is more reasonable to attribute the discrepancy to different properties of AGW sources in the troposphere, or a lower stratosphere at the observation sites. However, Gardner and Voelz (1987) stated that it is difficult to postulate that a source mechanism in the lower atmosphere is important to nightly distributions of WER, because AGW propagation to the sodium layer requires more than 20 h. Perhaps it is more reasonable to ascribe the discrepancy to different properties of AGW sources in the troposphere, or a lower stratosphere at the observation sites. However, Gardner and Voelz (1987) stated that it is difficult to postulate that a source mechanism in the lower atmosphere is important to nightly distributions of WER, because AGW propagation to the sodium layer requires more than 20 h. Perhaps it is more reasonable that the nightly variation is mainly determined by the in

propagation, AGWs need suffer considerable absorption, reflection, dissipation and filtration from the background atmosphere; and only a few AGWs can survive in the mesopause region. Hence, those “blocking effects” from background environment may be crucial to AGW propagation, and they may represent important influences on our observation of nightly variation of AGW activity near the mesopause.

To study seasonal variation of AGW activity, the WER in each month has been calculated and plotted with curve (a) in Fig. 10. Here, the monthly WER is calculated as the total number of wave events divided by the total observation hours in 1 month. It is shown that the monthly WER for total AGWs maximizes in July and minimizes in December. This means that the strongest and weakest AGW activity occur around summer and winter solstices, respectively.

Since the quantity of observing nights and hours varies between months in Fig. 1, some deviation of the WER values may be introduced in the statistic results. Therefore, to obtain a more reliable seasonal WER distribution, a least squares fit is applied to the data to generate curve (c), which is plotted as a red solid line in Fig. 10. It is seen that the WER gradually increases from winter to summer and decreases from summer to winter. Summer values are typically 2–3 times larger than winter values. Those illustrate that AGW activity at the observing site is most active in summer and passive in winter. During the winter to summer phase, AGW activity becomes stronger month by month, with just the opposite trend during summer to winter.

However, at other observation sites, different seasonal variations of AGW activity in the mesosphere have been reported (Senft and Gardner, 1991; Yang et al., 2008a; Reisin and Scheer, 2004; Wilson et al., 1991; Gavrilov and Fukao, 2003), and different formation mechanisms for those seasonal variations were proposed (Hirota et al., 1997; Gavrilov and Fukao, 1999). But, most believed that AGW activities have their own regional characteristics at different locations and the seasonal variation of AGW activity is principally ascribed to the seasonal change of temperature and background winds in troposphere and stratosphere below 20 km (Gavrilov and Jacobi, 2004; Gavrilov et al., 2003). When the temperature is high, the intensity and frequency of AGW sources will be enhanced for the stronger and more common tropospheric convections, and more AGWs will be generated. During the obliquely upward propagation process, AGWs need suffer severe “blocking effects” (such as absorption, dissipation and filtering) from the background winds (Gavrilov and Fukao, 1999; Medeiros et al., 2003). For AGWs propagating at the same direction as the background wind, they are easily absorbed into the mean flow and hard to survive in the mesopause region. Contrarily, for AGWs propagating opposite to the mean wind, they are easy to pass through and survive in the mesopause region for the weak “blocking effects” from background winds.

When convection over the Qinghai–Tibet Plateau is regarded as the dominant source of lidar-observed AGWs, the observation results in Fig. 10 can be interpreted, based on the analysis of influences from seasonally varying temperature and background winds.

Fig. 9. Local standard time dependence of wave event rate and the number statistic of experiments carried out in different time intervals.

Fig. 10. Monthly distribution of wave event rate. Curve (a) is for the total AGWs, curve (b) is for the waves of which $T_{\Delta} \geq 7$ h, and curve (c) is the least square fit to data in curve (a). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)
To the monthly varied background winds in tropospheric and lower-stratospheric segments over Beijing, they have been statistically studied by Zhang and Yi (2007), Fig. 3) used the data from Radiosonde observation. And here, for comparison, the altitude-season distribution of mean horizontal wind above Northern China is calculated with the mean horizontal wind model HWM93 (http://modelweb.gsfc.nasa.gov/) and plotted in Fig. 11. (Since the mean zonal wind is much stronger than the mean meridional wind, only the seasonal variation of the former is usually taken into account in analysis.) Both of the analysis results show that the seasonal distribution of mean zonal wind exhibits an apparent semiannual symmetry, westward wind in spring and summer, and eastward wind in autumn and winter. Minima of the mean zonal wind below 20 km altitude occur in July–September (Zhang and Yi, 2007, Fig. 4).

The average temperature in troposphere and lower-stratosphere over China maximizes in summer. More AGWs are generated by strong and frequent convection above the Qinghai–Tibet Plateau. Also in summer, the mean zonal wind above Northern China is westward (Fig. 11). AGWs traveling northeastward from the plateau to Beijing suffer fewer blocking effects during their upward propagation, because the propagation direction in the horizontal opposes the background wind. Consequently, more waves are observed in the mesopause region by lidar in summer. Hence, there is almost no long-period AGW observed in the mesopause region. The WER maxima in June and October are hard to explain.

In China, atmosphere temperature near the ground is a minimum in winter. Fewer AGWs are generated above the Qinghai–Tibet Plateau because this colder temperature makes convection relatively weak and less common. Moreover, the mean zonal wind is eastward in winter (Fig. 11). Because of blocking effects from the background wind, AGWs traveling northeastward from the plateau to Beijing are severely dissipated and absorbed during their obliquely upward propagations. Further, most are completely blocked by the mean flow, and disappear in the stratosphere and mesosphere. Therefore, fewer waves survive in the mesopause region to be detected by lidar, and the WER also has a summer maximum (Fig. 10).

Using the same rationale, the seasonal variation of AGW activity in Fig. 10 can be explained. The increase of tropospheric temperature between winter and summer generates stronger and more frequent convection. However, zonal winds slowly change from westward to eastward in mesosphere. As a result, the blocking effects of the mean flow to the northeastward propagating AGWs gradually strengthen. To attain more insights on the seasonal dependence of AGW activity, we have calculated the WER for long-period AGWs (periods are longer than 7 h in Fig. 5) in different months. These are plotted by curve (b) in Fig. 10. We find that the WER distributes semiannually and the long-period AGWs seldom occur from July to September. Comparing curve (b) with the seasonal distribution of horizontal zonal winds below 20 km in Fig. 11, it is interesting that both have the same semiannual variation tendency. Also, both have their minima in July–September. This temporal correspondence indicates that the activity of the long-period AGWs correlates with zonal winds below 20 km. And it suggests that the long period AGWs are possibly generated by the topography of the Qinghai–Tibet Plateau when the seasonal monsoon winds flow over it. During July through September, fewer topographic AGWs are generated since the horizontal zonal wind is minimized in the troposphere. Hence, there is almost no long-period AGW observed in the mesopause region. The WER maxima in June and October are hard to explain.

In addition, in the above explanation, we think those AGWs observed at Beijing are from the Qinghai–Tibet Plateau, and they travel northeast to Beijing. However, for the horizontal propagation directions of AGWs, it can not be measured with a single lidar. At Xinglong, Beijing (40.2°N, 117.4°E), OH airglow imager observations show that the distribution of AGW propagation in horizontal direction is anisotropic and almost all waves propagate northeastward in summer at an altitude of ~87 km (Li et al., 2011). This result matches our assumption that most AGWs observed in the mesopause region in summer originate from the Qinghai–Tibetan Plateau. For the horizontal propagation directions of AGWs in winter, however, OH airglow imager observations are different. Therefore, to precisely understand the climatological properties of AGW activity in China, more cooperated measurement methods are desired.

4. Conclusions

We obtained a lidar observation database of 2208 h from 253 nights, during the period April 2010 to September 2011. The regional characteristics of AGWs activity in the mesopause region above Beijing (40.3°N, 116.2°E) were statistically analyzed. The average WER of AGWs is 0.222 h⁻¹, and the relationship between vertical wavelengths and periods is \( \lambda_2 = 0.2127^{0.544} \). AGW is most active near midnight and passive in dusk and dawn, and seasonal
variations of AGW activity present a summer-maximum and winter-minimum characteristic. When convection and topography above the Qinghai–Tibet Plateau are regarded as the probable main sources of those lidar-observed AGWs, the seasonal variation characteristic is qualitatively interpreted. It is mainly related to the seasonally varied temperature and background winds in troposphere and lower-stratosphere. This work can assist understanding of the climatology of AGWs in mainland China, and benefit accurate parameterization of AGW effects within global models.

Acknowledgments

S. Gong is financially supported by the China Postdoctoral Science Foundation under the Grant no. 20110490609 and the Natural Science Foundation of China under the Grant no. 41264006. And this work is also partially supported by the Natural Science Foundation of Hainan province under the Grant no. 413130 and the Natural Science Foundation of China under the Grant nos. 40905012 and 41174129 (Yang). We acknowledge the use of data from the Chinese Meridian Project.

References