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Communication

# Thermospheric Density Response to the QBO Signal

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**Abstract:** In this study, we focused on the periodic variations of global average thermospheric density, derived from orbital decay measurements of about 5000 space objects from 1967 to 2013, by using the wavelet power spectrum method. The results demonstrated that the thermospheric density showed an ~11-year period, with semiannual and annual variations, while the seasonal variation was usually more significant under high solar activity conditions. Importantly, we investigated the possible link between the thermospheric density and the QBO, with the aid of the Global Average Mass Density Model (GAMDM) and the different density residuals method. The difference between the measured density and the GAMDM empirical model seemingly had QBO signal, but the ratio of them revealed that the QBO signal could not detect in the thermospheric density. Comprehensively, we found that the stratospheric QBO cannot impact on the thermosphere, and more data and numerical modeling are needed for further validation.

**Keywords:** thermospheric density; GAMDM; QBO; solar activity

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## 1. Introduction

The middle–upper atmosphere is a part of the Earth's atmosphere, including the near space and thermosphere. This region is not only important for coupling between the lower atmosphere and space weather, but also scientifically important for lower space objects operations because of the air drag. As we know, the thermospheric density is sensitive to both solar activity and lower atmosphere forcing. For instance, the periodic and explosive solar activity has a remarkable effect on the thermosphere, especially the significant 27-day and 11-year periodic variations [1–3]. However, the response of the middle–upper atmosphere to disturbances in the lower atmosphere has been gradually investigated by using the increased observational data and developed theoretical models. The negative long-term trend of thermospheric density should be attributed to the increased $CO_2$ warm gas in the troposphere [4,5]. In addition, the middle–upper atmosphere may exhibit various long-term oscillations, including the annual oscillation (AO), semi-annual oscillation (SAO), quasi-biennial oscillation (QBO), and solar cycle [4,6,7]. Among these oscillations, the QBO is a special and interesting phenomenon, which alternates easterly and westerly winds mostly in the tropical lower stratosphere, with a period of 22–34 months [8,9]. Obviously, the analyzing of different natural forces on the thermosphere density can increase the cognition of atmospheric coupling mechanisms and improve the model accuracy.

Some studies [8–15] present that the amplitude of the QBO has a maximum value at the equatorial stratosphere (30–40 km). However, the QBO signal in the mesosphere or thermosphere is still uncertain because of the limited observational data and weak signal. In recent years, some researchers have studied the impact of the QBO periodic variations in the upper atmospheric and ionospheric parameters. For instance, Kane [16] and Tang et al. [17] found that the ionospheric foF2 and hmF2 parameters had 26–27 month periodic variations. Using the WACCM model, Yu [12] studied the role of the QBO phenomenon in the stratospheric and mesospheric wind field, and analyzed the effects of gravity wave parameterization, model vertical resolution, and numerical calculation methods. In particular, Liu [18] used the thermospheric density, ENSO, and QBO data from 1967 to 2012 to discuss the potential connection features with each other, with the help of the common MSIS00 empirical model and the wavelet periodic analysis method. The results showed that the thermospheric density has 64-month and 28-month periodic variations superimposing on the 11-year period, and the impact of the QBO signal on the upper atmosphere was more significant around 1972, 1982, and 2002. Moreover, the author also pointed out that both solar activity and QBO may contribute to the 28-month periodic characteristics of the upper atmosphere. Sağır et al. [11] compared the QBO and solar activity effects on the total mass density (TMD) at 90 km altitude obtained from the MSIS00 model. It was observed that the QBO and F10.7 solar flux have an effect on the density, and about 69% of the variations in the TMD could be explained by the F10.7 and QBO. However, the total mass density is derived from the empirical model, so this conclusion is subject to deliberation. Recently, Yue et al. [15] discussed the contribution of the lower atmosphere to the day-to-day variation of the thermospheric density by using the SD-WACCM-X model. They found that the density variation at 300 km is mainly driven by geomagnetic and solar forcing while at 120 km it is exclusively controlled by the lower atmosphere. Koval et al. [13] used a 3D nonlinear mechanistic model of the middle and upper atmosphere to simulate the dynamical effect of the QBO on the planetary waves up to the thermosphere. They found that the stratospheric QBO causes statistically significant changes in the amplitudes of individual wave components up to 25% in the mesosphere–lower thermosphere and 10% changes above 200 km, and this conclusion is especially noticeable under low solar activity. Therefore, it is a critical issue to distinguish the solar and QBO signals among the similar periodic variations in the thermosphere [19,20]. In other words, the QBO signal in the thermospheric density needs further investigation and more solid evidence.

In this study, we use the GAMDM model, a more precise empirical model rather than the MSIS00 model [4], to remove solar and geomagnetic activities, annual/semi-annual variations in the thermosphere. Moreover, we also discuss the impact of ratio or difference between the observed and modeled density on extracting the QBO signal. Finally, we will confirm whether the thermospheric density is affected by the QBO signal or not, and discuss the possible reason.

## 2. Datasets

Figure 1 shows the monthly solar F10.7 and geomagnetic Ap indices, QBO zonal wind velocity, and thermospheric density at 250 km altitude from 1967 to 2013. Obviously, the solar activity has a significant 11-year periodic variation. Moreover, the monthly solar F10.7 can reach over 200 sfu under high solar activity conditions, but it is around 70 sfu during low solar activity periods. Meanwhile, the monthly geomagnetic Ap index is generally below 40, showing a positive correlation with the solar activity. Furthermore, the geomagnetic activity is generally greater during the declining phase of solar activity. For the QBO signal, the zonal wind velocity at 10 hPa varies from −370 to 200 m/s, along with a quasi-biennial periodic variation. In this study, the daily averaged thermopsheric density was obtained from orbital decay measurements of about 5000 space objects by Emmert [4]. The density data have a temporal resolution of 3–6 days, with an estimated daily relative accuracy of ~2%, and estimated absolute accuracy of 10%. Clearly, the thermospheric density has a strong correlation with the solar F10.7 index, and the correlation coefficient is over 0.9. In other words, the solar activity has a critical influence on the thermospheric density. Therefore, in order to study the effect of the QBO, it is necessary to effectively eliminate the influence of solar activity and other factors. In this study, we use the GAMDM model to achieve our purpose, which represents the global average thermospheric density at a fixed altitude as a function of solar EUV irradiance, geomagnetic activity, and the day of the year. Emmert et al. [20] optimized the temporal smoothing and lag of the F10.7 and Kp inputs and incorporated a linear term (modulated by geomagnetic activity) describing the response of mass density to increases in tropospheric $CO_2$. As a result, the correlation coefficient is over 0.99 between the GAMDM and monthly averaged thermopsheric density, and the Root-Mean-Square (RMS) is about 13.4% for the daily value. Clearly, this empirical model is more generally consistent with the observed density than the MSIS00 model [21], for which the RMS is over 15% for the daily thermospheric density at 250 km, and its correlation coefficient is about 0.96 [20]. Obviously, the GAMDM model can effectively remove the influence of seasonal variations, solar and geomagnetic activities, and the reserved residuals between the GAMDM and observed density may be more suitable for discussing the QBO signal than the MSIS00 model.

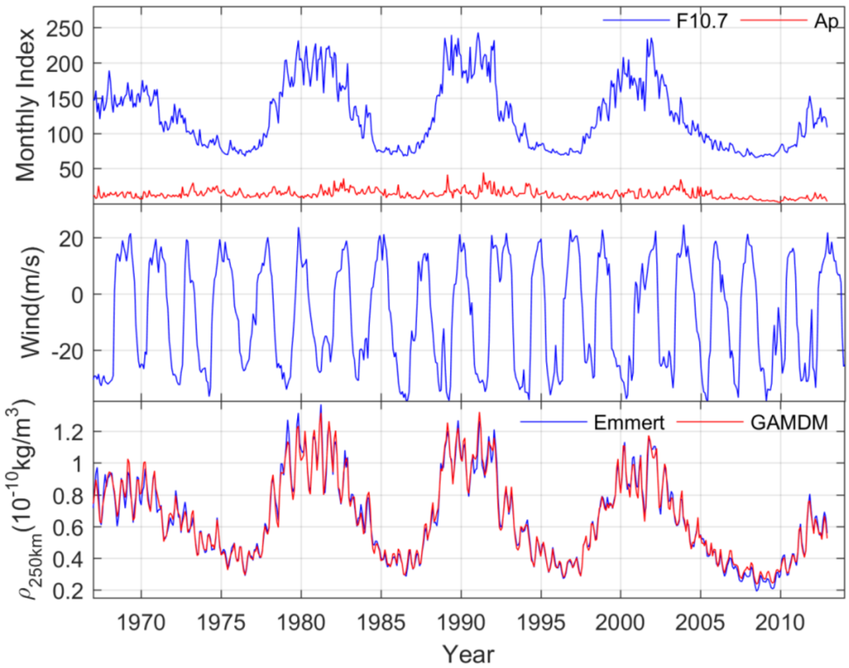


**Figure 1.** (**top**) The solar F10.7 (blue line) and geomagnetic Ap (red line) indices, (**middle**) zonal wind velocity at 10 hPa, and (**bottom**) monthly thermospheric density at 250 km (Emmert, blue line; GAMDM, red line).

## 3. Results and Discussion

### *3.1. Period Analysis*

The wavelet analysis can reveal more accurate information on the periodicities and temporal evolution of the space weather [22]. Figure 2 shows the wavelet power spectrum of the solar F10.7 index and geomagnetic Ap index during 1967–2013. It can be seen that the periodicity of the solar activity is centered around 11 years with a range of 110–140 months throughout all the years. In addition, during high solar activity, the F10.7 also exhibits significant oscillations with a period of 6–12 months, but there is almost no periodicity feature under low solar activity conditions. However, there seems to have been a periodic signal of 25–30 months under high solar activity conditions, especially during 1990–2000, but it is statistically not significant. This may overlap with the QBO signal and lead to some uncertainty in the thermospheric period.

Obviously, the geomagnetic Ap index exhibits a period of about 11 years. There seems to have been a ~6 month period in the geomagnetic activity, which may lead to the seasonal variations of thermospheric density. Similar to the F10.7 index, the geomagnetic Ap index also reveals a period of 20–32 months during high solar activity, but it is statistically not significant.

Emphatically, we investigated the zonal wind speed at 10 hPa by using the wavelet power spectrum decomposition. As seen in Figure 3, there is a very significant oscillation period of 24–32 months throughout the covered time, corresponding to the QBO signal. Particularly, the 11-year periodic variation, existing in the solar and geomagnetic activities, does not appear in the zonal wind. In other words, this indicates that the QBO phenomenon should be not modulated or influenced by the long-term variations of solar and geomagnetic activity.

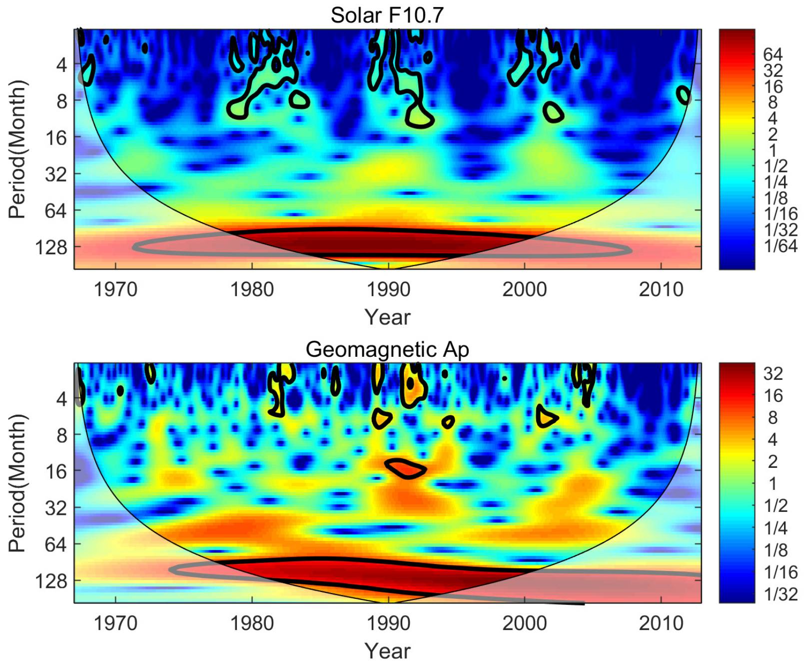


**Figure 2.** Period of solar F10.7 index (**top**) and geomagnetic Ap index (**bottom**) between 1967 and 2013.

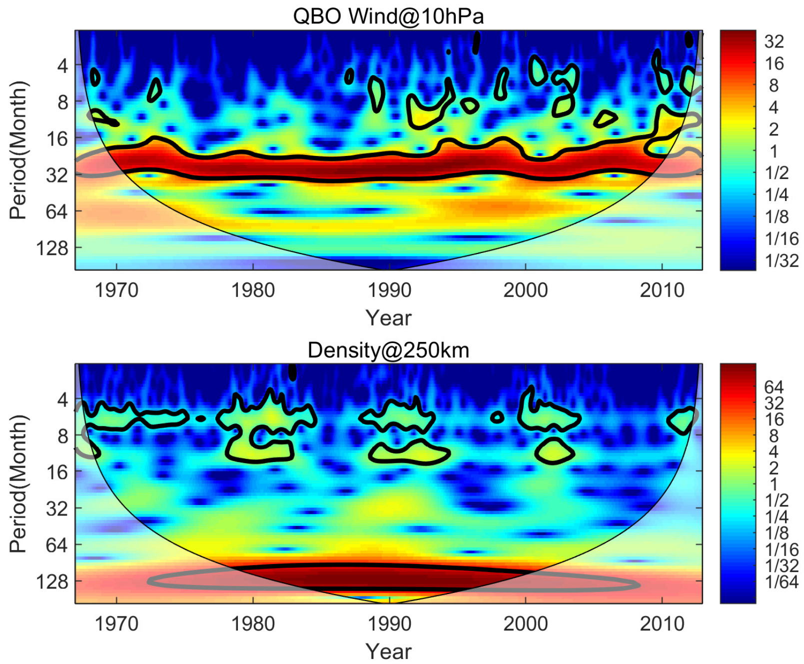


**Figure 3.** Same as Figure 2, but for the zonal wind speed at 10 hPa (**top**) and the thermospheric density at 250 km (**bottom**).

Many studies have shown that the thermospheric density exhibits semi-annual, annual, and solar cycle variations [1,2]. Clearly, Figure 3 shows that the density at 250 km has an ~11-year period during 1967–2013. This is mainly due to the effect of solar activity, which can account for over 90% of the variance in the thermospheric density [2]. In addition, the density also exhibits significant semi-annual and annual variations under high solar activity conditions, but the significance is weak during lower solar activity. Recent investigations suggest that the annual and semiannual variations in the upper atmosphere are related to both the solar activity and lower atmosphere [2,15,22]. Furthermore, during high solar activity, the thermospheric density also exhibits a 20–30 months periodic signal, but it is statistically not significant.

To further investigate how coherently these oscillations vary with each other, we used the cross-wavelet method, which combines cross-spectral analysis with wavelet transformation, to analyze the variations of thermospheric density and solar activity. As seen in Figure 4, the density varied with the 11 years solar cycle. Clearly, the arrows persist around 0°, meaning that there is almost no time lag with each other for a periodicity of ~128 months. In other periods, the black arrows are disorganized, meaning that the semiannual and annual variations of thermospheric density should be not directly affected by the solar activity. Moreover, the variations of thermospheric density at higher altitude are similar with the results in Figures 3 and 4.

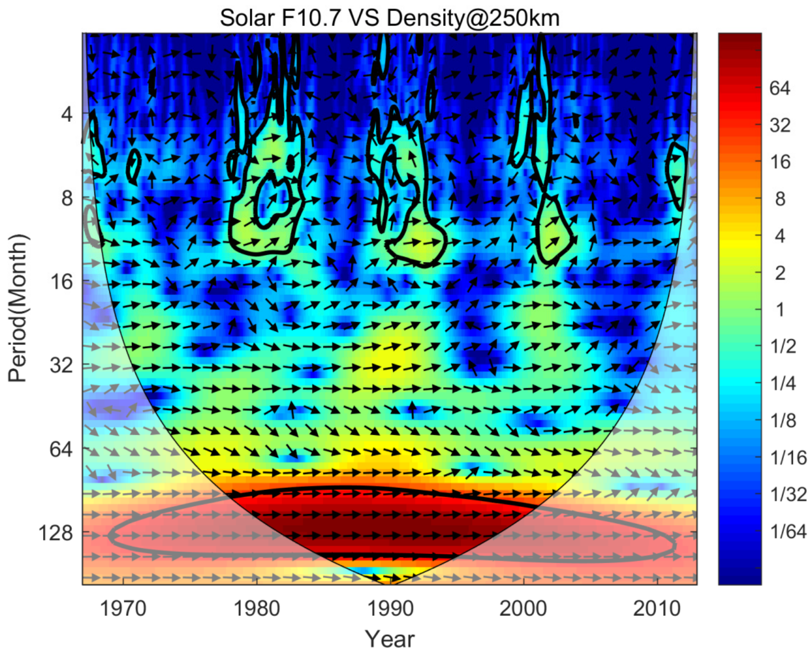


**Figure 4.** Cross-wavelet analysis between the monthly solar F10.7 index and thermospheric density at 250 km. The arrows indicate the relative phase relationship between the solar activity and thermospheric density series (right in-phase; left anti-phase).

### *3.2. QBO Signal Diagnosis*

In order to investigate the QBO signal in the upper atmosphere, we used the wavelet method based on the residuals, including the ratio or difference between the observed density and the GAMDM model. Figure 5 presents the period result of the density ratio at 250 km. Clearly, many short-term scale variations exist, but the semi-annual, annual, and solar cycle periods are absent. In particular, the QBO signal is not observed under high and low solar activities, meaning that the upper atmosphere density should be not affected by the QBO signal. On the other hand, Figure 5 also confirms that the GAMDM model can better reproduce the thermospheric density than other empirical models.

Moreover, Figure 5 also presents the wavelet power spectrum analysis results of the density difference at 250 km. As seen in this figure, the difference data show periods of 25–32 months around 1990, seemingly corresponding to the QBO period. Obviously, this conclusion is consistent with the results of Liu [18], while the signal intensity in this study is much weaker. Namely, a reasonable existence of the QBO signal in the thermospheric density requires a highly accurate model, which can remove the seasonal variations, solar, and geomagnetic activities as much as possible.

Comparing the different results in Figure 5, the density ratio does not show any QBO signal period, while the density difference under high solar activity still has some semi-annual and annual oscillations, accompanied by the QBO period. In other words, the analysis results are directly affected by the empirical model and residuals. However, we found that the QBO signal could not detect in the thermospheric density.

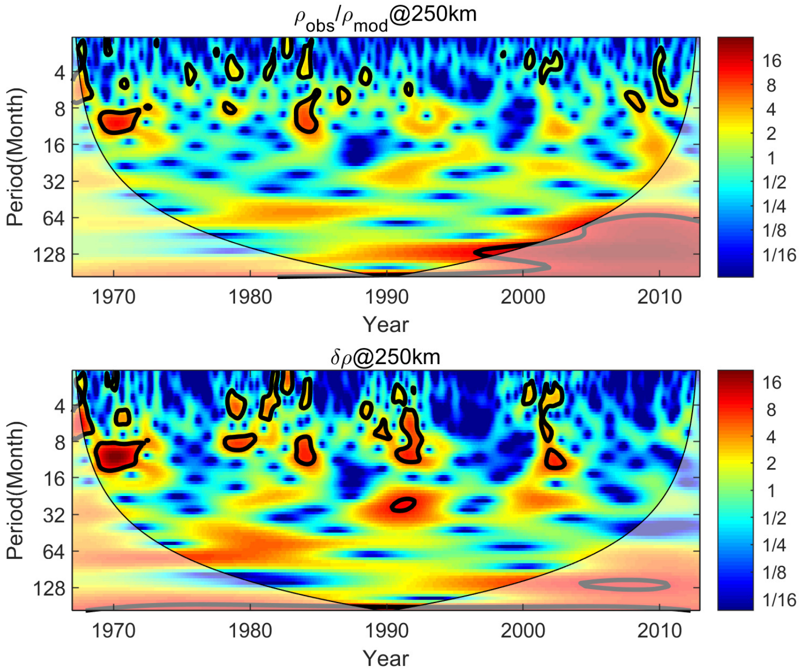


**Figure 5.** Wavelet power spectrum of the density ratio (**top**) and difference (**bottom**) at 250 km altitude.

Earlier, Liu [18] pointed out that there has been strong coherence between the density residual and the solar activity, and this makes it difficult to tell the direct link between the density and the QBO. In order to investigate this issue, the GAMDM model, a more precise empirical model than the previous, has been used to obtain the residuals between the observed and modeled thermospheric density. As a result, the conclusion of the issue is sensitive to the empirical model and analysis method. As we know, the MSIS00 empirical can capture most solar and seasonal driven variabilities in the thermospheric density, but its error still has a strong coherence with the solar activity [23–25]. Namely, the MSIS00 model can not only drastically remove the effect of solar activity, but also brings the signal of solar activity into the residuals. However, the GAMDM can represent the semi-annual and annual variations, solar and geomagnetic activities better than the MSIS00 model [4], and the conclusion found by using the GAMDM model is more believable.

## 4. Conclusions

In this study, we firstly discuss the periodic variations of solar activity, QBO, and monthly averaged thermospheric density by using the wavelet power spectrum method. Clearly, the QBO in the tropical lower stratosphere shows a very significant oscillation period of 24–32 months, while the solar and geomagnetic activities present a period of ~11 years. In addition, the thermospheric density has semiannual, annual, and 11-year variations, and the role of solar activity is dominant. In addition, the semiannual and annual variations of thermospehric density are usually more significant during high solar activity levels than the lower solar activity conditions. However, the thermospheric intra-annual variation is still not fully explained, but several mechanisms have been proposed; the details can be found in Qian et al. [1] and Emmert [2].

As for the results of the ratio and difference density, we found that the ratio between the GAMDM and measured density basically remains around one, but the density difference can reach up to five times between low and high solar activity conditions. Naturally, the periodic signals of the latter are more intense than the prior, and this is consistent with the results in Figure 5. In other words, the ratio and difference between the observed density and different empirical models directly leads to different results. In general, we found that the QBO signal could not detect in the thermospheric density. However, more data and numerical modeling are needed for further investigating this issue.

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**Data Availability Statement:** The QBO data is available from https://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/qbo.dat, accessed on 15 August 2023; Solar and geomagnetic indices data is available from http://celestrak.org/SpaceData/SW-All.txt, accessed on 15 August 2023; Global thermospheric density data is available from reference [4].

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