Latitudinal- and Height- Dependent Long-Term Climatology of Propagating Quasi-16-day in the Troposphere and Stratosphere

Wentao Tang
Wuhan University  https://orcid.org/0000-0002-7831-9447

Shao Dong ZHANG (✉ zsd@whu.edu.cn)
Wuhan University

Chun Ming HUANG
Wuhan University

Kai Ming HUANG
Wuhan University

Yun Gong
Wuhan University

Quan Gan
University of Colorado at Boulder: University of Colorado Boulder

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Latitudinal- and height-dependent long-term climatology of propagating quasi-16-day in the troposphere and stratosphere

Wen Tao TANG\textsuperscript{1,2,3} Shao Dong ZHANG*\textsuperscript{1,2,3} Chun Ming HUANG\textsuperscript{1,2,3} Kai Ming HUANG\textsuperscript{1,2,3} Yun GONG\textsuperscript{1,2,3} Quan GAN\textsuperscript{4}

\textsuperscript{1}School of Electronic Information, Wuhan University, Wuhan, China
\textsuperscript{2} Key Laboratory of Geospace Environment and Geodesy, Ministry of Education, Wuhan, China
\textsuperscript{3} State Key Laboratory of Information Engineering in Surveying, Mapping and Remote Sensing, Wuhan University, Wuhan, China
\textsuperscript{4} Laboratory for Atmospheric and Space Physics, University of Colorado Boulder, Boulder, US

Corresponding author: Zhang Shaodong
Email Address: zsd@whu.edu.cn

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**Abstract.** The global amplitude of the westward propagating quasi-16-day wave (16DW) with wavenumber 1 (Q16W1), the strongest component of 16DW, is derived from European Centre for Medium-Range Weather Forecasts ERA-Interim reanalysis temperature data set from February 1979 to January 2018. The strong climatological mean amplitudes of the Q16W1 appear in winter in the upper stratosphere at high latitudes in both hemispheres, and the wave amplitude is stronger in the Northern Hemisphere (NH) than in the Southern Hemisphere (SH). Multivariate linear regression is applied to calculate responses of the Q16W1 amplitude to QBO (quasi-biennial oscillation), ENSO (El Niño-Southern Oscillation), solar activity and the linear trend of the Q16W1 amplitude. The QBO signatures of the Q16W1 amplitude are mainly located in the stratosphere. In addition to the significant QBO response in the low latitude and low stratosphere, the largest QBO response occurs in the region with the strongest Q16W1 climatology amplitude. There no significant responses to ENSO and solar activity are observed. The linear trend of the monthly mean Q16W1 amplitude is generally positive, especially in the mid-high latitudes of the stratosphere. The trend is asymmetric about the equator and significantly stronger in the NH than in the SH. The trend shows obvious seasonal changes, that is, stronger in winter, weaker in spring and autumn. Further investigation suggests that the background and local instability trends contribute most of the increasing trend of the Q16W1 amplitude. In winter in both hemispheres, the weakening trend of eastward zonal wind provide more favourable background wind for Q16W1 upward propagation, in autumn and winter in the NH and in spring, autumn and winter in the SH, the increasing trend of local instability may enhance the wave excitation.
Introduction

Planetary waves (PWs), one of the main components of atmospheric waves, play a key role in transporting energy, momentum and chemical species among different atmospheric regions and are thus important in determining local and global atmospheric climatology and transient structures (Tsuda et al. 1994). PWs are global-scale oscillations predominantly generated by orography and diabatic heating caused by the distribution of land and sea in the troposphere (quasi-stationary PWs) or by irregular thermal or mechanical forcing in the lower atmosphere and/or by instabilities in the middle atmosphere (travelling PWs) with periods near 2, 5, 10 and 16 days (Andrews et al. 1987; Huang et al. 2013). Under certain conditions, PWs can propagate from the troposphere into the mesosphere and lower thermosphere (MLT), and wavenumber 1 and wavenumber 2 components are usually the predominant components (Charney and Drazin 1961).

The quasi 16-day wave (16DW) is one of the PWs and was identified as the second symmetric westward propagating Rossby mode with zonal wavenumber 1 (Salby 1981a, b). In the realistic atmosphere, due to Doppler shifting by the non-zero background flow, the period of 16DWs is from 12 to 20 days (Amitava et al. 2016). The 16DWs have been extensively reported over the past decades from ground-based measurements (Mitchell et al. 1999; Das et al. 2010), satellite-borne measurements (McDonald et al. 2011; Alexander and Shepherd 2010) and reanalyses data sets (Vineeth et al. 2010). Combinations of ground-based and satellite-based analyses are also used to reveal the characteristics of 16DWs (Meek and Manson 2009). These findings show that 16DWs are prominent in the MLT from October to April. However, the exploration of 16DWs is relatively insufficient in the lower atmosphere,
most likely due to the lack of high-quality data sets, i.e., data with a long duration, good
continuity, and high resolution. Since local observations cannot provide a global distribution,
and satellite observations with long-term duration usually are rare. Hence, global data with a
long duration are necessary for a further study.

Long-term variation is an important topic in atmospheric science. Previous
observational and modelling studies have shown some long-term trends in atmospheric
parameters, such as temperature (She et al. 2015) and wind fields (Kozubek et al. 2017).
These studies revealed some important changes in the atmosphere from the lower atmosphere
to the mesosphere. Hu and Tung (2002) determined that there were no obvious stratospheric
wavenumber 1 and wavenumber 2 PW activity trends in early and midwinter from November
to January during 1950–2000 at 200, 100, 50 and 20 hPa along the 60°N latitude circle.
However, a significant negative PW activity trend from January to February 1979–2000 at
100 hPa in the NH mid-high latitudes was revealed (Randel et al. 2002). Hu et al. (2019)
suggested that the trend for stratospheric wave intensity from 200 hPa to 10 hPa at NH
mid-high latitudes was strengthening during 1979–2000 and weakening during 2001-2015.
However, most of the studies are related to PW, research on travelling PW activity trends,
especially the Q16W1, is rare. Hence, the global trend in Q16W1 amplitude is far from being
fully understood.

The background wind can significantly affect the excitation, propagation and
dissipation of PWs. On the other hand, PWs will impact the background wind by depositing
energy and momentum into the background atmosphere through various dissipation processes.
Therefore, PWs might be related to the background wind at different time scales. Most
previous studies on the 16DW-mean flow interactions have focused on the dynamic process at
the time scale of the wave period (Huang et al. 2013), seasonal scale (Huang et al. 2017) and
intranasal variabilities (Espy et al. 1997; Day et al. 2011) rather than the climate scale. Thus,
to further understand the activity trend of 16DWs, we need more studies on 16DWs and their
links with the background wind at the climate time scale.

For the purpose of investigating the global-scale and long-term characteristics of
16DWs in the stratosphere and below, the ERA-Interim reanalysis datasets were applied in
our study. The responses to the quasi-biannual oscillation (QBO), El Niño-Southern
Oscillation (ENSO) and 11-year solar cycle (SC) and the linear trend of the strongest wave
mode of 16DW in the troposphere and the stratosphere during February 1979–January 2018
were examined. In addition, we attempt to find a possible link between the wave and
background wind and instability at the climate time scale. To this end, the rest of paper is
organized as follows. In the following section, we introduce the adopted data, the dominant
modes of the 16DW and the calculation method. Subsequently, the global climatology of
wave amplitude is presented. In sections 4 and 5, we present the latitude- and
height-dependent responses of the 16DW to the QBO and the linear trend of the strongest
wave mode of 16DW, respectively. In the last section, we provide a brief summary of our
analyses.

2. Data description and analysis approach

The global 6-hourly temperature and zonal wind data from the ERA-Interim dataset
were downloaded from the European Centre for Medium-Range Weather Forecasts (ECMWF)
for the period from February 1979 to January 2018 (39 years in total) at 37 pressure levels
from 1000 hPa to 1 hPa and utilized in this study (Kallberg et al., 2004). The ERA-Interim uses cycle 31r2 of the ECMWF’s Integrated Forecast System, which was introduced operationally in September 2006, with a reduced Gaussian grid with approximately 79 km spacing from surface and other grid-point fields and a 60-level vertical resolution extending to 0.1 hPa. The vertical resolution of the temperature product decreases with altitude, with a range of 0.1–1 km in the troposphere, which is reduced to 1–4.5 km in the stratosphere. For each day, the temperatures are interpolated at four UTCs with a 6-hour interval: 0000 UTC, 0600 UTC, 1200 UTC and 1800 UTC. We chose the products on a grid of 72×143 points with 2.5° longitude and 2.5° latitude resolution.

At each pressure level, we first calculated the background temperature by a linear fitting within a 60-day sliding window with a 1-day shift interval. Then, the temperature disturbance could be obtained by subtracting the background temperature and zonal mean temperature from the raw data. To demonstrate the dominant modes of 16DWs, we calculated the frequency-wavenumber spectra by performing a two-dimensional fast Fourier transform on the temperature disturbance in each sliding 60-day window at each height (Huang et al. 2013; Gong et al. 2019). Furthermore, at each height, all spectra at different days were averaged to determine the temporal averaged spectra. Finally, a mean spectrum was obtained by averaging the temporal averaged spectra at all pressure levels. The mean frequency-wavenumber spectrum averaged from 38,475,745 spectra is shown in Figure 1, which shows that the most prominent spectral peak has a period of 15 days and a wavenumber of W1, with the largest amplitude of 0.46 K. The secondary wave mode with a period of 20 days and a wavenumber of E1 can also be recognized. Here, we focus only on the strongest
PW, i.e., 16DW with wavenumber W1, which is named as Q16W1 for simplicity.

To extract the monthly averaged amplitudes of Q16W1, in each sliding 60-day window to determine the amplitude at the centre day of the window (Wu et al. 1995), we employed a harmonic fitting to the temperature perturbations at each latitude bin and each pressure level, according to Equation (1).

\[ T' = B_j \cos\left[2\pi\left(t_i/p_j - s\lambda_i\right)\right] + C_j \sin\left[2\pi\left(t_i/p_j - s\lambda_i\right)\right] \]  

(1)

\( T' \) is the time series of the temperature perturbation; \( p_j, t_i, \lambda_i \) are, respectively, the jth wave period, ith time, and longitude; and \( s = 1 \) is the wavenumber. In each window, \( p_j \) varies from 12 to 20 days with an interval of 0.25 days, which accord to 6-hourly data interval in ECMWF. \( B_j \) and \( C_j \) are the two coefficients to be fitted for the jth period, and then the wave amplitude \( T_j \) can be specified by \( T_j = \sqrt{B_j^2 + C_j^2} \). In each 60-day window, we can specify 33 wave amplitudes corresponding to 33 periods \( p_j \) in total, among which, the maximum amplitude and the corresponding period are regarded as the Q16W1 amplitude and period, at the centre day of the 60-day window, respectively. Finally, all Q16W1 amplitudes at different centre days within each month were averaged to derive the monthly mean amplitude of the Q16W1 amplitude, i.e., \( T_A \).

Multivariate linear regression (MLR) analysis was extensively utilized to isolate specific signals for zonal-mean anomalies in temperature, zonal wind, ozone, and gravity wave energy from the simulation and observation data (Gan et al., 2017; Weber et al., 2018). PWs could be modulated by QBO, ENSO and SC, which display as interannual variation in PWs. There are also seasonal changes in PWs, which are mainly reflected in annual, semi-annual, tri-annual and quarter-annual oscillations. Therefore, when performing MLR
analysis on the amplitude of the Q16W1, the influences from all these factors should be considered. So, we chose a particular set of indices for the regression.

Before implementing MLR, some inflection point analysis based on the piecewise fittings of the Q16W1 amplitude had been performed during the 39-year period, so confirming that the linear trend fit over entire time range is appropriate. In this study, MLR analysis was performed on the time series of the monthly mean amplitude of the Q16W1, i.e., $T_A(t)$. The fitting equation is written as:

$$T_A(t) = A + B \times t + C \times \text{Solar}(t) + D \times \text{ENSO}(t) + E \times QBO1(t) + F \times QBO2(t) + G_1 \times \cos(\omega t) + G_2 \times \sin(\omega t) + H_1 \times \cos(2\omega t) + H_2 \times \sin(2\omega t) + I_1 \times \cos(3\omega t) + I_2 \times \sin(3\omega t) + J_1 \times \cos(4\omega t) + J_2 \times \sin(4\omega t)$$

(2)

where $t$ is time in months (478 months over 39 years), $\omega = 2\pi/12 \text{ months}$, and $B$ is the coefficient of the linear trend. The third to the fourteenth terms on the right side of Equation (2) are the linear correlations between the $T_A(t)$ and the SC, ENSO, two QBO components, annual oscillation (AO), semi-annual oscillation (SAO), tri-annual oscillation (TAO) and fourth-annual oscillation (FAO), respectively, which are thought to be the dominant contributors to the variations in Q16W1. Among them, the third to the sixth terms denote the inter-annual variations in Q16W1; the seventh to the fourteenth terms are the intra-annual variations in Q16W1. $G = \sqrt{G_1^2 + G_2^2}$, $H = \sqrt{H_1^2 + H_2^2}$, $I = \sqrt{I_1^2 + I_2^2}$ and $J = \sqrt{J_1^2 + J_2^2}$ represent the annual, semi-annual, tri-annual and fourth-annual oscillation components, respectively. Here, the indices of $F_{10.7cm}$ (unit: sfu, 1sfu = $10^{-22} W m^{-2} Hz^{-1}$) and multivariate ENSO index (MEI) (downloaded from http://www.esrl.noaa.gov/psd/), shown in
Figure 2a and 2b, respectively, are used as proxies of the SC and ENSO activities. The time series QBO1 and QBO2, shown in Figure 2c are the two QBO components with a quarter-cycle phase difference (Gan et al. 2017). These two QBO time series correspond to the first two components of the empirical orthogonal functions (EOFs) extracted from the equatorial stratospheric zonal winds at 5 different levels (70, 50, 30, 20, and 10 hPa) measured by radiosonde over Singapore (downloaded from http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/index.html) (Wallace et al. 1993).

The delay autocorrelation coefficients of all independent variables, including SC, ENSO, QBO1, QBO2, AO, SAO, TAO and FAO are calculated and all close to zero. The delay cross-correlation coefficients between all variables are also obtained, except that the correlation between the SOLAR and the ENSO index is 0.27, all others are lower than 0.20. These small correlations indicate that they are all independent. Gan et al. [2017] have also proved that multiple linear regression with these independent variables is a commonly used credible algorithm (Gan et al. 2017). And, in the MLR calculation, the confidence levels of the regression coefficients are estimated according to the variance-covariance matrix and Student’s t-test (Kutner et al. 2004).

3. Global Q16W1 Climatology

Figure 3 demonstrates the latitude-pressure distribution of the monthly mean Q16W1 amplitude averaged over 39 years. It is notable that the latitude-pressure distribution exhibits a well-defined hemispheric symmetry for the similarity in increase with altitude. More specifically, the maximal amplitudes occur at 2 hPa in both hemispheres, due to the decreasing atmospheric mass density decreases with height. However, markable differences
also clearly appear in the latitudinal variations. Wave amplitudes in the NH are larger than in
the SH, with the maxim of 1.98 K (at 60°N, 2 hPa) for NH and 1.32 K (at 45°S, 2 hPa) for SH,
respectively, which are quantitatively consistent with the results in Gong et al. (2019).

The monthly zonal-mean Q16W1 amplitudes at six latitudes, representing high,
middle, and low latitudes in two hemispheres, are shown in Figure 4. At 65°N/S, the AO of
the Q16W1 amplitude is dominant in the whole stratosphere (100–1 hPa), with peak
amplitude appearing in winter months, and the amplitude is larger in the NH than in the SH.
For instance, the maximum amplitude in the NH is 7.8 K in December 2000 at 1 hPa, which is
much larger than the maximum of 4.3 K in June 2002 at 3 hPa in the SH. At 35° N/S,
significant AO of the Q16W1 amplitude is concentrated only in the height of 10–1 hPa, with
peak amplitude also appearing in winter months. At 10°N/S, the amplitudes are smaller than
those at middle and high latitudes, with maximum peak smaller than 1.2 K, and the annual
variation of wave amplitudes still exists but is not as clear as those in the middle and high
latitudes. Besides the annual variation, the wave amplitude also displays SAO above 5 hPa
and QBO above 20 hPa.

4. Response to the quasi-biannual oscillation

The latitude-pressure patterns of the monthly mean Q16W1 amplitude response to the
QBO1 and QBO2 components, those regression coefficients E and F are calculated by Eq.(2),
are shown in Figure 5. As expected, significant positive response to QBO1 at low latitudes
(30°N–30°S) from 100 hPa to 50 hPa can be observed, and this response is almost
symmetrical about the equator. Besides the low latitude response, strong response can also be
clearly seen in the higher stratosphere at the middle and high latitudes. In the NH, the strong
positive and negative response to QBO1 occur at 40°N–75°N, 10–1 hPa and 50°N–85°N, 100–30 hPa, with a positive maximum of 0.12 K at 60°N, 3 hPa and a negative maximum magnitude of ~0.06 K at 72.5°N, 50 hPa, respectively. Lu et al. (2020) explained the high latitude response to the context of Holton-Tan effect, that is more planetary-scale Rossby waves of zonal wave-number 1 can propagate upward to higher stratosphere via high-latitude waveguide during QBO’s easterly phase in winters and successive Rossby wave breaking events occur in the middle stratosphere in the middle-high latitudes during QBO’s westerly phase in winters. In the SH, the response to the QBO1 illustrates a different pattern. The positive value region is mainly is concentrated in mid-latitudes, that is in 25°–55°S, 20–1 hPa, with a positive peak of ~0.11 K at 35°S, 7 hPa.

The response to the QBO2 shown in Figure 5(b) illustrates a different pattern. The response to the QBO2 is mainly negative, which is attributed to the phase difference between the QBO1 and QBO2 wind fields. At low latitudes, the response has weak negative largest values of ~0.04 K/m/s at 30°N–30°S from 50 hPa to 30 hPa and are nearly symmetrical around the equator. Similar to the response to the QBO1, the response to the QBO2 has the strongest value at higher latitudes and heights but with a negative peak of ~0.16 K/m/s at 62.5°N at 2 hPa. Moreover, the stronger negative response at high latitudes appears only in the NH, exhibiting significant hemispheric asymmetry, which is obviously different from the response to the QBO1.

Our multiple regression analysis results don’t show statistically significant responses of Q16W1 amplitude to the ENSO and solar cycle.

5. Long-term trend
Figure 6 displays the long-term trend in the monthly mean Q16W1 amplitude in 39 years as a function of pressure and latitude. The spatial regions of the significant positive trend regions are almost consistent with those of the strong Q16W1 climatological amplitude as highlighted in Figure 3, which indicates that the wave activities in the mid-upper stratosphere are generally strengthening. It is obvious that the prominent positive trend appears in 20–1 hPa in the NH and 7–1 hPa in the SH, respectively, and it is asymmetric about the equator, with a larger positive trend in the NH. The positive trend increases with height from 30 hPa to 3 hPa and then decreases with height in the NH. Moreover, with increasing latitude in both hemispheres, the positive trend increases poleward, reaches a maximum in the mid-high latitudes and then decreases with latitude. In the NH, the trend has a peak of 0.21 K/decade at 3 hPa around the latitude of 67.5°N. In the SH, the positive peak of 0.10 K/decade occurs at 3–2 hPa around the latitude of 60°S. A negative trend occurs below 300 hPa, especially at high latitudes in the NH, with a peak negative trend of −0.08 K/decade at 950 hPa around the latitude of 75°N.

Some previous studies have revealed the significant seasonal variation in Q16W1 (Williams and Avery 1992; Luo et al. 2002b; Hibbins et al. 2009; Day and Mitchell 2010). Here, the Q16W1 amplitude trend in four seasons are investigated. We take December, January, and February to represent the NH winter and SH summer, and March to May, June to August, and September to November to represent the NH (SH) spring (autumn), summer (winter), and autumn (spring), respectively. In each season in each year, there are three values in the monthly mean Q16W1 amplitude. Thus, in the calculation of the trend in each season, a time series of wave amplitudes of 117 months in 39 years are obtained. Similar processes
were performed on the indices of $F_{10.7\text{cm}}$, the multivariate ENSO index (MEI) and the time
series of QBO, et al. These time series were substituted into Equation (2) to calculate the
trend in each season. Then, in each season, all month dependent trends were averaged to
specify the trend in this season. From Figure 7, it can be seen that the positive trends are in
40°N–85°N, 20–1 hPa and 70°S–80°S, 3–2 hPa in spring, 50°N–82.5°N, 3–1 hPa and 20°S–
62.5°S, 5–1 hPa in autumn, and 30°N–87.5°N, 30–1 hPa and 20°S–85°S, 7–1 hPa in winter.
The negative trends are located near the ground at high latitudes of spring and winter in the
NH. The strong enhancement trend is generally consistent with the latitude, height, and
seasonal changes of the climatological mean peak amplitude, and generally appears in the
mid-high latitudes and high stratosphere in winter. The strongest trend appears in the NH
winter (shown in Figure 7d), with a peak of 0.54 K/decade at 3 hPa around the latitude of
67.5°N, which is significantly larger than trend in the SH winter (shown in Figure 7b), in
which the positive peak of 0.19 K/decade occurs at 3 hPa around the latitude of 50°S,
indicating the obvious hemispheric asymmetry in Q16W1 amplitude trend.

From above analyses, it can be significantly seen that the Q16W1 climatological
amplitudes and trends appear in middle and high latitudes. Dickinson (1968) proposed a polar
waveguide theory, which predicted that PWs will propagate from the troposphere to the
stratosphere at high latitudes. Mastuno (1970) obtained similar results using the
quasi-geostrophic model. Luo et al. (2002a; 2002b) confirmed that the westward-traveling
16-day wave with a small phase velocity can propagate upward through the winter polar night
jet to reach the MLT region only in an eastward background flow of moderate speed which is
present in the winter hemisphere. The zonal wind was confirmed by Smith (1983) to be a key
factor for the vertical propagation and dissipation of PWs. For simplification, a PW can
propagate through a region only when the PW zonal phase velocity $c$ and background zonal
wind $u_o$ satisfy the following conditions (McDonald et al. 2011):

$$0 < u_o - c < \frac{\beta}{(k^2 + l^2) + \frac{f_0^2}{4H^2N^2}} \equiv U_c$$

where $k = \frac{2\pi}{\lambda_x}$, $l = \frac{2\pi}{\lambda_y}$ is the zonal and meridional wavenumber of the Q16W1, in
which $\lambda_x$ and $\lambda_y$ are the zonal and meridional wavelengths of the Q16W1, respectively. $f_0$
and $\beta$ represent the Coriolis parameter and Rossby parameter, respectively. The zonal phase
velocity of the Q16W1 $c = \frac{\omega}{k}$, where $\omega = \frac{2\pi}{T}$ is the frequency of the Q16W1. The
positive (negative) values of $u_o$ and $c$ indicate the eastward (westward) direction. $U_c$ is
the critical Rossby velocity determined by the PW. Equation (3) shows that weak eastward
zonal wind is favourable for Q16W1 propagation, otherwise, energy is trapped/reflected in
regions where the zonal winds are westward or strongly eastward. Therefore, the zonal mean
wind plays an important role in the PW propagation and its long-term variation may be related
to the long-term trend of Q16W1 amplitude.

Figure 8 displays the trends and the climatological distributions of monthly mean
zonal wind in four seasons. Combined with Figure 7, it is shown that the amplitude of the
Q16W1 is usually strong in regions where the background zonal wind is weak eastward wind
(Day et al. 2011). The zonal wind trend has significant positive values in the height range
from 1000 hPa to 7 hPa in mid-high latitudes of the SH summer. More interestingly, the zonal
wind trend has significant negative values in the height range from 1000 hPa to 50 hPa at high
latitudes in the NH winter, with a negative peak of -1.4 m/s/decade at 50 hPa around the
latitude of 67.5°N. Another negative trend of the zonal wind appears in 30°S–50°S, at 30–20
hPa. It should be noted that these negative trend regions correspond to the climatological eastward wind region, implying the gradual weakening of the eastward wind $u_o$. This wakened eastward wind will lead to a more favourable background for the upward-propagation of the Q16W1, which in turn, may cause an increasing trend of wave amplitude. Obviously, the negative zonal wind trend could contribute to the positive trend of the Q16W1 amplitude.

It is known that the mean flow barotropic and baroclinic instabilities are important in local excitation for PWs (Hartmann 1983; Huang et al. 2021; William and Leslie 1991). Then, we will investigate possible influences of the local excitation mechanism on the trend of the Q16W1 amplitude by analysing the mean flow instability. A necessary condition for instability of the mean flow is that the quasi-geostrophic potential vorticity gradient ($\bar{q}_\phi$) must change sign somewhere in the flow domain (Andrews et al. 1987). Then, the overturning of the $\bar{q}_\phi$ can be regarded as the local instability, which means that relatively small $\bar{q}_\phi$ implies high probability of the overturning of $\bar{q}_\phi$, as well as the local instability (Lu et al. 2020). $\bar{q}_\phi$ can be expressed as:

$$\bar{q}_\phi = 2\Omega \cos \Phi - \left[ \left( \frac{\overline{u} \cos \phi}{a \cos \phi} \right)_\phi - \frac{a}{\rho_o} \frac{f^2 u_z}{N^2} \right]$$  (4)

Where overbar, prime and subscript denote respectively zonal average and derivative: $u$, $\rho_o$, $a$, $\Omega$, $\Phi$, and $f$ represent the zonal wind, background density, Earth radius, angular velocity of the Earth, latitude and Coriolis parameter, respectively; $z$ is the altitude above the Earth’s surface; $N$ is the buoyancy frequency, which is specified by calculating from $N^2 = \frac{g}{T} \left( \frac{\partial \bar{T}}{\partial z} + \frac{\rho_o \bar{T}}{c_p} \right)$, where $g$, $\bar{T}$, and $c_p$ are the height-dependent gravitational acceleration,
background temperature, and specific heat at constant pressure, respectively.

Considering validity limitations of the quasi-geostrophic approximation near the equator and surface, and numerical singularities near the poles, the climatological distributions and the negative trends of monthly mean $\bar{q}_\phi$ values in two latitudes zones, those are 15°S–85°S and 15°N–85°N, and altitude above 500 hPa are shown in Figure 9. In the NH, it is intriguing to note that in all seasons, the monthly mean $\bar{q}_\phi$ values are mostly positive in almost all regions except at about 300 hPa of the low and middle latitudes and in the high latitudes of summer. Large values of $\bar{q}_\phi$ are found in the troposphere. We concentrate on the regions with relatively small $\bar{q}_\phi$ and negative $\bar{q}_\phi$ trend, where increasing instability trend is most likely to occur. These regions are located in 70°N–80°N from 5 hPa to 2 hPa in summer, 75°N–85°N from 200 hPa to 100 hPa in autumn and 55°N–75°N from 250 hPa to 70 hPa. Combined with the wave trend in the NH in Figure 7 and the probability of wave upward propagation, the increased possibility of instability could partly explain the Q16W1 amplitude trends in autumn and winter.

Similar to that in the NH, the climatological $\bar{q}_\phi$ in the SH in Figure 9 is also mainly positive, interestingly, it has significant large positive value in the middle and high latitudes of the stratosphere in both spring and winter and negative value at high latitudes in all seasons except autumn. The regions located in 57.5°S–62.5°S at 2 hPa in spring, high latitudes from 200 hPa to 100 hPa in autumn and 30°S–40°S at 50–20 hPa in winter, where the $\bar{q}_\phi$ represent negative trends, indicating an enhancement of instability. Generally, the increasing trend of instability located in 50°N–82.5°N from 3 hPa to 1 hPa in autumn and 30°N–87.5°N from 30 hPa to 1 hPa in winter in the NH and in 70°S–80°S, from 3 hPa to 2 hPa in spring,
20°S–62.5°S from 5 hPa to 1 hPa in autumn and 20°S–85°S from 7 hPa to 1 hPa in winter in the SH, may contribute to the increasing trend of Q16W1 amplitude.

6. Summary

The Q16W1 was shown to be the dominant mode of 16DW globally from the surface to the stratopause by analysing the ERA–Interim reanalysis datasets from February 1979 to January 2018. The response of the monthly mean Q16W1 amplitude to QBO, ENSO and solar activity and their linear trend were investigated by multiple regression analysis. Possible mechanisms of inducing the trend of the Q16W1 in NH winter are discussed. The primary results are summarized as follows.

For the 39 years climatological mean value, strong Q16W1 occurs in the upper stratosphere at high latitudes in both hemispheres, and the wave amplitude is stronger in the NH than in the SH. The Q16W1 present obvious seasonal variation, that is, strong in winter and weak in summer. This seasonal variation is more prominent in the middle and high latitudes. The Q16W1 in the stratosphere exhibits AO, especially in high latitudes, where the AO is evident in the whole stratosphere.

The QBO1 signatures of the Q16W1 amplitude are mainly positive and more pronounced in the stratosphere. In low latitudes (30°N–30°S) at 100–50 hPa, the positive signatures are almost symmetrical around the equator. The strongest positive signatures occur at higher latitudes and heights, i.e., in 35°N–80°N and 20°S–55°S at 10–1 hPa. Because of the phase difference between the QBO1 and QBO2 wind components, the QBO2 signatures of the Q16W1 amplitude are mainly negative. Notably, unlike the QBO1 signatures, the QBO2 signature of the Q16W1 amplitude exhibits significant hemispheric asymmetry, with strong
negative signatures at high latitudes appearing only in the NH. No obvious responses to solar
activity and ENSO are found.

The long-term trend of the monthly mean Q16W1 amplitude is generally positive and
mainly concentrated in the stratosphere. The trend is asymmetric around the equator at 30–1
hPa and significantly stronger in the NH than in the SH. Weak negative trend is mainly
located below 300 hPa at high latitudes in the NH.

The trend of the monthly mean Q16W1 amplitude has evident seasonal variation. The
positive trend is largest in winter at 30–1 hPa at all latitudes in both hemispheres. To
investigate the possible causes of the trend of Q16W1, we calculated the long-term trend of
the monthly mean zonal wind and $\bar{q}_\phi$ in each of the four seasons. In winter of both
hemispheres, the weakening trend of eastward zonal wind contributes to the increasing trend
of the Q16W1 amplitude because the weak eastward zonal wind is favourable for Q16W1
propagation. Moreover, in autumn and winter in the NH and in spring, autumn and winter in
the SH, increasing trend of instability will enhance the wave excitation and thus lead to the
increasing trend of the Q16W1 amplitude.

Declarations

Availability of data and materials

The ERA-Interim data set were freely downloaded from the European Centre for Medium-Range
Weather Forecasts (https://apps.ecmwf.int/datasets/data/interim-full-daily/levtype=pl/), The $F_{10.7cm}$
solar flux data and multivariate ENSO index data were downloaded from
http://www.esrl.noaa.gov/psd/, and the QBO data series were from
Competing interests

The authors declare that they have no competing interests.

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Authors’ contributions

Wen Tao TANG carried out the reanalysis data processing and wrote the first draft of the paper. Shao Dong ZHANG conceived and coordinated this study and also assisted in manuscript preparation. Chun Ming HUANG performed analyses related to the present study, and interpreted the results. Kai Ming HUANG, Yun GONG, and Quan GAN contributed to the scientific interpretation. All authors read and approved the final manuscript.

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References

Alexander SP, Shepherd MG (2010) Planetary wave activity in the polar lower stratosphere. Atmos
Amitava G, Paulo PB, Barclay RC, Ricardo AB, Nelson JS (2016) Latitudinal variability of the quasi-16-day wave in the middle atmosphere over Brazilian stations. Ann Geophys 34:411–419. https://doi.org/10.5194/angeo-34-411-2016

Andrews DG, Holton JR, Leovy CB (1987) Middle atmosphere dynamics. New York NY USA: Academic Press.

Charney JG, Drazin PG (1961) Propagation of planetary-scale disturbances from lower into upper atmosphere. J Geophys Res 66:83–109. https://doi.org/10.1029/JZ066i001p00083

Das SS, Kumar KK, Veena SB, Ramkumar G (2010) Simultaneous observation of quasi 16 day wave in the mesospheric winds and temperature over low latitudes with the SKiYMET radar. Radio Sci 45:RS6014. https://doi.org/10.1029/2009RS004300

Day KA, Hibbins RE, Mitchell NJ (2011) Aura MLS observations of the westward-propagating $s=1$, 16-day planetary wave in the stratosphere, mesosphere and lower thermosphere. Atmos Chem Phys 11:4149–4161. https://doi.org/10.5194/acp-11-4149-2011

Day KA, Mitchell NJ (2010) The 16-day wave in the Arctic and Antarctic mesosphere and lower thermosphere. Atmos Chem Phys 10:1461–1472. https://doi.org/10.5194/acp-10-1461-2010

Dickinson RE (1968) Planetary Rossby waves propagating vertically through weak westerly wind wave guides. J Atmos Sci 25:984–1002

Espy PJ, Stegman J, Witt G (1997) Interannual variations of the quasi-16-day oscillation in the polar summer mesospheric temperature. J Geophys Res 102:1983–1990. https://doi.org/10.1029/96JD02717

Gan Q, Du J, Fomichev VI, Ward WE, Beagley SR, Zhang S, Yue J (2017) Temperature responses to
the 11 year solar cycle in the mesosphere from the 31 year (1979-2010) extended Canadian
Middle Atmosphere Model simulations and a comparison with the 14 year (2002-2015)
TIMED/SABER observations. J Geophys Res Space Phys 122:4801–4818,
https://doi.org/10.1002/2016JA023564

Gan Q, Oberheide J, Pedatella NM (2018) Sources, sinks, and propagation characteristics of the quasi
6-day wave and its impact on the residual mean circulation. J Geophys Res Atmos 123:9152–
9170. https://doi.org/10.1029/2018JD028553

Gong Y, Wang H, Ma Z, Zhang S, Zhou Q, Huang C, Huang K (2019) A statistical analysis of the
propagating quasi 16-day waves at high latitudes and their response to sudden stratospheric
warmings from 2005 to 2018. J Geophys Res Atmos 124:12617–12630. https://doi.org/10.1029/2019JD031482

Hartmann DL (1983) Barotropic instability of the polar night jet stream. J Atmos Sci 40:817–835.
https://doi.org/10.1175/1520-0469(1983)040<0817:BIOTPN>2.0.CO;2

Huang C, Li W, Zhang S, Chen G, Huang K, Gong Y (2021) Investigation of dominant traveling 10-
day wave components using long-term MERRA-2 database. Earth Planets Space, 73:85.
https://doi.org/10.1186/s40623-021-01410-7

Huang C, Zhang S, Chen G, Zhang S, Huang K (2017) Planetary wave characteristics in the lower
atmosphere over Xianghe (117.00°E, 39.77°N), China, revealed by the Beijing MST radar and
MERRA data. J Geophys Res Atmos 122:9745–9758. https://doi.org/10.1002/2017JD027029

Huang KM, Liu AZ, Zhang SD, Yi F, Huang CM, Gan Q, Gong Y, Zhang YH (2013) A nonlinear
interaction event between 16-day wave and a diurnal tide from meteor radar observations. Ann
Geophys 31:2039–2048. https://doi.org/10.5194/angeo-31-2039-2013
Hu Y, Tung KK (2002) Interannual and decadal variations of planetary wave activity, stratospheric cooling, and northern hemisphere annular mode. J Climate 15:1659–1673. https://doi.org/10.1175/1520-0442(2002)015<1659:IADVOP>2.0.CO;2

Hu D, Guo Y, Guan Z (2019) Recent Weakening in the Stratospheric Planetary Wave Intensity in Early Winter. Geophys Res Lett 46:3953–3962. https://doi.org/10.1029/2019GL082113

Hibbins RE, Jarvis JM, Ford EAK (2009) Quasi-biennial oscillation influence on long-period PWs in the Antarctic upper mesosphere. J Geophys Res 114:DO9109. https://doi.org/10.1029/2008JD011174

Hitchman MH, Huesmann AS (2007) A seasonal climatology of Rossby wave breaking in the 330–2000 K layer. J Atmos Sci 64:1922–1940.

Kallberg P, Simmons A, Uppala S, Fuentes M (2004) The ERA-40 archive. ERA-40 Project Rep. Series 17, European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom, 31 pp.

Kozubek M, Krizan P, Lastovicka J (2017) Comparison of the long-term trends in stratospheric dynamics of four reanalyses. Ann Geophys 35:279–294. https://doi.org/10.5194/angeo-35-279-2017

Kutner MH, Nachtsheim CJ, Neter J, Li W (2004) Applied Linear Statistical Models, 5th ed, pp:40–88 and pp:214–247. Mcgraw-Hill/Irwin, San Francisco, Calif

Lu H, Hitchman MH, Gray LJ, Anstey JA, Osprey SM (2020) On the role of Rossby wave breaking in the quasi-biennial modulation of the stratospheric polar vortex during boreal winter. Q J R Meteorol Soc 146:1939–1959. https://doi.org/10.1002/qj.3775

Luo Y, Manson AH, Meek CE, Meyer CK, Burrage MD, Fritts DC, Hall CM, Hocking WK,
MacDougall J, Riggin DM, Vincent RA (2002b) The 16-day planetary waves: multi-MF radar observations from the arctic to equator and comparisons with the HRDI measurements and the GSWM modelling results. Ann Geophys 20:691–709. https://doi.org/10.5194/angeo-20-691-2002

Luo Y, Manson AH, Meek CE, Thayaparan T, MacDougall J, Hocking WK (2002a) The 16-day wave in the mesosphere and the lower thermosphere: simultaneous observations at Saskatoon (52°N, 107°W), London (43°N, 81°W), Canada. J Atmos Terr Phys 64:1287–1307. https://doi.org/10.1016/S1364-6826(02)00042-1

Matsuno T (1970) Vertical propagation of stationary planetary waves in winter Northern Hemisphere. J Atmos Sci 27(6): 871–883. https://doi.org/10.1175/1520-0469(1970)027<0871:Vpospw>2.0.Co;2

Mitchell NJ, Middleton HR, Beard AG, Williams PJS, Muller HG (1999) The 16-day planetary wave in the mesosphere and lower thermosphere. Ann Geophys 17:1447–1456. https://doi.org/10.1007/s00585-999-1447-9

McDonald AJ, Hibbins RE, Jarvis JM (2011) Properties of the quasi-16 day wave derived from EOS MLS observations. J Geophys Res Atmos 116:D06112. https://doi.org/10.1029/2010JD014719

Meek CE, Manson AH (2009) Summer planetary-scale oscillations: aura MLS temperature compared with ground-based radar wind. Ann Geophys 27:1763–1774. https://doi.org/10.5194/angeo-27-1763-2009

Randel WJ, Wu F, Stolarski R (2002) Changes in column ozone correlated with the stratospheric E-P flux. J Meteor Soc Japan 80:849–862. https://doi.org/10.2151/jmsj.80.849

Salby ML (1981a) Rossby Normal Modes in Nonuniform Background Configurations. Part I: Simple fields. J Atmos Sci 38:1803–1826.
Salby ML (1981b) Rossby Normal Modes in Nonuniform Background Configurations. Part II: Equinox and Solstice Conditions. J Atmos Sci 38:1827–1840. https://doi.org/10.1175/1520-0469(1981)038<1803:RNMINB>2.0.CO;2

She CY, Krueger DA, Yuan T (2015) Long-term midlatitude mesopause region temperature trend deduced from quarter century (1990-2014) Na lidar observations. Ann Geophys 33:363–369. https://doi.org/10.5194/angeo-33-363-2015

Smith AK (1997) Stationary Planetary Waves in upper mesospheric winds. J Atmos Sci 54:2129–2145. https://doi.org/10.1175/1520-0469(1997)054<2129:SPWIUM>2.0.CO;2

Tsuda T, Murayama Y, Wiryosumarto H, Harijono SWB, Kato S (1994) Radiosonde observations of equatorial atmosphere dynamics over Indonesia, 1, Equatorial waves and diurnal tides. J Geophys Res Atmos 99:10491–10505. https://doi.org/10.1029/94JD00355

Vineeth C, Pant TK, Kumar KK, Sumod SG (2010) Tropical connection to the polar stratospheric sudden warming through quasi 16-day planetary wave. Ann Geophys 28:2007–2013. https://doi.org/10.5194/angeo-28-2007-2010

Weber M, Coldewey-Egbers M, Fioletov VE, Frith SM, Wild JD, Burrows JP, Long CS, Loyola D (2018) Total ozone trends from 1979 to 2016 derived from five merged observational datasets-the emergence into ozone recovery. Atmos Chem Phys 18:2097–2117. https://doi.org/10.5194/acp-18-2097-2018

Wallace JM, Panetta RL, Estberg J (1993) Representation of the equatorial stratospheric quasi-biennial oscillation in EOF phase space. J Atmos Sci 50:1751–1762. https://doi.org/10.1175/1520-0469(1993)050<1751:ROTESQ>2.0.CO;2
Williams CR, Avery SK (1992) Analysis of long-period waves using the mesosphere-stratosphere-troposphere radar at poker flats, Alaska. J Geophys Res Atmos 97:20855–20861. https://doi.org/10.1029/92JD02052

William JR, Leslie RL (1991) Dynamics of the 4-day wave in the Southern-Hemisphere polar stratosphere. J Atmos Sci 48:2496–2508. https://doi.org/10.1175/1520-0469(1991)048<2496:DOTDWI>2.0.CO;2

Wu DL, Hays PB, Skinner WR (1995) A least squares method for spectral analysis of space-time series, J Atmos Sci 52:3501–3511. https://doi.org/10.1175/1520-0469(1995)052<3501:ALSMSF>2.0.CO;2
Figure captions:

**Fig. 1** Mean frequency-wavenumber spectrum of temperature (in K) from February 1979 to January 2018 (39 years in total) at 37 pressure levels from 1000 hPa to 1 hPa. W (E) represents westward (eastward) propagation.

**Fig. 2** The time series of (a) SC index (F10.7cm flux), (b) multivariate ENSO index (MEI), and (c) the QBO indices on the monthly basis from February 1979 to January 2018, respectively.

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**Fig. 4** Month-latitude sections of the monthly and zonal-mean Q16W1 amplitude at high, middle, and low latitudes in the NH (three upper rows) and SH (three lower rows), respectively.

**Fig. 5** Latitude-pressure sections of the responses of the monthly-mean Q16W1 amplitude to (a) QBO1 and (b) QBO2, respectively. Only the results with the confidence level at/above 95% are plotted in contours. The solid and dashed contours denote the positive and negative responses, respectively.

**Fig. 6** Long-term trend (in K per decade) as a function of pressure and latitude of the monthly mean Q16W1 amplitude obtained from the 39 years ERA-interim temperature data set. Only the results with the confidence level at/above 95% are plotted in contours. The solid and dashed contours denote the positive and negative trends, respectively.

**Fig. 7** Seasonal variation of the Long-term trend (in K per decade) as a function of latitude and pressure of the monthly-mean Q16W1 amplitude from the 39 years ERA-interim temperature data set. The solid and dashed contours denote the positive and negative trends, respectively. The black
contours denote the trend with confident level at/above 95%. The colors represents the climatological
distributions of the monthly mean Q16W1 amplitude in four seasons.

**Fig. 8** Trend (contours, units: m/s/decade) of the monthly mean zonal wind in four seasons derived
from the 39 years ERA-interim zonal wind set. The solid and dashed contours denote the positive and
negative trends, respectively. The thick black contour represents the 0 value. The stippled regions
represent the trends at/above 95% confident level. The colors present the climatological distributions
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**Fig. 9** Trend (contours, units: $10^{-5}$ m$^{-1}$ s$^{-1}$/decade) of the monthly mean $\bar{q}_\phi$ in four seasons. The
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Figures

Figure 1

Mean frequency-wavenumber spectrum of temperature (in K) from February 1979 to January 2018 (39 years in total) at 37 pressure levels from 1000 hPa to 1 hPa. W (E) represents westward (eastward) propagation.
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Figure 6

Long-term trend (in K per decade) as a function of pressure and latitude of the monthly mean Q16W1 amplitude obtained from the 39 years ERA-interim temperature data set. Only the results with the confidence level at/above 95% are plotted in contours. The solid and dashed contours denote the positive and negative trends, respectively.
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Seasonal variation of the Long-term trend (in K per decade) as a function of latitude and pressure of the monthly-mean Q16W1 amplitude from the 39 years ERA-interim temperature data set. The solid and dashed contours denote the positive and negative trends, respectively. The black contours denote the trend with confident level at/above 95%. The colors represents the climatological distributions of the monthly mean Q16W1 amplitude in four seasons.
Trend (contours, units: m/s/decade) of the monthly mean zonal wind in four seasons derived from the 39 years ERA-interim zonal wind set. The solid and dashed contours denote the positive and negative trends, respectively. The thick black contour represents the 0 value. The stippled regions represent the trends at/above 95% confident level. The colors present the climatological distributions of the monthly mean zonal wind in four seasons.
Figure 9

Trend (contours, units: 10−5 m−1 s−1/decade) of the monthly mean $q\Phi$ in four seasons. The dashed contours denote the negative trend. The stippled regions represent the trends at/above 95% confident level. The colors present the climatological distributions of the monthly mean zonal $q\Phi$ in four seasons.

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