Journal of Atmospheric and Solar-Terrestrial Physics 73 (2011) 1616–1628

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Long term behaviour of the MLT quasi-7-day wave at two radar-sites at northern polar latitudes

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ARTICLE INFO

Article history:
Received 6 August 2010
Received in revised form
4 February 2011
Accepted 8 February 2011
Available online 18 February 2011

Keywords:
Planetary waves
Polar latitude
MLT
Meteor radar

ABSTRACT

The activity of the mesospheric-lower-thermosphere (MLT) quasi-7-day wave at two northern polar meteor-radar sites is presented. The study is based on long term meteor wind observations over Resolute Bay (75°N, 95°W) (May1998 to Feb 2009) and Yellowknife (62.5°N, 114.3°W) (June 2002 to Oct 2008). The wave showed clear seasonal variations, with strong activity during winter, more modest occurrence in the equinoxes, and minimum strengths during summer. The period of the quasi-7-day wave was 7.4 ± 0.3 days with little to no systematic seasonal variation in the wave period. The wave was characterized by increasing amplitude with increasing height and with downward phase propagation, suggesting that the wave had its origin at lower heights. The planetary wave (PW) activity was stronger in the zonal component than in the meridional component. The PW activity shows year to year variations, and appears to be sensitive to the background wind. The possible source mechanisms for the quasi-7-day wave are briefly discussed in the light of current understanding about planetary waves.

1. Introduction

Planetary waves (PWs) are quasi-periodic oscillations in atmospheric parameters such as wind and temperature, with periods generally in excess of one day, and horizontal wavelengths which are a significant fraction of the Earth's circumference. They play a vital role in all layers of the Earth's atmosphere. These waves affect the circulation by transporting momentum and chemical species both horizontally and vertically over scales of the order of hundreds of kilometers and more and hence, in general, they are often treated as agents for transportation. Planetary waves comprise mainly two types: free travelling waves and forced planetary waves (Andrews et al., 1987). Atmospheric wave theory predicts the existence of selected free normal mode oscillations with periods of a few days. For example, Longuet-Higgins (1968) gives periods of 2, 5, 7 and 10 days. However, sometimes strong PW activity with periods different from those of the free normal atmospheric modes has been observed. Examples are discussed by Pancheva and Lastovicka (1998) and Clark et al. (2002).

Planetary waves have been observed in measurements of winds, temperature, trace gases and ionospheric parameters like $f_{\min}$ (Forbes, 1994; Parish et al., 1994). In the past few decades, understanding planetary waves has become an important objective. Experimental observations have been carried out over different latitudes by using ground-based (single site observations as well as network observations) and space-borne instruments, and modelling calculations have also been pursued (e.g., Madden, 1979; Meyer and Forbes, 1997; Clark et al., 2002; Pancheva et al., 2008; Offermann et al., 2009). Sometimes these planetary waves will interact nonlinearly with tidal components and gravity waves and alter the background dynamics. Generally, three different source mechanisms are proposed for the existence of the PWs in the MLT region viz.: (1) propagation from lower heights in the stratosphere and even the troposphere, possibly via ducting across the equator; (2) barotropic or baroclinic instability causing the presence of the PWs at MLT; and (3) *in situ* nonlinear interaction between gravity waves and other planetary waves.

Observations with a meteor radar at Resolute Bay over the period 1998–2009 have shown a particularly strong oscillation at periods of 7–8 days, sometimes with amplitudes of 20 m/s or more, and persistently seen for over 10 years, which will be the focus of this article. This oscillation is the most prominent PW study at this radar site. Corresponding observations at a more southerly observatory at Yellowknife complement these observations.

There have been only a limited number of studies of quasi-7-day waves in the MLT region. Pancheva and Lastovicka (1998) suggested that PW activity with a period 7–8 days is more prominent in the lower ionospheric region (heights about 80–100 km). They used data from the CRISTA 1 campaign. They also concluded that

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doi:10.1016/j.jastp.2011.02.004

the 7–8 day waves which they studied were eastward propagating with wave number 3. Clark et al. (2002) reported the presence of the 7 day wave with wave number 1 using MLT radars and UARS-HRDI observations. They found that over low latitudes, the enhancement in the 7 day wave was strong during equinoxes, with maximum at fall equinox and almost no wave signature during mid-summer. The wave amplitude appeared to decrease poleward from the equator to a minimum around 30°, and then increase again in the 40–50° latitude region. The wave response was slightly biased towards the Northern hemisphere. Occurrence over high latitudes was sporadic. Clark et al. (2002) observed that the wave signature was primarily evident in the zonal wind. The meridional wave amplitudes were weak and primarily confined to high latitude. Haldoupis and Pancheva (2002) and Pancheva et al. (2003) observed the signature of a strong 7-day wave propagating westward with zonal wave number 1 using ionosonde and MLT radar observations over mid-latitudes. Pogoreltsev et al. (2002) identified a 7 day wave with horizontal wave number $m=2$ in UKMO assimilated data. They also proposed that the nonlinear interaction of a 7 day, $m=2$ wave with a stationary planetary wave having $m=1$ will produce a 6.5 day wave.

Until now, most studies have been concentrated on delineating the characteristics of the 7 day wave over low- and mid-latitude. No report exists dealing with the 7 day wave over polar latitudes. In the present study, for the first time, we report the presence of a 7–8 day wave (hereafter the quasi-7-day) in the Polar MLT region using meteor radar observations.

Details about the data used for the present study are presented in Section 2. The background conditions over the study region are discussed in Section 3. The methodology followed for the wave analysis, and the subsequent results from the study, are discussed in Sections 4 and 5, respectively. Sections 6 and 7 present a discussion, as well as the summary and conclusions made from the study.

2. Details of observations and analysis

For the present study, we have used long term observations made by two radars located at Resolute Bay (hereafter RB) (75°N, 95°W) and Yellowknife (hereafter YK) (62.5°N, 114.3°W). The measurements span almost an 11 year interval from May 1998 to Feb 2009 for RB, and almost a 7 year interval from June 2002 to Oct 2008 for YK.

The RB VHF radar is located at the Early Polar Cap Observatory and this radar was operated in interferometric mode at a frequency of 51.5 MHz. A full system description can be found in Hocking (2001). The YK radar is a SKiYMET Radar (Hocking et al., 2001) and operates at 35.65 MHz. Table 1 lists the main specifications of the radars used in the present study. The wind analysis has been carried out using software developed by Hocking et al. (2001). The same software was used for each data set from each site, and each radar was properly phase-calibrated on all receiver antennas, providing consistency in data-collection and analysis procedures at the two locations. The two radars are separated by 1600 km, mostly in a north–south direction. More specifically, they are separated by 1400 km along a meridian, and 770 km along a latitude circle. Both radar systems provide wind information as either 1 or 2 h averages. We used 2 hourly data in this study. More details about the background wind and tidal information over RB and YK can be found in Kishore Kumar and Hocking (2010).

Table 1
Basic parameters of the Resolute Bay VHF radar and Yellowknife SKiYMET radar.

Parameter	Resolute Bay	Yellowknife
Frequency (MHz)	51.5	35.65
Peak power (kW)	12	6
Pulse width (km)	2	2
Pulse repetition frequency (Hz)	750	2144
Pulse type	5-bit Barker	Monopulse
TX antenna	Four 2 element Yagis	One 3 element Yagi
RX antenna	Four 3 element Yagis	Five 3 element Yagis
Height resolution (km)	~3	~3

3. Background conditions

Before discussing the details of the results, we briefly describe the background prevailing zonal wind and temperature distribution over the observational sites. Figs. 1(a) and (b) illustrate the climatological monthly mean zonal wind estimated from the meteor radar observations over RB and YK, respectively. Note that the zonal wind over RB is an average of 11 years of data (1998–2009) and over YK it is an average of 7 years (2002–2008). Figs. 1(c) and (d) illustrate the temperature distribution from the CIRA 86 model data over RB and YK. The CIRA temperatures at 60°N and 65°N were averaged and the average value taken as the CIRA86 representative for YK.

Over both stations, the prevailing zonal wind shows similar patterns but with slight differences in magnitude. On average, during late Fall and Winter (Nov, Dec, Jan and Feb), the background wind is eastward at all heights, with larger magnitude at the lower heights compared to the upper heights. During late Spring and Summer (May, June, July and Aug), the background wind is westward at lower heights and eastward at upper heights. During summer months, the upper level eastward wind propagates to lower heights with the progression of summer. During the Spring Equinox (Mar and Apr) and Fall Equinox (Sept and Oct) the prevailing wind shows a seasonal transition. The YK zonal winds are stronger than the RB zonal winds throughout the year. The observed background zonal flow is similar to earlier observations made over high latitudes (Hocking, 2001; Manson and Meek, 1991; Hall et al., 2003). More details about the background wind structure and its inter-annual variations can be found in Kishore Kumar and Hocking (2010).

Over both stations, the temperature behaviour has a clear seasonal variation, with larger temperatures (200–240 K) during winter and lower temperatures (140–170 K) during summer. The difference between the winter and summer temperature is about 70 K. The temperature plays a vital role in regard to the wave period of free modes, and this is illustrated in Fig. 2, where the variation of wave periods as a function of temperature for selected resonant modes is presented. Fig. 2 is re-plotted based on the westward travelling modes from Figs. 2–6 of Longuet-Higgins (1968). The hatched boxes in Fig. 2 indicate the background temperature over the observational sites for summer and winter. The figures in Longuet-Higgins (1968) are shown as a function of equivalent depth. The equivalent depth can be written as

$$h=\gamma H$$
$$=\gamma(RT/Mg) \quad (1)$$

where H is the scale height, γ is the ratio of equivalent-depth to scale-height, R is the ideal gas constant (8.314 J K^{-1} mol^{-1}), T is the temperature, M is the apparent molecular weight (28.964) and g is the acceleration due to gravity.

For the isothermal condition ($T=244$ K), the equivalent depth is about 10 km. From the above equation it is clear that the equivalent depth is a function of temperature. We have therefore plotted the variation of periods as a function of temperature from 100 to 300 K, with the main focus on the periods between 4 and 9 days. From Fig. 2 it is clear that the wave periods with low zonal wave number are strongly dependent on temperature. In other words, the

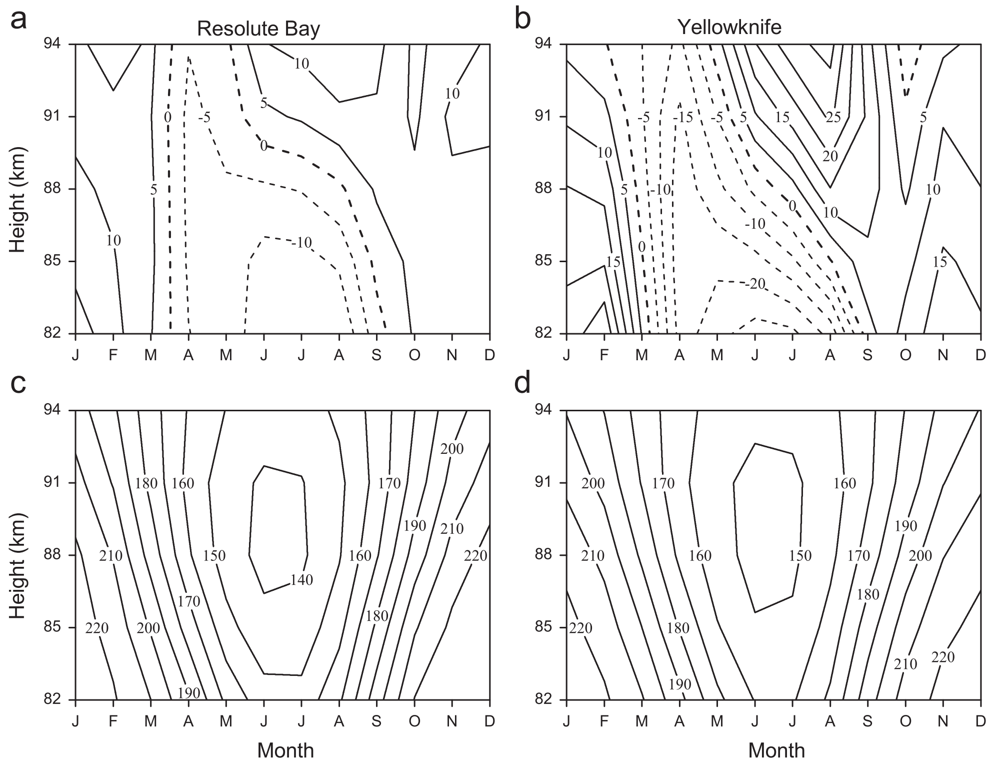

Fig. 1. (a) and (b) Monthly mean zonal winds derived from radar observations over Resolute Bay and Yellowknife, respectively. The solid lines indicate the eastwardwind, and the dashed lines indicate the westward wind. (c) and (d) Monthly mean temperature over Resolute Bay and Yellowknife from CIRA 86.

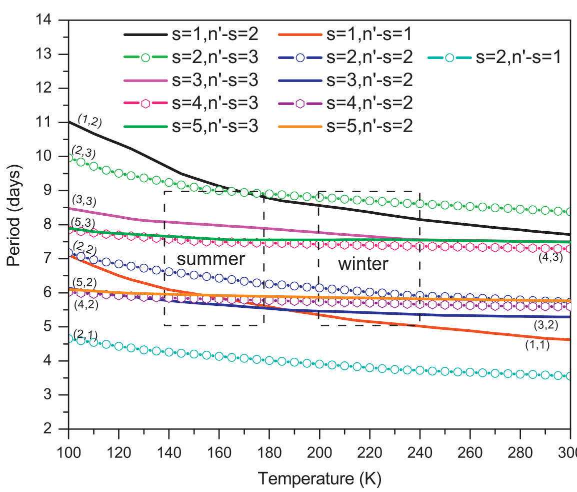

Fig. 2. Variation of period of planetary waves with respect to temperature for selected modes. This plot is reproduced for the westward travelling modes, and is adapted from Figures 2–6 of Longuet-Higgins (1968).

wave period changes considerably as a function of temperature for the first few zonal wave numbers like $s=1$, 2. The wave-period can change by as much as a day from winter to summer for some modes. It is very important to consider this point, at least at MLT heights over polar latitudes, and we will discuss it further in later sections.

4. Wave analysis procedure

A typical example of the zonal winds for the period 20 Sept 2005 to 31 Oct 2005 is shown in Figs. 3(a) and (c), for a selected height of 88 km. The raw winds show a clear signature of the quasi-7-day wave, even without the aid of post-processing. In order to more completely identify the dominant periodicities present in the zonal wind, the zonal winds have been subjected to Lomb-Scargle Periodogram analysis, and the normalized power spectra for both RB and YK observations are illustrated in Figs. 3(b) and (d), respectively. The dashed lines in Figs. 3(b) and (d) represent the 99%, 90% and 80% significant levels. From the figure the presence of a quasi-7-day wave with period of about 7.2–7.4 days over RB and 7.4–7.6 days over YK is evident. In the presented example, the normalized power of the quasi-7-day wave is larger over YK than RB. The normalized power spectra show that the quasi-7-day wave is more prominent over both stations than other long period oscillations.

In order to obtain an overview about the long period oscillations at both locations, the normalized dynamic power spectra for the two sites are presented in Fig. 4 for the period Aug 2005 to Aug 2006 at 88 km altitude. The dynamic spectrum has been calculated by using a sliding Lomb–Scargle (LS) Periodogram applied to a 50 day window, and then shifting the window 1 day at a time. The output of the window is assigned to the middle day of the window. Normalized power values with a significance level below 80% are set to zero. From inspection of Fig. 4, it is evident that there is often a strong presence of wave activity with periods from 7 to 8 days. In general, the wave activity is observed most strongly in the fall equinox and winter months. Over RB, the winter wave activity often appears stronger than during the fall equinox, and persists for a longer time than at YK. In order to show the wave activity with emphasis on the winter period, some more examples are illustrated in Fig. 5 for the months of December, January and February. The 50-day window includes 25 days in November and 25 days in March, which are used to generate the points near the start and the end of the time-sets.

Some strong wave activity is evident in both Figs. 4 and 5 with periods around 5.5 and 12–20 days (the latter is the so-called 16 day), but discussions of these oscillations is outside the scope of the present work. With regard to the waves of interest in this paper, the RB plot (Fig. 5(a)) shows an interesting steady drift in

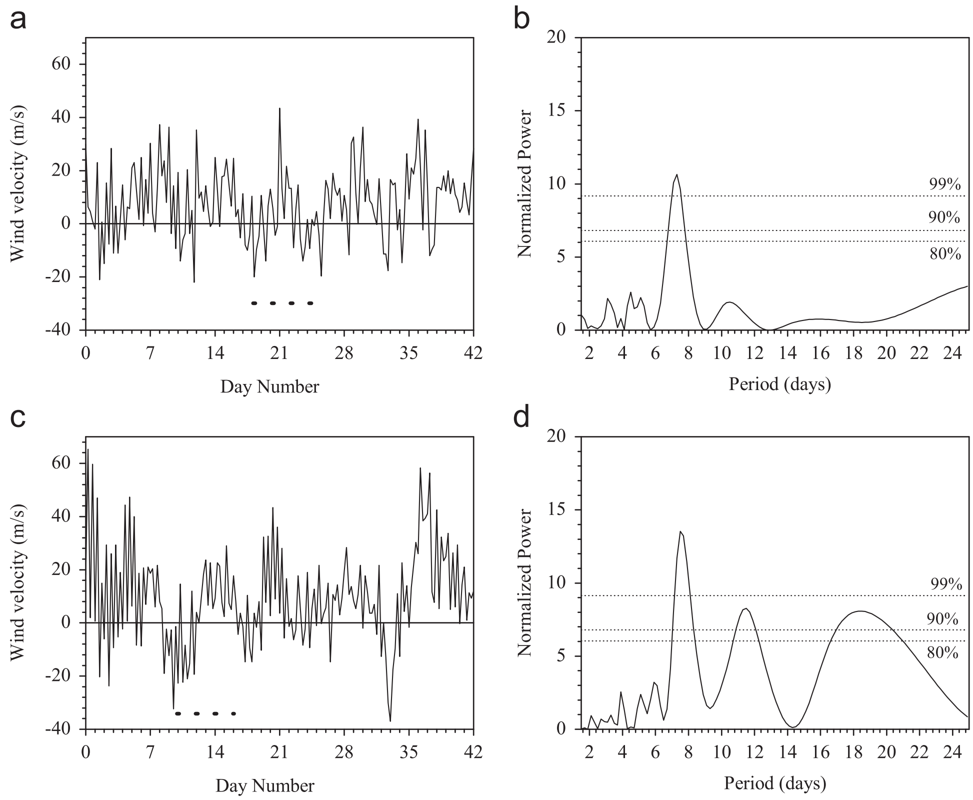

Fig. 3. (a) Six hourly mean winds of the zonal component for a height of 88 km for the period 20 Sept 2005 to 31 Oct 2005 over RB. The four small lines spanning the region around day 21 show a minimum, zero-crossing, maximum and zero-crossing of a typical 7-day oscillation. (b) Lomb-Scargle Periodogram spectrum for winds shown in (a). (c) and (d) similar to (a) and (b), but for YK. Significance levels for 80%, 90% and 99% are noted with dotted lines in (b) and (d).

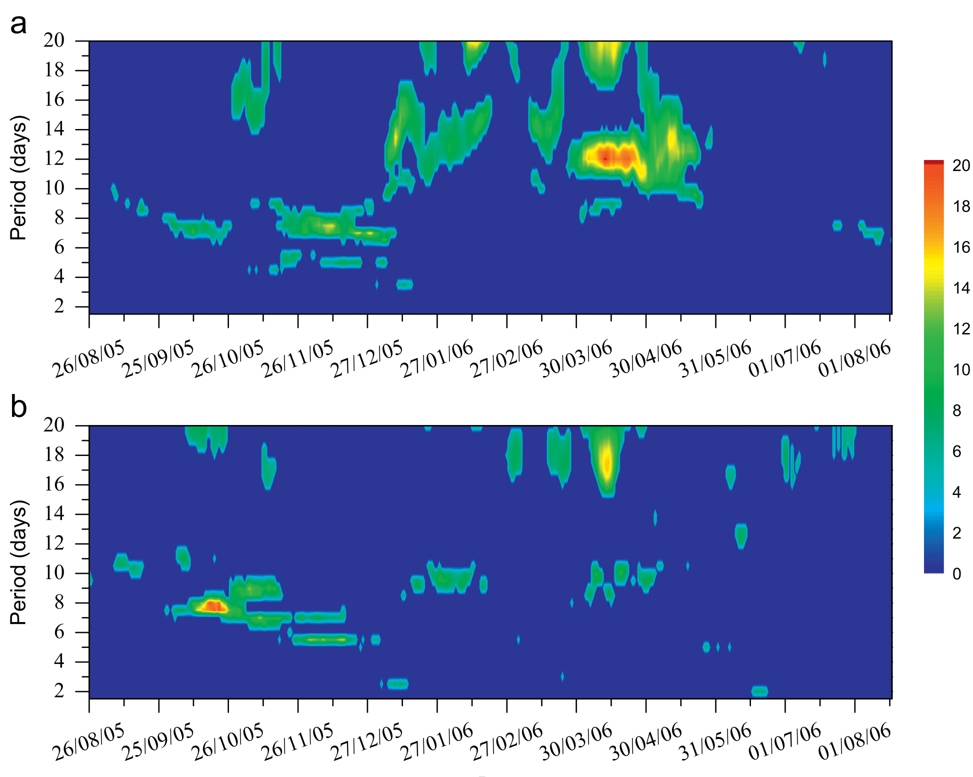

Fig. 4. Normalized running power spectra for the zonal winds for a selected height of 88 km over (a) RB and (b) YK during the period Aug 2005–Aug 2006. A Lomb–Scargle Periodogram has been applied to data within a window of length 50 days, and the window has been stepped through the data in 1-day steps. More details in the text.

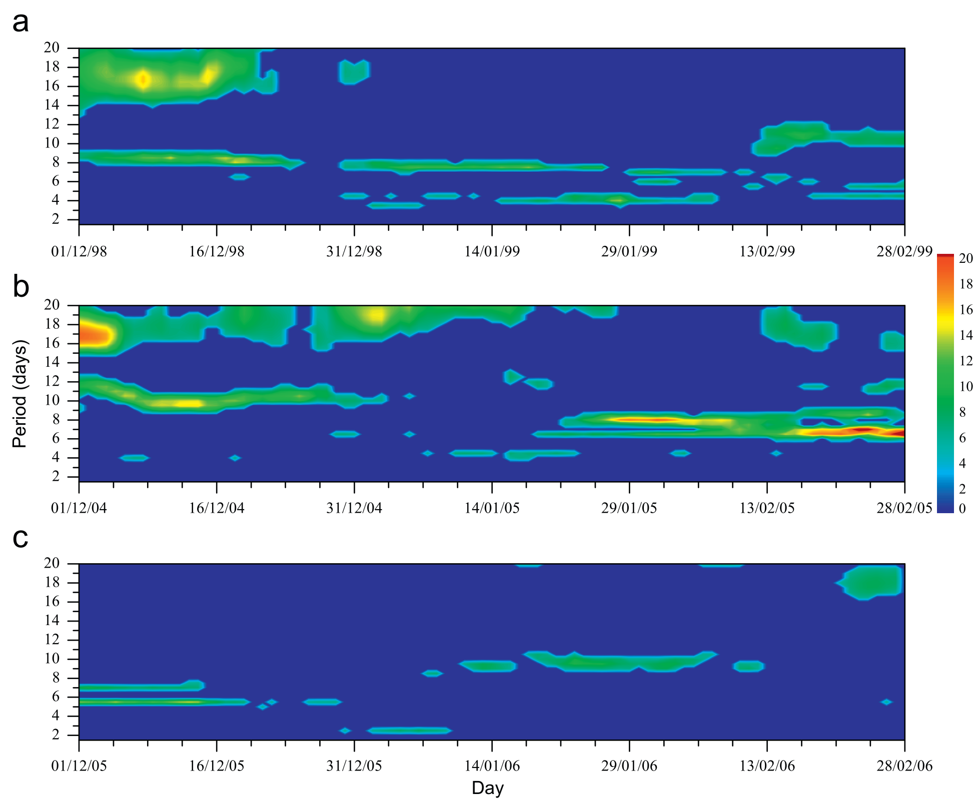

Fig. 5. Same as Fig. 4, but only for winter time. The graphs show dynamic spectra for a selected height of 88 km over (a) RB for 1998–1999 winter, (b) YK for 2004–2005 winter and (c) YK for 2005–2006 winter. Day 1 represents 1st December. (The mid-point of the first 50-day window covers data from 6 Nov to 25 Dec, and the window slides from this point onward. The last point includes data to March 25.)

period from 8.5 days at the start of the period to about 6.5 days at day 70, along with a 4-day oscillation, which starts around day 30 (close to the beginning of 1999) and persists (on and off) to the end of the data-set. Fig. 5(b) shows strong 7-day wave activity over YK from days 50 to 80 (essentially late January and all of February in 2005), and Fig. 5(c) shows a clear distinction between the 7-day wave and the 5-day wave from days 1 to 16 (first half of December in 2005).

In order to reduce the random noise, the data points were further averaged in 6 h bins, producing 4 points per day with 6 h resolution. This resolution is sufficient for the present wave analysis. Data gaps sometimes occurred in the wind series. The data gaps were filled based on some assumptions. When the length of the data gap was small (≤ 2 days) then the gaps were filled by linear interpolation. When the length of the data gap was longer than 2 days and less than 6 days, it was filled with Gaussian distributed random values with the same mean and standard deviations as that determined using 5 points before and 5 points after the data gap. If the data gap was longer than 6 days then we have left it unfilled and no further analysis has been performed on that interval.

To investigate the 7 day wave further, we used a Finite Impulse Response (FIR) band-pass filter with cut off frequencies of 0.117 and 0.15 cycles per day. As an example, the filtered zonal and meridional winds for the heights 82, 85, 88, 91 and 94 km for the period Aug 2005 to Aug 2006 are illustrated in Figs. 6 and 7.

5. Results

5.1. PW activity during Aug 2005–Aug 2006

We will start our analysis by examining the PW activity for a selected height of 88 km. From the zonal components presented in Figs. 6 and 7 (left panel), there is clear evidence for the existence of the quasi-7-day wave at 88 km. Sudden enhancements in amplitude are evident, revealing the burst-like nature of the wave. This bursty nature of PW activity is consistent with the behaviour seen in earlier observations (Wu et al., 1994). The bursts are persistent for typically more than one month, but generally less than 2 months. Larger amplitudes are observed in the zonal component than the meridional component, and this feature is evident over both stations.

From Figs. 6 and 7, it is clear that the PW activity over RB and YK has noticeable differences. For example, over RB at 88 km there was PW activity (Case 1) in the zonal component from day 115 to day 145 with peak amplitude of 15 m/s. PW activity was also observed in the zonal component at YK, from day 120 to day 150 (slight temporal shift compared to RB Case 1) with peak amplitudes of 6 m/s. Another interval of strong PW activity (Case 2) was observed during days 55–95, with peak amplitudes of 10 m/s over YK. Over RB, PW activity was observed from day 60 to day 85 (slight temporal shift compared to YK Case 2) with a peak amplitude of 6 m/s. Neither Case 1 nor Case 2 was particularly strong in the meridional component over either station. These two examples reveal that the PW activity may not be present at all latitudes simultaneously, consistent with observations elsewhere (Wu et al., 1994).

In order to investigate the vertical structure of the wave activity, we now further discuss the difference in amplitudes, and temporal displacements in maxima, as a function of height. The phase difference between waves at two different heights can be found as the time-difference of times of maximum velocity divided by the wave period and multiplied by 360°. Smaller phase differences with increasing height indicate longer vertical wavelengths.

On average, PW activity was stronger in the zonal component than in the meridional component at all heights over both sites.

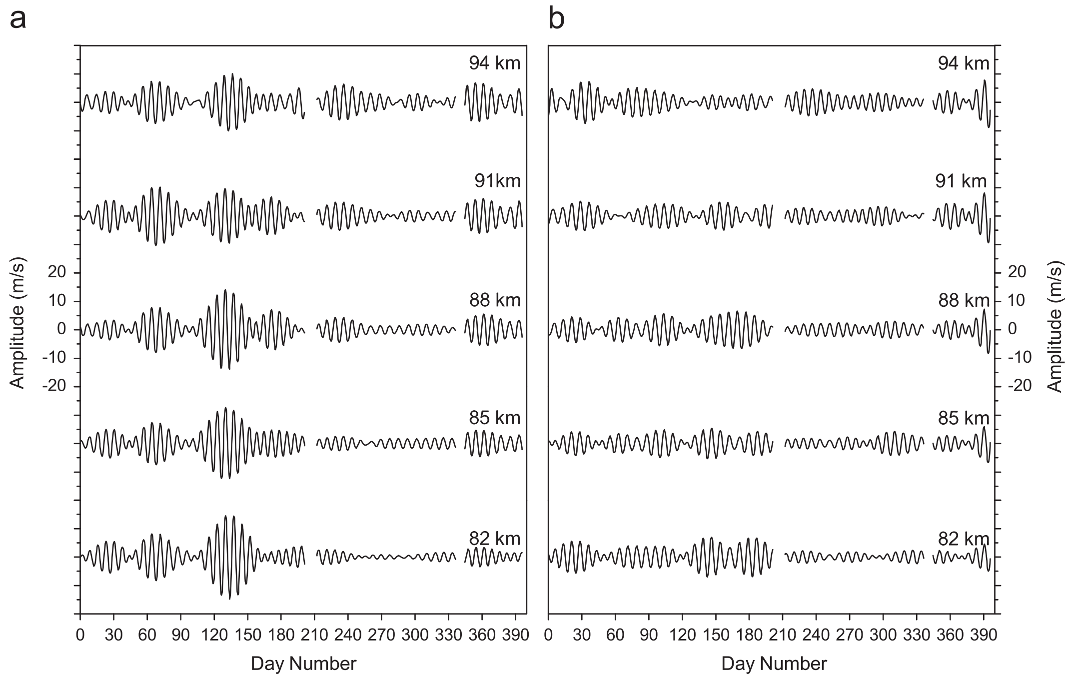

Fig. 6. Filtered winds for the period Aug 2005–Aug 2006 over RB, (a) zonal component and (b) meridional component. Note Day 1 is the first day of August 2005.

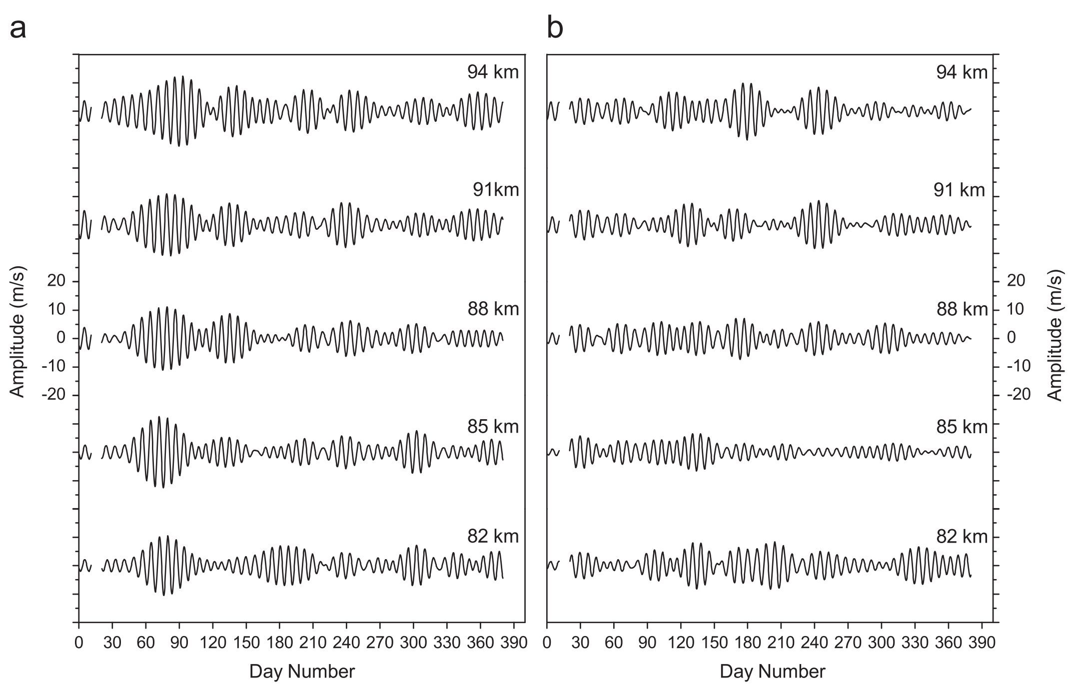

Fig. 7. Same as Fig. 6, but for YK.

For example, the Case 1 activity over Resolute Bay observed at 88 km is also observed at lower heights at 82 and 85 km (see the zonal component) with slight phase differences. The Case 1 activity is weaker at the upper heights in comparison to lower heights. The wave amplitude of Case 2 activity over RB has a peak value at 91 km. The Case 2 activity over YK (see the zonal component) is present in all heights with an increase in amplitude as one increases in height. Here also the phase variation with height is more gradual, indicating a large vertical wavelength. On average, the wave amplitudes were stronger at the upper heights than the lower ones, suggesting that the wave amplitudes increase with height. In contrast, the meridional component shows PW activity that is not consistent in all heights, indicating that PW activity is highly sporadic in the meridional component, both in time and height, when compared to the zonal component.

5.2. Wave climatology

In this section, we discuss the wave parameters in a climatological sense. In order to determine wave characteristics like amplitude, period and their seasonal variation, we followed a simple criterion to identify a PW event. Based on the criterion, a burst that has a peak-to-peak amplitude of more than 6 m/s, with more than three cycles, is considered as an event. The number of events is highly variable both in space and time. On average, the number of events observed over RB was 27 in the zonal component and 24 in the meridional component. Over YK, the numbers were 18 and 14 in the zonal and meridional components, respectively. The number of cycles in the events, which gives the life time of the PW activity, was generally larger over RB than YK.

5.2.1. *Amplitudes*

To identify the seasonal variation of the wave characteristics, the events were binned based on season. The peak amplitudes of each event for different heights and different seasons are plotted in Fig. 8. Both zonal and meridional components are plotted together in order to allow comparison of the amplitude distributions in the two components. In general it is clear that the peak amplitudes in the zonal component in winter and spring are larger than the corresponding meridional ones, and this is evident over both stations. The dominance of the zonal component is especially apparent in winter over Resolute Bay. The amplitudes grow weakly as a function of height. In all seasons the peak amplitudes are generally concentrated in the range 5–10 m/s over RB and 8–12 m/s over YK. During winter the peak amplitudes reach up to 20 m/s over RB. This is also evident in the spring season but with less frequent occurrence. Occasionally the meridional peak amplitudes have larger values at the upper heights. It is important to remember that Fig. 8 reveals the peak amplitude in the event, rather than an average. In some events, the waves have sudden enhancements in amplitude, and such events represent the larger values in Fig. 8. The mean values of the peak amplitudes (figure not shown here) indicate that, in general, the amplitudes are larger during the winter season than the other seasons.

5.2.2. *Period and vertical wavelengths*

In order to determine the period of the quasi-7-day wave we have applied harmonic analysis in a least square sense. We found the distribution of the wave period is spread between 7 and 8 days, occasionally up to about 8.4 days. The mean wave periods were about 7.4 ± 0.3 days over both sites. The wave period did not show any noticeable seasonal variation. This may indicate that the waves were not free modes, but rather were forced, since according to Fig. 2 we might expect a change in period with season for free modes.

By applying a simple linear least squares fit with period of 7.4 days, we found the phase profile for the two selected PW activities (Case 1 and Case 2) mentioned in Section 5.1. The vertical phase structure shows increasing phase as the height descends, which implies upward energy propagation. Vertical wavelengths have been estimated from the phase profiles, and the values are as follows for the zonal winds for Case 1 and Case 2, respectively: approximately 67 and 115 km over RB, and 50 and 75 km over YK. These values are consistent with the theoretical calculations demonstrated in Appendix A, which suggests that typically the vertical wavelengths should be long, of the order of 50–100 km and more.

For the meridional component, the phase profiles are not uniform and hence estimation of the vertical wavelengths leads to spurious values. The amplitude and phase profiles of selected events are illustrated in Fig. 9. The mean zonal wind is also plotted along with the wave amplitudes in Fig. 9.

In order to check whether the vertical wavelengths were dependent on the temporal period of the wave, we extended our estimation of vertical wavelengths using periods from 7.1 day to 7.7 day with 0.1 day increments. From the distribution of the vertical wavelengths, it seems that the calculated vertical wavelengths are independent of the period, at least when the PW activity is strong.

Since the wave activity is not always present at all heights simultaneously, it is not possible to identify the vertical wavelength

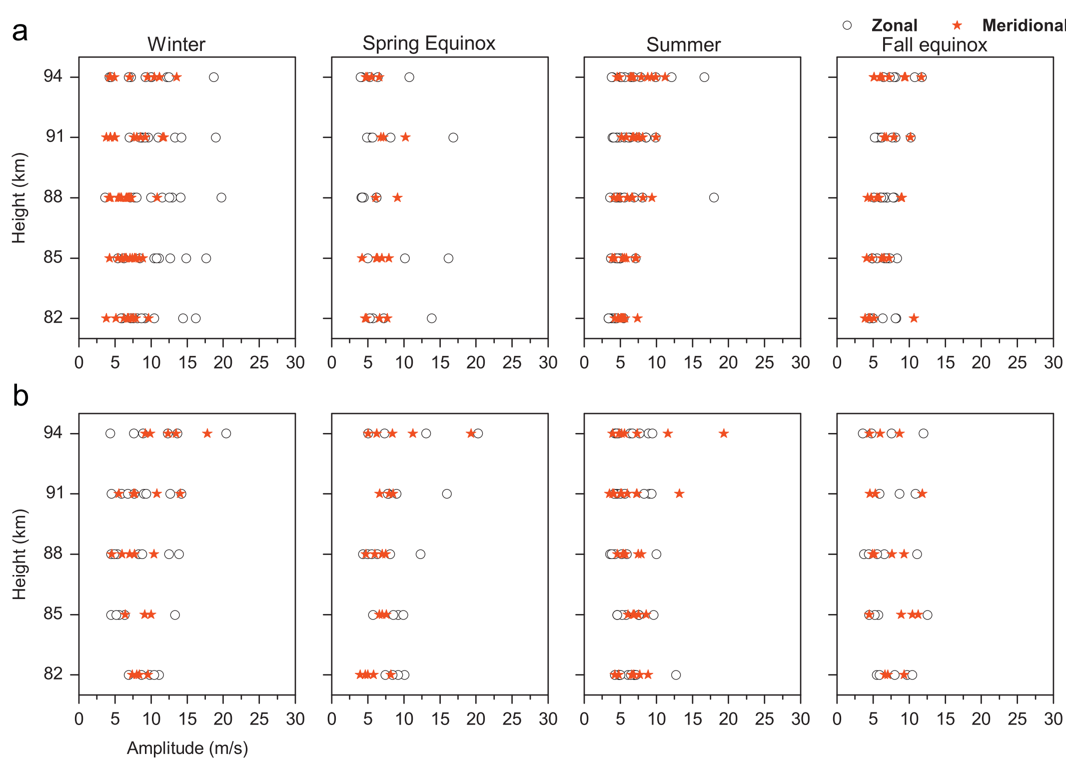

Fig. 8. Vertical distribution of peak amplitudes of the events for different seasons viz., winter, spring equinox, summer and fall equinox over (a) RB and (b) YK. The black open circles are used for the zonal component, and the red filled stars represent the meridional component. (References to colour in this caption can be understood by referring to the web version of this article.)

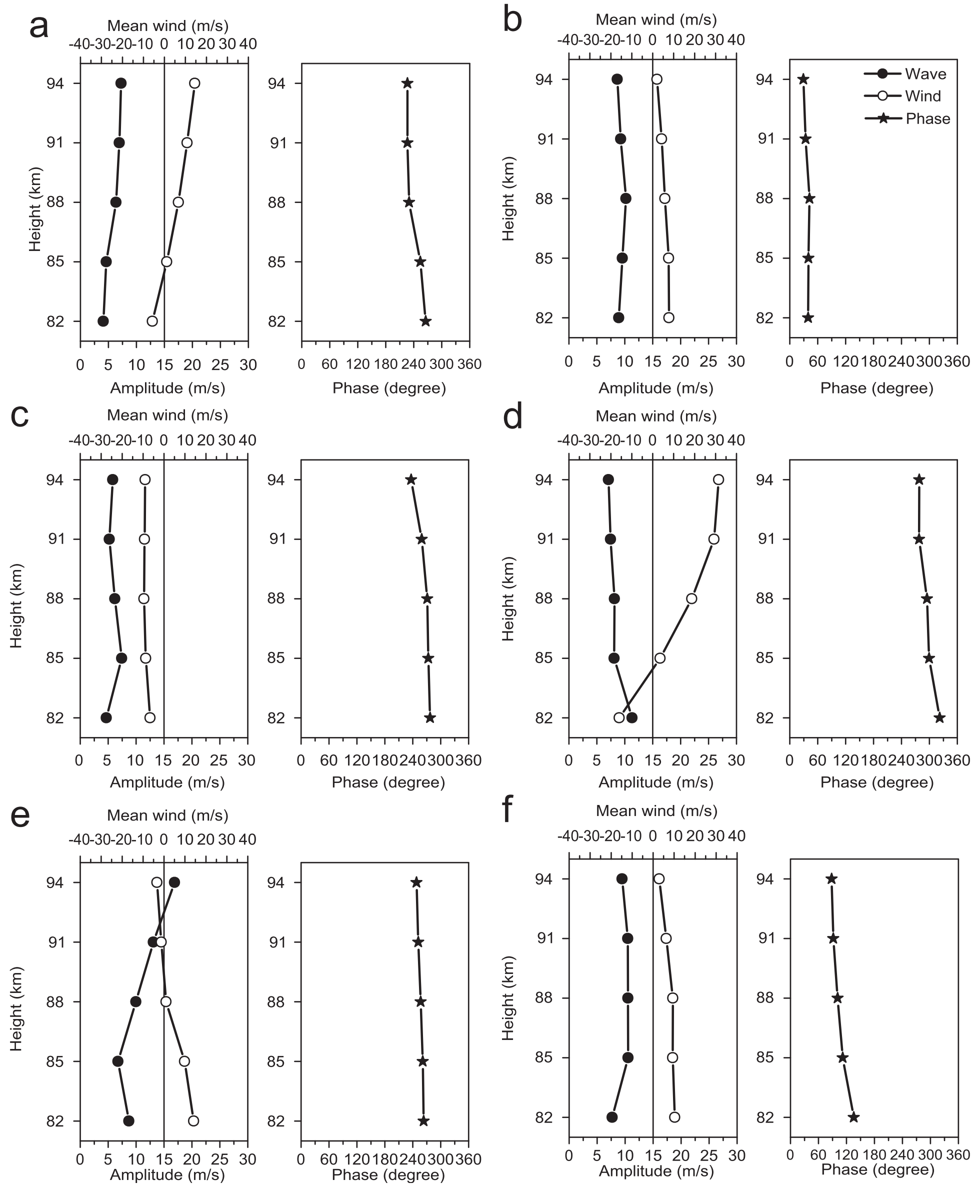

Fig. 9. Vertical amplitude and phase profile with mean zonal wind for selected events. (a)–(c) for RB zonal component and (d)–(f) for YK zonal component. The selected periods: (a) 21 Aug 2000–20 Sept 2000; (b) 14 Dec 2004–25 Mar 2005; (c) 11 Apr 2005–06 May 2005; (d) 05 Aug 2003–08 Sept 2003; (e) 20 Feb 2004–23 Mar 2004; and (f) 18 Jan 2005–08 Mar 2005. More details can be found in Table 2.

for all events. We found that sometimes the wave activity was not present in all height regions. The wave activity occurred at all heights on 13 occasions in the zonal component and 6 occasions in the meridional at RB. At YK the wave could be seen at all heights on 4 occasions for the zonal and 3 for the meridional components. The vertical wavelengths observed during these occasions are listed in Table 2. In a few cases, the phase profiles did not change uniformly with increasing height, and for such situations the wavelengths are denoted as 'NR' (not regular). In few other cases the wavelengths were very large. For each occasion, except for NR cases, the period of the wave is also presented in Table 2. In most cases the vertical wavelengths over RB were in range 55–90 km, and were between 70 and 110 km over YK, consistent with Appendix A.

5.3. *Composite monthly mean variability and inter-annual variability*

For further analysis, we have used the monthly variances as a proxy for PW activity. The band passed filtered winds over a month were used to calculate the monthly variance. In order to investigate the monthly variation of PW activity, a composite monthly mean (superposed epoch) analysis was applied for all the available data. A simple arithmetic mean of the monthly variances was used. Figs. 10(a) and (b) illustrate the mean monthly variances over RB for the zonal and meridional components respectively, while Figs. 10(c) and (d) show the same components for YK. The background zonal wind (previously shown in Fig. 1) is superimposed on the monthly variances. The solid lines represent eastward flow and the dashed lines represent westward flow.

Inspection of Fig. 10 reveals that the wave activity was predominantly a winter-time activity at both sites, with greatest activity in December/January/February. The activity often extended to March/April over YK. YK also shows a secondary maximum around October. There is a pronounced minimum in summer, especially at around 88 km, and in general the activity is quite low from April to August. Although summer strengths are generally weak it is interesting that, in contrast to the other seasons, the wave activity is stronger in the meridional component than the zonal component by a factor of 1.2–1.6 during that season. The meridional component seems

Table 2
Details of the wave events observed over RB and YK. The list contains starting and ending dates of the wave events, with vertical wavelengths (when calculable) and dominant periods also shown. Periods are expressed in days and wavelengths are in km.

Zonal RB

Starting date	Ending date	Wavelength (period)
21 Aug 2000	20 Sept 2000	−87(7.4)
12 Dec 2000	10 Jan 2001	−72(7.4)
16 Aug 2001	16 Oct 2001	NR
14 Dec 2001	12 Feb 2002	Large (7)
05 Mar 2002	18 Apr 2002	−66(7.1)
14 Dec 2004	25 Mar 2005	Large (7.5)
11 Apr 2005	06 May 2005	−95(7.2)
21 Sept 2005	25 Oct 2005	Large (7.5)
21 Nov 2005	07 Jan 2006	−67(7.4)
23 Oct 2006	29 Nov 2006	−79(7.1)
03 Jan 2007	01 Feb 2007	−88(7.3)
31 Mar 2007	30 Apr 2007	−65(7.5)
22 Nov 2008	10 Feb 2009	−58(7.2)

Meridional RB

Starting date	Ending date	Wavelength (period)
07 Aug 2000	06 Sept 2000	Large (7.4)
11 Jan 2002	25 Feb 2002	NR
26 Apr 2003	22 May 2003	−74(7.5)
28 Jan 2005	23 Feb 2005	NR
17 Aug 2006	19 Sept 2006	Large (7.4)
24 Oct 2008	05 Jan 2009	−87(7.4)

Zonal YK

Starting date	Ending date	Wavelength (period)
05 Aug 2003	08 Sept 2003	−90(7.4)
20 Feb 2004	23 Mar 2004	Large (7.4)
18 Jan 2005	08 Mar 2005	−82(7.5)
21 Sept 2005	11 Nov 2005	−69(7.5)

Meridional YK

Starting date	Ending date	Wavelength (period)
17 Aug 2003	20 Sept 2003	NR
13 Nov 2004	01 Mar 2005	−90(7.8)
27 Nov 2005	22 Dec 2005	−109(7.2)

* NR stands for not regular; this is due to random variation of the phase profile.

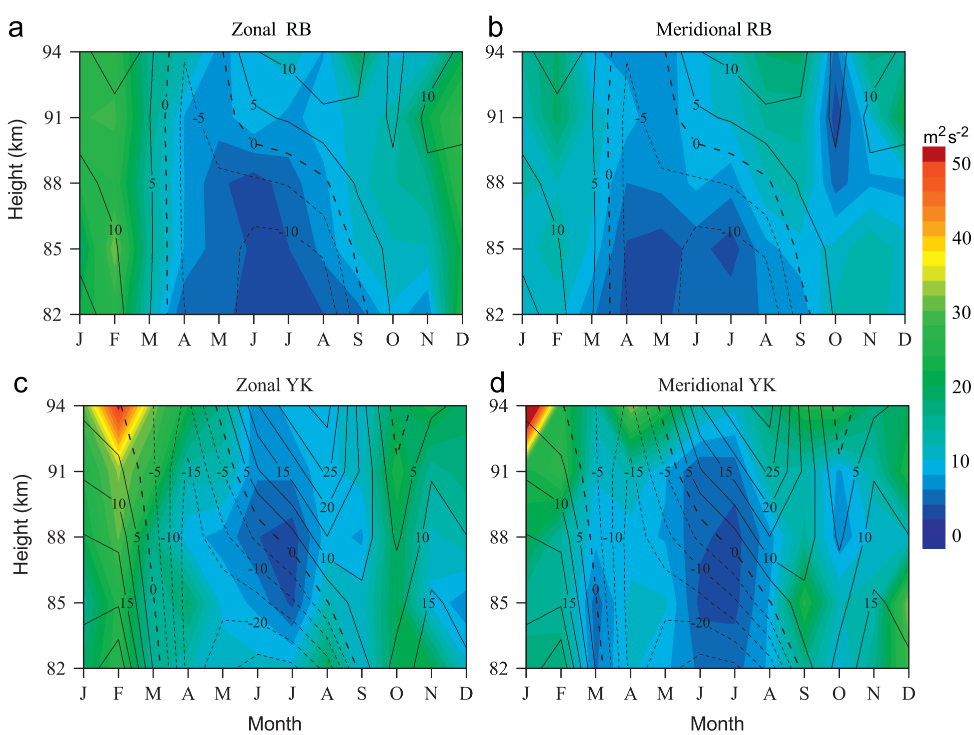

Fig. 10. Coloured shading represents climatological monthly mean variances of (a) zonal component over RB and (b) meridional component over RB. The climatological monthly mean zonal wind is also over-plotted in all plots. The solid lines indicate the eastward wind, the dashed lines indicate the westward wind, and the zero wind line is highlighted. The graphs (c) and (d) are the same as (a) and (b), but for YK.

somewhat more pronounced at YK than at RB, at least on occasion. There is a wide variation in the magnitude of PW activity, and the difference is particularly apparent during the equinoxes. The difference in PW activity over RB and YK may be due to latitudinal differences in the PW activity, but it should also be recognized that the composite monthly mean variances over RB were based on 11 years of data, while those over YK were based on only 7 years of data.

From Figs. 10(a)–(d), it seems that the wave activity is strongest when the zonal winds are eastward, or only weakly westward, and the waves are generally absent during the stronger westward flows of the zonal wind. This indicates that the wave activity is sensitive to the background wind flow. The possible reasons for the variation in the wave activity are discussed later.

To examine the long-term variability of the PW activity, running 4 week variances with one week shifts for the zonal and meridional components over RB and YK are illustrated in Fig. 11 for the entire period of observation. From the figure it is clear that, in general, the zonal variance was larger than the meridional variance. The zonal variances over RB show large values during the 2004–2005 winter months, which is evident in all height regions. Large zonal variances were also observed during 2000–2001, 2005–2006 and 2008–2009 winter months. The YK zonal variances also showed large values during the 2004–2005 and 2005–2006 winter months. Occasionally the variances were especially large during the equinox months at both sites. This feature is more evident over YK than RB.

The meridional variances also showed peak values during the winter months over RB and YK, with weaker magnitude compared to zonal variances. Over YK, the meridional variances showed peak values during non-winter months also, as for the zonal variances. Occasionally, the meridional variances were larger than the zonal variances for at least a few heights. For example, during 2004–2005 winter months the meridional variance was higher than the zonal variance at the upper heights (94 km), but this was not the normal situation.

The observations over RB and YK show strong inter annual variability. In order to find the dominant oscillations in the wave activity we subjected the monthly variances to the Lomb–Scargle analysis and the results are illustrated in Fig. 12. The analysis indicates the existence of an annual variation, but it is not significant in all heights. It is significant over RB in the zonal component at all heights except for 94 km and significant at the lower heights (82 and 85 km) in the meridional component. The annual oscillation above YK is significant at the lower heights (82, 85 and 88 km) in the meridional component. We also found a 20–30 month oscillation in the zonal components, but it is not statistically significant.

6. Discussion

A limited number of planetary wave studies have been carried over high latitude regions compared to low and mid latitudes. Those studies dealt with the normal modes such as 2, 5 and 16 day oscillations. There are no studies about the 7 day planetary waves over high latitudes, except Clark et al. (2002) and that was confined to selected latitudes due to limitations of the HRDI satellite. A few studies of the quasi-7-day wave at MLT heights have been carried out over low and mid latitudes (Pancheva and Lastovicka, 1998; Clark et al., 2002; Haldoupis and Pancheva, 2002; Pancheva et al., 2003).

Clark et al. (2002) reported the presence of the quasi-7-day wave using HRDI and MLT radars. They reported that the quasi-7-day wave is an *in situ* generated unstable mode with zonal wave number 1. The occurrence of the wave was highly sporadic at high latitudes compared to low- and mid-latitudes. Even though the wave signature was largely confined to the zonal component over all latitudes, it showed a weak signature in the meridional wind over high latitudes. The general occurrence of strong amplitudes in the zonal component compared to the meridional component in our observations strongly supports the observations made by Clark et al. (2002). Clark et al. (2002) did not discuss the seasonal variation of the quasi-7-day wave, and mainly concentrated on fall equinox conditions. In the present study we have been able to produce a better description of the seasonal variations of the quasi-7-day wave, at least for our selected sites.

A few studies over mid-latitudes reported the presence of the quasi-7-day wave at lower ionospheric heights using radio propagation data and data based on E-s layer occurrence. Pancheva and Lastovicka (1998) identified PW activity with a period of 7–8 days in radio propagation data in the lower ionospheric region (heights of about 80–100 km) during the CRISTA 1 campaign (Oct–Nov 1994). Again, this study was confined to fall equinoxes. They also observed an unusual phenomenon, in that their quasi-7-day

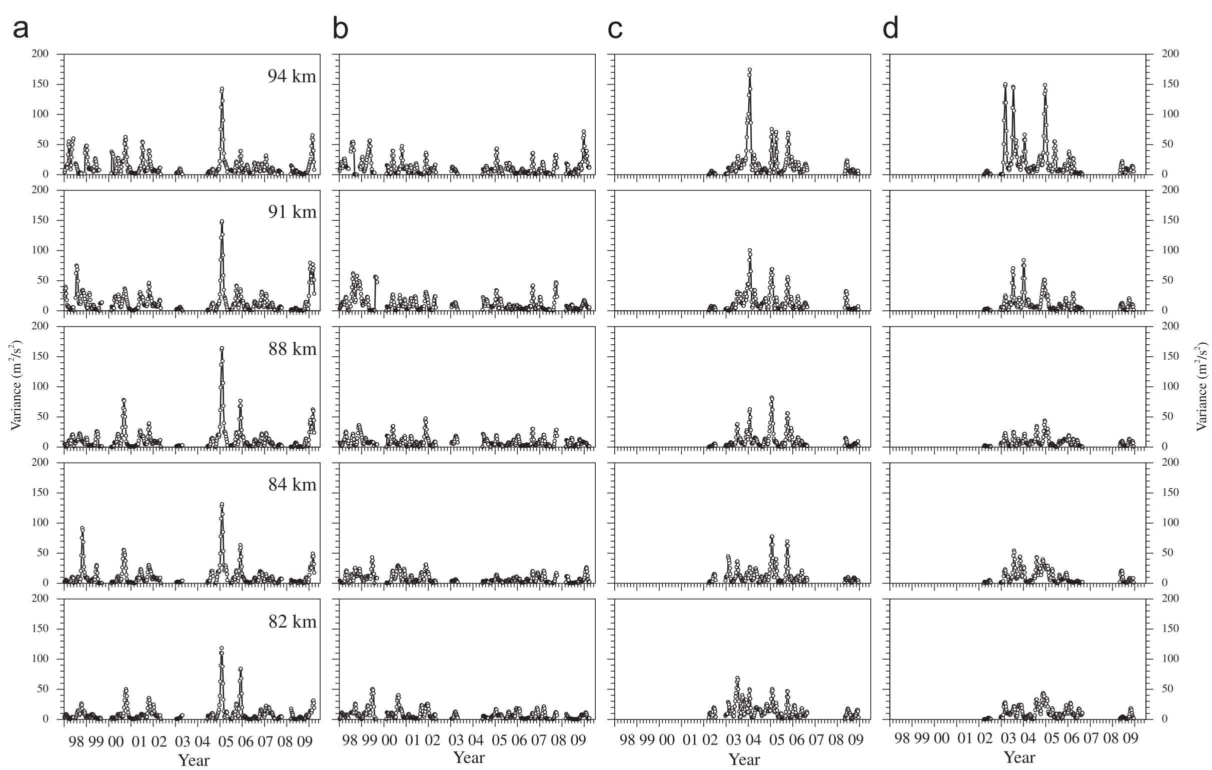

Fig. 11. (a) and (b) Running four week variance of zonal and meridional component over RB, in steps of 1 week, for the period 1998–2009 for heights 94, 91, 88, 85 and 82 km. (c) and (d) same as (a) and (b), but for YK.

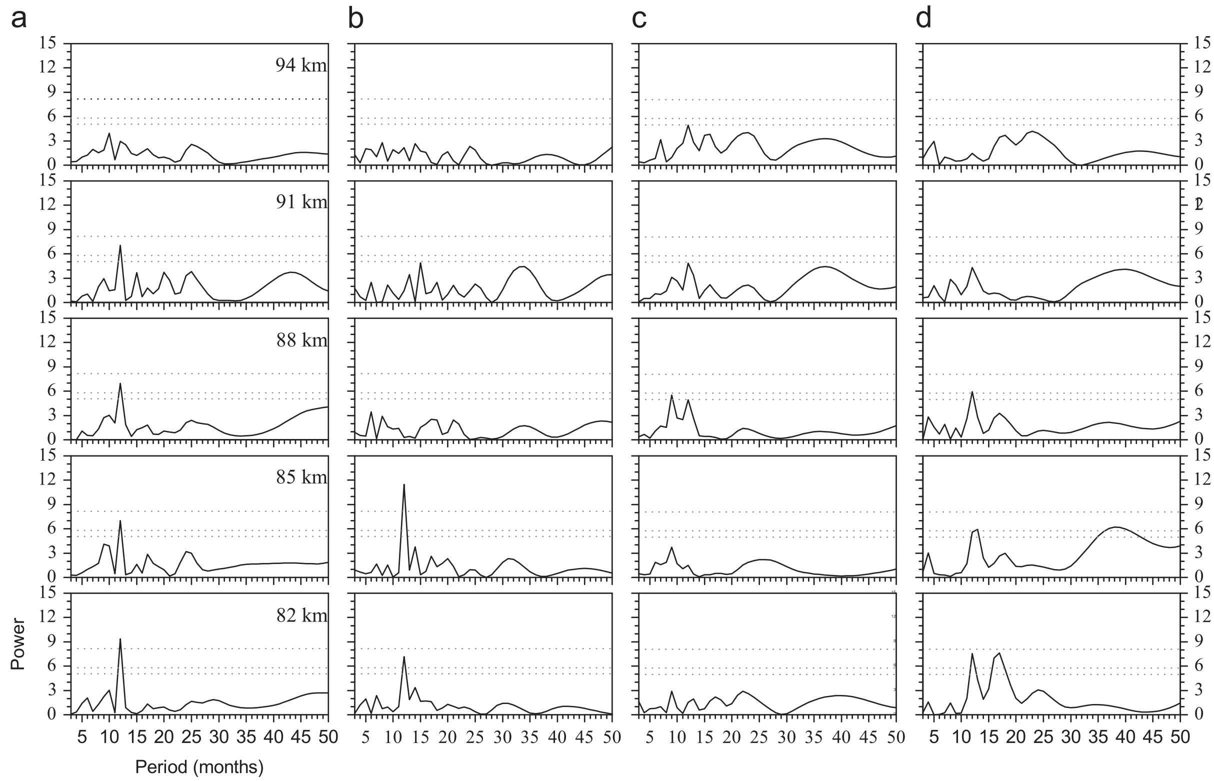

Fig. 12. Dominant periodicities observed in the monthly mean wave activity of the quasi-7-day wave (a) and (b) zonal and meridional components over RB, (c) and (d) same as (a) and (b), but for YK. Note that the dotted line shows the significance level upper line for 99%, middle for 90% and bottom line for 80% significance.

wave may have had eastward propagation with zonal wave number 3. This is unusual—normally westward propagation prevails in this height region.

Haldoupis and Pancheva (2002) reported the presence of a quasi-7-day wave in the rate of occurrence of Es layers using global ionosonde observations over mid-latitudes for the period Aug–Sept 1993. They found that the quasi-7-day wave is westward propagating with zonal wave number 1. These studies are strongly supported by Pancheva et al. (2003) using MLT radar wind observations in addition to the ionosonde observations. They also found a clear 7 day amplitude modulation of the semidiurnal tide and diurnal tide. In fact, their studies gave higher emphasis to the wave activity in the meridional wind than in the zonal component.

Most of the observations discussed so far indicate that the quasi-7-day wave is generally westward propagating with zonal wave number 1. Based on these observations we have calculated the zonal phase speed for a mean period of 7.4 days with zonal wave number 1. The phase speed of the quasi-7-day wave would be about -16 m/s over RB and -29 m/s over YK if this assumption is valid. If the background zonal wind is more eastward than the phase speed of the wave then the wave may propagate vertically. According to Charney and Drazin (1961), the planetary waves should obey the condition $0<u-c_x<U_c$ to propagate to further heights. Here u is the mean zonal wind speed, c_x is the phase speed of the planetary wave, and U_c is the critical Rossby speed. This means that the wave can propagate upward if the eastward zonal speed is more positive than -16 m/s over RB and -29 m/s over YK. As a general rule, then, if the zonal mean wind is more than about 20 m/s westward, propagation will be blocked, broadly in line with our observations.

Smith (2003) proposed a mechanism for the existence of stationary planetary waves in the upper mesosphere. According to that theory, gravity waves modulated by lower stratospheric dynamics might pass through the jet and deposit their energy at greater heights and thus regenerate planetary waves. This mechanism may explain the wave activity observed at upper mesospheric heights in summer.

Riggin et al. (2005) studied global 5 day wave signatures using space based observations from SABER aboard TIMED and ground based observations from meteor and MF radar. They concluded that the 5 day wave originated in the winter hemisphere and was ducted across the equator into the summer hemisphere, where it was amplified by baroclinic instability. This is true for some cases only. Recently, Day and Mitchell (2010) studied the 5 day wave using long term observations made by meteor radars located at Esrange (68°N, 21°E) and Rothera (68°S, 68°W). They also reported that the hemispheric ducting is not valid for all time. Similar conclusions may be valid for the 7-day wave.

Based on the all these observations, we can propose that the seasonal behaviour of the observed planetary wave activity is potentially dependent on the background zonal flow. The absence of wave activity during summer below the zero wind line is probably due to blocking of the wave activity by strong westward flow. The wave activity at upper heights may be either due to regeneration of PWs by gravity waves (*in situ* generation) as proposed by Smith (2003) or due to inter hemispheric ducting. We did look for correlations with stratospheric winds using ECMWF model outputs, but no significant correlations were found. However, the activity over Yellowknife and Resolute Bay was at times noticeably different, suggesting significant local effects are involved in the wave generation. This would favour the gravity-wave modulation hypothesis, since we might expect a large-scale process like equatorial ducting to produce greater behavioural consistency at the two sites. We cannot resolve this issue further in this report.

In Fig. 2, we examined the dependence of wave period on temperature, and concluded that the period should change from winter to summer if the mode was a normal mode. The fact that the period does not show a seasonal dependence is possible evidence that the wave is not a normal mode, but probably a forced one. Alternatively, it is possible that the wave is one with high zonal wave number, which would mean a weaker dependence of period on temperature. But in view of the satellite and multi-site studies discussed above, which generally suggest small wave numbers at MLT heights, we think this is unlikely.

7. Summary and conclusions

The main focus of this work has been to study the quasi-7-day wave over northern polar latitudes. The study was carried out with 11 years of observations made over Resolute Bay using a VHF radar in meteor mode, and 7 years of observations made over Yellowknife with a SKiYMET meteor radar. The present study reveals a strong seasonal variation of the quasi-7-day wave activity. The main findings are summarized below:

- The wave activity is highly sporadic in nature. It is generally strongest during winter, moderate during the equinoxes and minimum during summer.
- The period of the wave varies between 7 and 8 days with mean period about 7.4 days.
- The wave activity is generally stronger in the zonal wind than in the meridional wind.
- Considerable year to year variation has been observed. Occasionally the wave activity reaches amplitudes of 20 m/s or more.
- The phase profiles indicate downward phase propagation and hence upward energy propagation, so the source should be located at around 80 km altitude or lower.
- The wave activity appears to be sensitive to the background wind. Strongest wave activity has been observed during eastward and weak westward flow. The wave activity is almost absent during strong westward flow.

Based on the earlier observations it seems that the quasi-7-day wave is a westward propagating wave with zonal wave number 1. The wave activity may be due to inter hemispheric ducting or (more likely) may be due to *in situ* generation. Detailed study about the source mechanism is left for future work.

Acknowledgements

The Resolute Bay radar was built with support of the Natural Sciences and Engineering Research Council of Canada (NSERC). Additional support logistics were provided by Narwhal and by SRI International. The Yellowknife radar was built with support from NSERC, and from Mardoc Inc., and is positioned on land owned by Natural Resources Canada. We are especially grateful to George Jensen for site monitoring. We also acknowledge Mitch Kline for earlier, preliminary work associated with the 7-day wave. We are thankful to Dieter H.W. Peters for valuable discussion. We also like to thank the two reviewers for their comments and suggestions while evaluating this paper.

Appendix A. Calculation of typical vertical wavelengths of the 7-day wave

The vertical wavelength of the wave can be found from the relation (Andrews et al., 1987):

$$\lambda_v = \frac{2\pi}{\sqrt{(N^2/gh)-(1/4H^2)}}$$

where λ_v is the vertical wavelength, N^2 the square of buoyancy frequency, g the acceleration due to gravity (10 m/s^2), h the equivalent depth (4–5 km for 7 day wave) and H the scale height (4.5–7 km, seasonally dependent).

The vertical wavelength mainly depends on N^2, h and H. The scale height can be found from the expression $H=RT/Mg$, and it has seasonal variation mainly over polar MLT region. The H value is about 7 km during winter and 4.5 km during summer. Here we assume that the quasi-7-day wave is the first asymmetric mode with zonal wave number 1. The equivalent depth must be read from tables or graphs. We have used Longuet-Higgins (1968, Figure 2b) and Madden (1979, Figure 3). From Madden (1979, Figure 3), we may read the period on the left-hand scale and the equivalent depth on the top side scale. From mode $\boldsymbol{n}-\boldsymbol{m}=\mathbf{1}$ in Madden (1979) or $\boldsymbol{n}'-\boldsymbol{s}=\mathbf{1}$ in Longuet-Higgins (1968), we estimated the equivalent depth to be about 4–5 km for a 7 day period. The vertical wave lengths estimated for different combinations of N^2, h and H are listed below. Since H is small during summer, the wavelengths are imaginary (evanescent).

N^2 (s^{-2})	$H=7$ km λ_v with $h=4$ km (5 km)	$H=4.5$ km λ_v with $h=4$ km (5 km)
5×10^{-4}	73 (90)	505 (130)
4×10^{-4}	90 (116)	130 (95)
3×10^{-4}	128 (210)	90 (79)

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