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The 16-day variation in the mean flow at Grahamstown (33.3° S, 26.5° E)

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Abstract. Data from the Grahamstown (33.3° S, 26.5° E) meteor radar have been used to study the short-term variations of the mean flow at ∼ 90 km altitude. The results show considerable variation characterised by a superposition of fluctuations on different planetary time scales. Wavelet multi-resolution and spectral techniques reveal that the quasi-16-day oscillation dominates the wave spectrum in the ∼ 2–20-day period range. This quasi-16-day oscillation, which is thought to be related to a similar oscillation in the lower atmosphere, is found to be dominant in winter and the equinoxes. However, it is sometimes significant in summer, which could be due to cross-equatorial ducting and the selective transmissivity of gravity waves.

Key words. Meteorology and atmospheric dynamics (waves and tides)

1 Introduction

Apart from the short (≤ 1 day) period gravity waves and tides, the atmospheric wave field has strong planetary (∼ 2–20 day periodicities) components. The periodicities of about 2-, 5-, 10-, and 16-days that are observed in the mesosphere lower thermosphere (MLT) region are similar to those in the troposphere and the stratosphere (Forbes et al., 1995). The quasi-16-day oscillation is one of the dominant and regularly observed planetary components. A number of studies have focussed on the signatures of this oscillation in both the temperature (e.g. Espy et al., 1997) and wind (e.g. Williams and Avery, 1992; Luo et al., 2000) fields. As a result of its sensitivity to the mean flow, this oscillation is found to be stronger in winter, with a peak at ∼ 60–65 km, extending up to 100 km, but in summer it tends to be weaker and is confined to above 85 km, with a shorter vertical wavelength than in winter (Luo et al., 2000). There are also suggestions that the interannual variations of the 16-day oscillation are associated with the equatorial quasi-biennial oscillation (Espy et al., 1997; Luo et al., 2000).

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2 Data analysis

For this study mean winds were deduced by averaging 4-day time sequences of hourly averaged horizontal (zonal and meridional) wind velocities. This 4-day data window was advanced by 1 day at a time, and the average of the data window was attributed to the second day of the interval. Positive and negative values of the velocity represent the eastward (northward) and westward (southward) wind flow for the zonal (meridional) mean circulation, respectively.

The variations of mean flow tend to be a superposition of variations of different scales. Also, these variations are generally transient due to the fact that the planetary waves that modulate the mean flow are not necessarily long-lived, but are sometimes characterized by transient bursts of activity (Smith, 1985; Vincent, 1990; Beard et al., 2001). The transience and superposition of these variations are conveniently studied by using wavelet spectral techniques and wavelet multi-resolution analysis (MRA), respectively. The simultaneous use of these two techniques, to the knowledge of the authors, has not been done before in MLT dynamics. The wavelet spectral techniques offer good time-frequency resolution. This is due to the fact that, unlike the short-time Fourier transform (STFT), which is sometimes used for dynamic spectra and is based on a fixed window width, the effective width of the wavelet depends on the scale (frequency) of interest. More specifically, this approach allows for the high-frequency (small scale) components to be better resolved in time using a narrow wavelet; one is able to zoom-in on the short-lived high-frequency components like transients (Daubechies, 1992). At the same time, a broader (large-scale/low-frequency) wavelet ensures that the long period cycles are captured effectively.

The MRA capabilities enable us to look hierarchically at the embedded fluctuations in detail by successively remov-

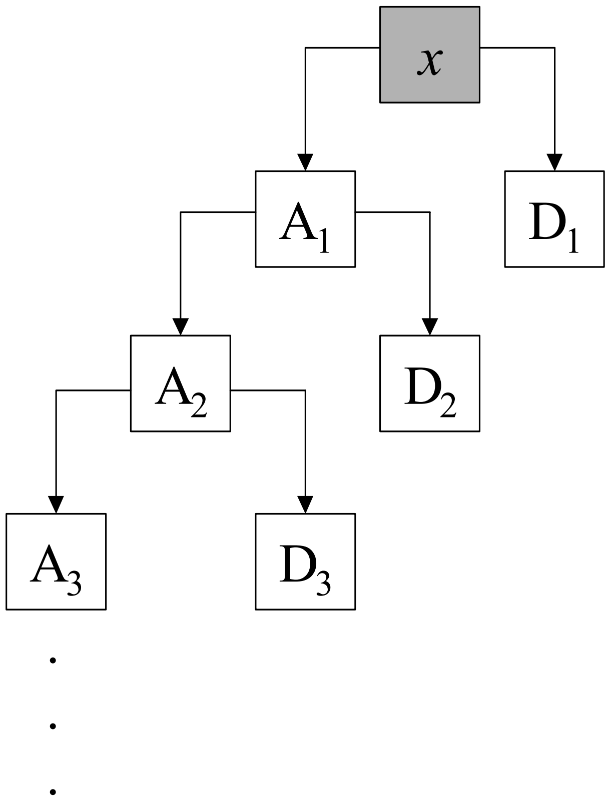

Fig. 1. Schematic diagram of a wavelet multi-resolution analysis. (Modified from Misiti et al., 1996).

ing the smaller scale (i.e. high-frequency) fluctuations while leaving a coarser signal. Kaiser (1994) summarises the multi-resolution process as follows. Consider a signal $x(t)$ with discrete samples x and regular sample interval $\Delta t = \tau$. The signal x is split into an "approximation/blurred" version A_1 at a coarser scale $\Delta t_a = 2\tau$ and "detail" D_1 at a finer scale $\Delta t_d = \tau$ at level 1. This process is repeated on A_1, giving more blurred versions A_2, A_3, ... and more details D_2, D_3, ... that have been removed from A_j at every scale $\Delta t_a = 2^j\tau$, where j is the level. The details of the implementation of this process, which involves intermediate steps of decomposition and reconstruction, are given by Misiti et al. (1996) and are schematically shown in Fig. 1.

For the MRA, we have used the Daubechies' family of wavelets. While these wavelets are suitable for the decomposition and reconstruction processes of the MRA, they unfortunately do not have a well-defined relationship between their scales and Fourier frequencies, which have a clearly understood physical interpretation and are commonly used. To solve this problem, we have also used wavelet software from Torrence and Compo (see Acknowledgements) to do the wavelet spectral analysis. In particular, we have used a Morlet wavelet from their software. Although this wavelet is incapable of decomposing and reconstructing a signal, it has a well-defined relationship between its scales and the Fourier periods, and is, therefore, suitable for the spectral analysis.

3 Results

3.1 Planetary scale fluctuations

Figure 2 shows the mean flow at Grahamstown for the years 1987 to 1994 and the corresponding interannual average (IA; obtained as an average of the other panels excluding data gaps). As has been noted by others (e.g. Jacobi et al., 1998), the zonal wind is consistently larger than the meridional component, and the same is true of the variations. Short-term variations, with time scales of several days, are superimposed on long-term changes (seasonal and interannual, to be discussed in detail elsewhere). The present emphasis is on the short-term variations, which are characterised by changeable periodicities and are thus conveniently studied using wavelet techniques, as described in the previous section.

For the wavelet analysis, we analyzed the data interval starting from January 1987 to December 1988 because it is the longest 2-year interval with superior data availability. Over this period there are just two data gaps exceeding 24 h, both of which occur in 1988: 72 h in April and 202 h in December. Apart from these, less than 6% of the hours are blank and it was assumed that minimal error would be introduced into the wavelet analysis through the use of simple linear interpolation over the gaps. Figure 3 shows the multi-resolution and spectral analysis of the mean-corrected (i.e. reduced to zero mean) mean flow at Grahamstown. The top row of the panels in these figures represents the zonal (u, black line) and the meridional (v, red line) mean-corrected mean flow (after data gaps had been linearly interpolated). In rows 2 to 5 and starting from the left, the first column (of panels) show the low frequency approximations (A_m) for levels m, starting from 1 to 4. The finer resolution details (D_m) are shown in the second column. The parameter s is a characteristic time scale in days. The ranges of s are given for both the approximations and details.

The MRA panels (columns 1 and 2) show the variations of different time scales that are embedded in the total mean wind field. Specifically, the long-term seasonal trend emerges in the approximations as the details are being successively extracted. The details for level 1 are attenuated due to the partial filtering by the 4-day running window. Details for levels 2 and 3 can be as high as $\sim 5 - 10\,\mathrm{ms}^{-1}$ indicating a significant contribution when compared to the peak ($\sim 20\,\mathrm{ms}^{-1}$) of the longest-term trend (level 4). From the details we can see the transient nature of the planetary modulation, characterized by intermittent bursts of activity.

The spectra of the zonal and meridional details obtained by using the software of Torrence and Compo (private communication) are shown in the third and fourth columns, respectively. The yellow solid line demarcates the region where edge effects arising from truncation of the time series will be significant (the "cone of influence"; Torrence and Compo, 1998); periods above this line are expected to suffer from distortion. The red dashed lines represent 95% confidence levels.

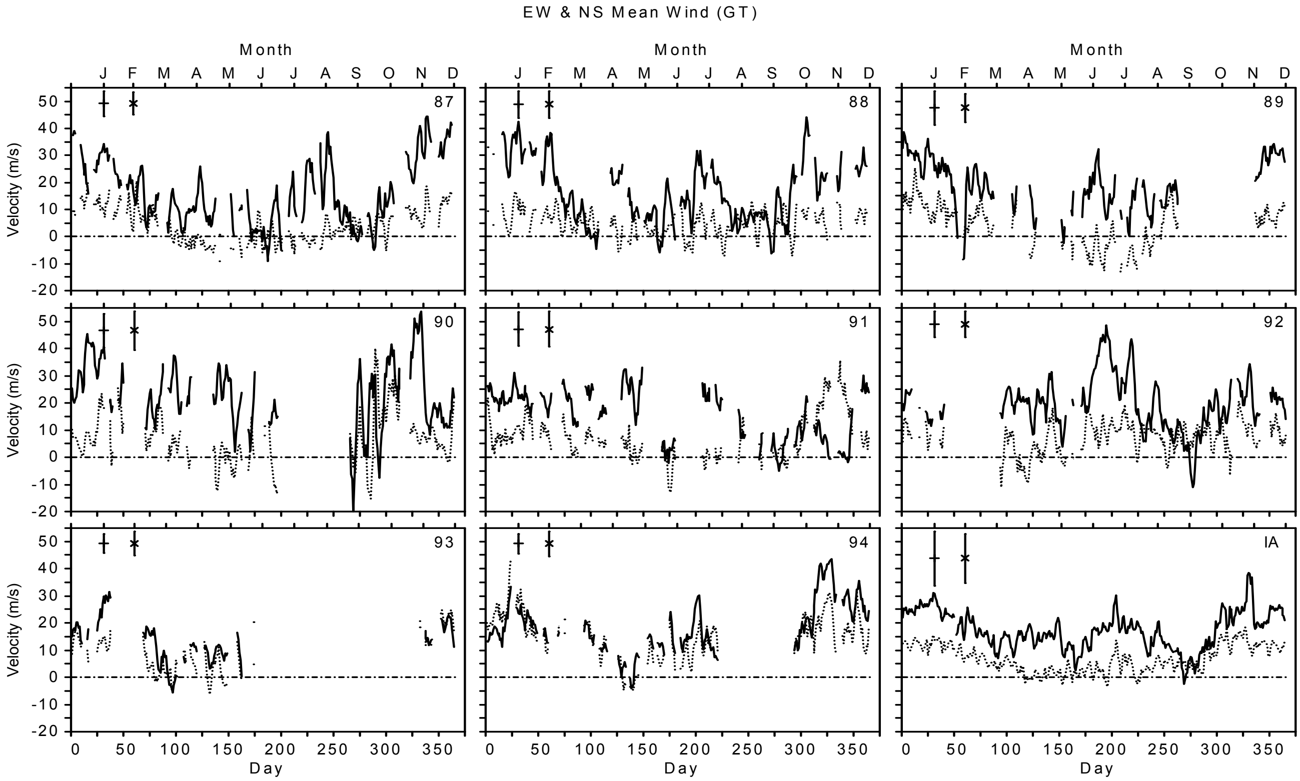

Fig. 2. The zonal (solid line) and the meridional (dotted line) mean winds for the years 1987–1994 and for the corresponding 8-year interannual average (IA). The maximum error (one standard deviation of the mean) for each series is shown at the top left-hand corner with symbol − and ×, representing the zonal and the meridional series, respectively.

The dynamic spectra show a number of planetary scale oscillations in the ∼ 2–20-day period range, with the quasi-16-day (periods of ∼ 12–20 days) oscillation being the most frequent and dominant for both the zonal and the meridional flows. As pointed out by Forbes et al. (1995), the periodicities of about 2-, 5-, 10-, and 16-days that are observed in the MLT region are similar to those in the troposphere and the stratosphere. These transient waves have been shown by longitudinal studies to be westward propagating (Vincent, 1990). Although the sources of these waves are not known with certainty, it is widely assumed that they are due to Rossby-gravity normal modes originating from the lower atmosphere (Vincent, 1990; Williams and Avery, 1992; Forbes et al., 1995). These waves are free waves that are due to random forcing and are determined by the resonant characteristics of the atmospheric mean state as opposed to forcing mechanisms (Ahlquist, 1982). It should also be noted that the interannual differences evident in Fig. 3 are characteristic of the other years covered by the analysis, indicating a general interannual variability in the sources of planetary scale fluctuations.

3.2 The 16-day oscillation

As seen above, the 16-day oscillation is the most dominant planetary scale wave in the ∼ 2–20-day period range. Published work (e.g. Williams and Avery, 1992) shows that the period of this wave is variable and that the peak power is not necessarily at 16 days, which is also confirmed by our results. Williams and Avery (1992) found that the centroid period of the quasi-16-day wave varies from 12 to 17 days, and 12 to 19 days in the troposphere/lower stratosphere and the mesosphere, respectively. However, for brevity we will henceforth omit the prefix quasi.

The seasonal trends of atmospheric waves are governed by, among other factors, the mean flow environment through which they propagate. A wave can only propagate vertically if it satisfies a mean wind filter relation given by $\overline{u} - c > 0$, where $\overline{u}$ is the mean zonal wind and c is the horizontal phase speed of the wave (Williams and Avery, 1992). This implies that a wave will be blocked from propagating vertically when it reaches its critical level which is the level at which its phase speed is equal to the horizontal wind speed.

Since the lower atmospheric mean flow is westward (eastward) in summer (winter) (Kazimirovsky et al., 1988), we would expect that the long-period (> 10 days) waves (being westward propagating), as a result of the filtering effects of the mean wind, will be able to propagate into the upper levels of the atmosphere in winter, but be trapped in the lower atmosphere in summer. Our results (Fig. 3) show that although the wave is frequent and strongest in winter (as found by others – e.g. Jacobi et al., 1998; Beard et al., 2001) and the equinoxes, there are instances when it is at least above the 95% confidence level in summer. While this might seem to contra-

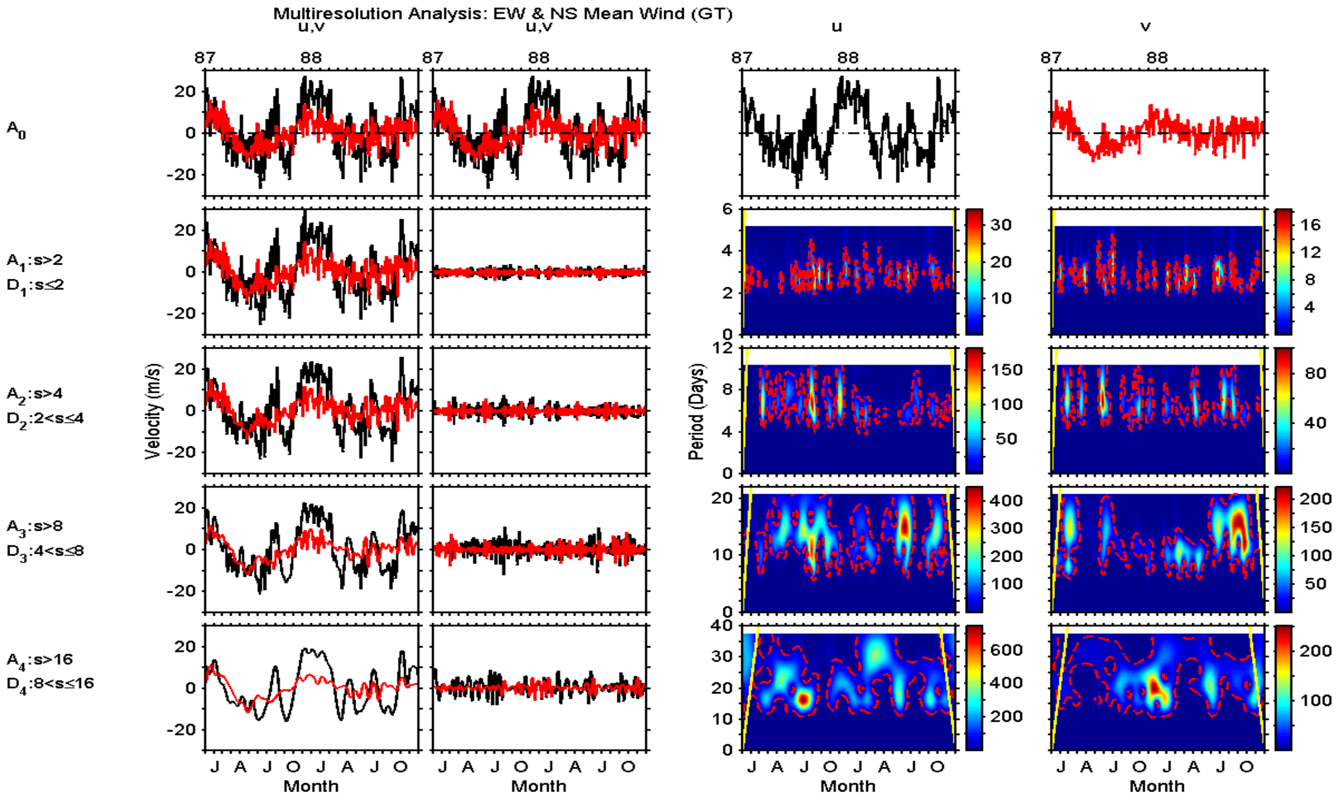

Fig. 3. Analysis of the mean wind at Grahamstown: Top row, the original signal A_o. Rows 2–5, starting from the left show (1st column) the approximations (A_m where m is the level), (2nd column) the details (D_m), (3rd column) the spectrum of the zonal details and (4th column) the spectrum of the meridional details. The black and red time series lines represent the zonal (u) and meridional (v) mean flow, respectively. The scale (s) ranges are shown on the left. The units of the colour bars are arbitrary.

dict expectations, the mesospheric summer 16-day wave has been detected in hydroxyl temperatures (Espy et al., 1997), winds (Williams and Avery, 1992), and has also been simulated (Forbes et al., 1995). Williams and Avery (1992) found significant 16- and 5-day wind oscillations right through the year at almost all heights in the 0–100 km height range at Pokar Flat (65° N, 147° W). In fact, their results show the peak ($\sim 6\,\mathrm{ms}^{-1}$) of the 16-day wave to be in summer at about 85 km. However, from their results, one would have expected this wave to be precluded from propagating above ~ 60 km based on its phase speed of $-15.8\,\mathrm{ms}^{-1}$ and the presence of westward (negative) flows with comparable speeds during the summer months at this height (Williams and Avery, 1992).

A number of authors (Williams and Avery, 1992; Forbes et al., 1995; Espy et al., 1997) have advanced two mechanisms that could possibly explain the occurrence of the 16-day wave in the summer mesosphere above the strong westward filtering flow in the stratosphere. The first is a cross-equatorial ducting of the wave into the summer mesosphere. This process, which has also been simulated by Forbes et al. (1995), involves the generation of the 16-day wave in the lower levels of the winter hemisphere. This wave then propagates vertically through the winter eastward flow. According to Espy et al. (1997), wave energy is shifted during this propagation to regions whose wind is weakly eastward relative to the wave, resulting in diffraction of the wave from its source region in the winter hemisphere into the equatorial waveguide/duct created by the penetration of the mesospheric eastward flow across the equator (Forbes et al., 1995; Espy et al., 1997).

The second possible source of the 16-day wave in the summer hemisphere is due to gravity wave effects. Williams and Avery (1992) point out that the total zonal wind field consists of the mean and the 16-day component, which is the dominant long-period tropospheric wave. Consequently, the critical level of a particular wave will be subjected to a 16-day periodicity, and gravity waves will propagate vertically or be trapped at a 16-day period, depending on their phase speed (Williams and Avery, 1992). This periodic transmissivity results in a similarly modulated breaking or viscous dissipation of gravity waves, and hence, a modulated momentum flux divergence, which could act as a source of a secondary 16-day wave in the MLT which eventually spreads to both hemispheres (Forbes et al., 1995). At the same time it should be noted that Forbes et al. (1995) demonstrated that gravity wave stress can significantly reduce the 16-day response in the winter MLT region and eliminate interhemispheric ducting. Therefore, there is a possibility of a complicated interaction between the ducting and the gravity wave mechanism.

A general observation made at Grahamstown is that the 16-day wave does not always show correlation between the zonal component and the meridional component. This lack of correlation suggests that, in general, the relevant sources of the observed variations are different or that each component responds differently to the same source. This is consistent with the fact that, even if there are no mean wind variations, the zonal and meridional velocities of Rossby waves have different horizontal characteristics (Salby and Roper, 1980). Another possible explanation for the lack of correlation with regard to the 16-day wave could be the interhemispheric ducting of this wave which, as found by Forbes et al. (1995), has a strong zonal response and no meridional response. The periodic transmissivity mechanism could also enhance a particular component and not the other, depending on the directions of the transmitted gravity waves.

4 Summary

The results presented in this paper show a number of important features regarding the mean flow at about 33° S and at about 90 km altitude. We have made use of wavelet and multi-resolution (MRA) techniques, which, due to their time-frequency flexibility, are particularly suited to the study of transient structures, such as those which characterize planetary waves. Applying MRA to the mean flow we observe significant planetary scale signatures that are superimposed on long-term trends. The planetary scale modulations are most likely due to the effects of Rossby-gravity normal modes originating from the lower atmosphere. While various planetary waves are observed, our results reveal that in the planetary scale range, the 16-day wave is the most dominant. As expected from the filtering effects, this oscillation is strongest during the eastward stratospheric winter jet. The equinoxes also have a strong 16-day signature. Contrary to expectations based on the expected westward stratospheric mean jet, this wave is sometimes found to be at least above the 95% confidence level in summer. Such behaviour is not unique to our results. For instance, the mesospheric summer 16-day wave has been detected in hydroxyl temperatures (Espy et al., 1997) and winds (Williams and Avery, 1992), and has also been simulated (Forbes et al., 1995). Two mechanisms are thought to be the cause of this summer occurrence. The first is the cross-equatorial ducting of the wave due the penetration of the mesospheric eastward flow across the equator (Forbes et al., 1995; Espy et al., 1997). The second is the selective transmissivity of gravity waves at 16-day periods due to the modulation of the mean flow filtering process by the lower atmospheric 16-day oscillation.

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References

Ahlquist, J. E.: Normal-mode global Rossby waves: Theory and observations, J. Atmos. Sci., 39, 193–202, 1982.

Beard, A. G., Williams, P. J. S., Mitchell, N. J., and Muller, H. G.: A spectral climatology of planetary waves and tidal variability, J. Atmos. Solar-Terr. Phys., 63, 801–811, 2001.

Daubechies, I.: Ten lectures on wavelets, Society for Industrial and Applied Mathematics, Philadelphia, USA, 1992.

Espy, P. J., Stegman, J., and Witt, G.: Interannual variations of the quasi-16-day oscillation in the polar summer mesospheric temperature, J. Geophys. Res., 102, 1983–1990, 1997.

Forbes, J. M., Hagan, M. E., Miyahara, S., Vial, F., Manson, A. H., Meek, C. E., and Portnyagin, Y. I.: Quasi 16-day oscillation in the mesosphere and lower thermosphere, J. Geophys. Res., 100, 9149–9163, 1995.

Jacobi, C., Schminder, R., and Kürschner, D.: Planetary wave activity obtained from long period (2–18 days) variations of mesopause region winds over Central Europe (52° N, 15° E), J. Atmos. Solar-Terr. Phys., 60, 81–93, 1998.

Kaiser, G.: A friendly guide to wavelets, Birkhäuser, Boston, 1994.

Kazimirovsky, E., Manson, A. H., and Meek, C. E.: Winds and waves in the middle atmosphere at Saskatoon (52° N, 107° W), Collm (52° N, 15° E) and Badary (52° N, 105° E), J. Atmos. Terr. Phys., 50, 243-250, 1988.

Luo, Y., Manson, A. H., Meek, C. E., Meyer, C. K., and Forbes, J. M.: The quasi 16-day oscillations in the mesosphere and lower thermosphere at Saskatoon (52° N, 107° W), 1980–1996, J. Geophys. Res., 105, 2125–2138, 2000.

Misiti, M., Misiti, Y., Oppenheim, G., and Poggi, J.: Wavelet Toolbox, The MathWorks, Inc. Natick., 1996.

Salby, M. L. and Roper, R. G.: Long-period oscillations in the meteor region, J. Atmos. Sci., 37, 237–244, 1980.

Smith, A. K., Wave transience and wave-mean flow interaction caused by the interference of stationary and traveling waves, J. Atmos. Sci., 42, 529-535, 1985.

Torrence, C. and Compo, G. P.: A Practical Guide to Wavelet Analysis, Bull. Am. Met. Soc., 79, 61–78, 1998.

Vincent, R. A.: Planetary and gravity waves in the mesosphere and lower thermosphere, Adv. Space Res., 10, (12), 93–101, 1990.

Williams, C. R. and Avery, S. K.: Analysis of long-period waves using the mesosphere-stratosphere-troposphere radar at Poker Flat, Alaska, J. Geophys. Res., 97, 20 855–20 861, 1992.