HF Radar Observations of a Quasi Biennial Oscillation in Mid-Latitude Mesospheric Winds

Garima Malhotra,[1] J. M. Ruohoniemi,[1] J. B. H. Baker[1] R. E. Hibbins[2] and K. A. McWilliams[3]

Corresponding author: Garima Malhotra, Electrical and Computer Engineering, Virginia Tech, VA, USA. (garima@vt.edu)

[1]Bradley Department of Electrical and Computer Engineering, Virginia Tech, USA.

[2]Department of Physics, Norwegian University of Science and Technology, Trondheim, Norway and Birkeland Centre for Space Science, Bergen, Norway

[3]University of Saskatchewan, Canada

Abstract.

The Equatorial Quasi Biennial Oscillation (QBO) is known to be an important source of interannual variability in the mid and high-latitude stratosphere. The influence of the QBO on the stratospheric polar vortex in particular has been extensively studied. However, the impact of the QBO on the winds of the mid-latitude mesosphere is much less clear. We have applied 13 years (2002-2014) of data from the Saskatoon SuperDARN HF radar to show that there is a strong QBO signature in the mid-latitude mesospheric zonal winds during the late winter months. We find that the Saskatoon mesospheric winds are related to the winds of the equatorial QBO at 50 hPa such that the westerly mesospheric winds strengthen when QBO is easterly, and vice-versa. We also consider the situation in the late-winter Saskatoon stratosphere using the ECMWF ERA-Interim reanalysis data set. We find that the Saskatoon stratospheric winds between 7 hPa and 70 hPa weaken when the equatorial QBO at 50 hPa is easterly, and vice-versa. We speculate that gravity wave filtering from the QBO-modulated stratospheric winds and subsequent opposite momentum deposition in the mesosphere plays a major role in the appearance of the QBO signature in the late winter Saskatoon mesospheric winds, thereby coupling the equatorial stratosphere and the mid-latitude mesosphere.

1. Introduction

The zonal winds in the equatorial stratosphere exhibit a marked Quasi Biennial Oscillation (QBO) that is characterized by switching between easterlies and westerlies with an average period of ∼28 months [*Reed*, 1965; *Naujokat*, 1986; *Baldwin et al.*, 2001; *Kawatani and Hamilton*, 2013]. The QBO was discovered independently by *Reed et al.* [1961] and *Ebdon* [1960] and is an important mode of interannual variability in the tropics. The easterly and westerly shears originate at ∼3 hPa (∼35-40 km) and propagate downward with a speed of ∼1-2 km/month until they dissipate near ∼90 hPa (∼18 km) [*Reed et al.*, 1961; *Baldwin and Dunkerton*, 1998]. QBO is zonally symmetric and is strongest at the equator with a Gaussian-like latitudinal half-width of ∼12° [*Wallace*, 1973; *Baldwin et al.*, 2001]. Numerous modeling and simulation studies have established that its generation mechanism is an interaction between equatorial gravity waves and the background mean flow [*Lindzen and Holton*, 1968; *Holton and Lindzen*, 1972; *Plumb and Bell*, 1982; *Dunkerton*, 1997]. Even though QBO is a tropical phenomenon, it is observed to modulate the extratropical circulation in mid- as well as high-latitudes [*Sprenger and Schminder*, 1968; *Belmont and Nastrom*, 1979; *Holton and Tan*, 1980; *Dunkerton and Baldwin*, 1991; *Baldwin and Dunkerton*, 1998]. Specifically, the interannual variation of the winter polar vortex due to QBO has been the subject of studies since the 1980s [*Holton and Tan*, 1980; *Dunkerton and Baldwin*, 1991; *Baldwin and Dunkerton*, 1998].

The relationship between the polar vortex and equatorial stratospheric QBO is widely known as the Holton-Tan (HT) relationship, in which the easterly phase of QBO (∼50 hPa) results in a warmer and weaker polar vortex. *Holton and Tan* [1980] first described a mechanism to explain this synchronization between QBO and polar stratospheric winds using 16 years of geopotential height data in the Northern Hemisphere. They proposed that easterly QBO (∼50 hPa) shifts the zero-wind line into the subtropics of the winter hemisphere, narrowing the waveguide for planetary-wave propagation, resulting in poleward refraction of planetary waves and hence, a disturbed polar vortex. By contrast, westerly QBO causes the planetary waves from the extratropics to leak into the summer hemisphere, resulting in a colder, more stable vortex in the winter hemisphere. Though plausible, this mechanism has not been adequately verified due to inconclusive observations of QBO modulation of planetary wave fluxes [*Holton and Tan*, 1980, 1982; *Dunkerton and Baldwin*, 1991] and several other mechanisms have been suggested to explain the HT relationship [*Gray et al.*, 2001a, b; *Pascoe et al.*, 2006; *Naoe and Shibata*, 2010; *Garfinkel et al.*, 2012]. Some studies have also observed modulation of the HT relationship by the 11 year solar cycle [*Labitzke and Loon*, 1988; *Gray et al.*, 2004; *Lu et al.*, 2008, 2009].

The existence of the QBO is not just limited to the stratosphere but extends into the mesosphere as well [*Burrage et al.*, 1996]. Mesospheric QBO maximizes at the equator but extends to ±30° latitudes [*Burrage et al.*, 1996]. Equatorial Mesospheric QBO maximizes during the spring equinox and is opposite in phase with the stratospheric QBO [*Venkateswara Rao et al.*, 2012]. It is most probably generated by momentum deposition of gravity waves selectively filtered by the stratospheric winds [*Mayr et al.*, 1997; *de Wit et al.*, 2013]. At high-latitudes, a mesospheric QBO signal has been previously observed in planetary wave activity [*Espy et al.*, 1997; *Hibbins et al.*, 2009], semidiurnal tides [*Jarvis*, 1996; *Hibbins et al.*, 2007, 2010], diurnal tides [*Xu et al.*, 2009], temperatures [*Espy et al.*, 2011; *Mayr et al.*, 2009] and winds [*Ford et al.*, 2009; *Hibbins et al.*, 2009].

However, at mid-latitudes, the mesospheric QBO signal is comparatively less understood. Its amplitude and period have been observed to vary between 1-7 m/s and 22-36 months, respectively [*Sprenger and Schminder*, 1968; *Groves*, 1973; *Sprenger et al.*, 1975; *Neumann*, 1990; *Namboothiri et al.*, 1994; *Kane et al.*, 1999; *Manson et al.*, 1981]. *Belmont and Nastrom* [1979] reported a weak QBO in the Saskatoon mesosphere below 118 km with a phase shift of 180° between 94 and 97 km. *Namboothiri et al.* [1993] found a biennial periodicity in the winds at Saskatoon but could not link it to the equatorial QBO due to an inconsistent phase relationship. *Kürschner and Jacobi* [2003] found a QBO effect in mesospheric winds at Collm (∼50°N) in phase with stratospheric winds at 30 hPa. However, several studies have searched for, but been unable to find, a robust QBO signal [*Middleton et al.*, 2002; *Baumgaertner et al.*, 2005]. Thus, the relationship of mid-latitude mesospheric QBO with equatorial QBO and its generation mechanism remains unclear.

This study aims to investigate the extent to which a QBO signature appears in the mid-latitude mesospheric winds measured by the SuperDARN HF radar at Saskatoon (52.16°N, 106.53°E). We demonstrate the existence of such a signature and investigate its correlation with the equatorial QBO and its seasonal dependence and discuss its possible source. This paper is organised as follows: Section 2 describes the data sets employed and how they were pre-processed, Section 3 describes the results obtained by comparing the Saskatoon winds with equatorial measurements and Section 4 discusses and interprets these results followed by Section 5 which gives the Conclusions.

2. Data sets and Pre-processing

2.1. Saskatoon SuperDARN radar: Mid-Latitude Mesospheric Winds

The primary data set relates to the prevailing mesospheric winds measured by the HF radar located at Saskatoon (52.16°N, -106.53°E). This radar belongs to the Super Dual Auroral Radar Network (SuperDARN) which is a network of 30+ HF radars distributed across various sites in the mid to high latitude regions of the Northern and Southern hemispheres. The primary purpose of SuperDARN is to study plasma convection in the ionosphere by receiving backscatter from magnetic field aligned plasma irregularities [*Greenwald et al.*, 1985]. This study makes use of the 'Grainy Near-Range Echoes' (GNREs) observed in the first few range gates which are backscattered from meteor ionization trails at 94±3 km altitude [*Hall et al.*, 1997; *Chisham et al.*, 2007]. Meteor backscatter usually has a peak during local midnight and early morning hours. The longest and most reliable time series of such measurements is from the radar at Saskatoon which has been operating almost continuously since 1994.

The meteor echoes observed by the SuperDARN radars can be used to derive wind velocities at mesospheric heights of 94±3 km [*Jenkins et al.*, 1998; *Hussey et al.*, 2000]. Extracting hourly mean zonal and meridional components of the mesospheric winds from the Saskatoon radar meteor echoes requires some pre-processing steps to isolate them from other forms of backscatter and to remove noise. Specifically, we have excluded echoes having line of sight velocity greater than 100 m/s, error in velocity greater than 50 m/s [*Hibbins et al.*, 2009], spectral width less than 1 m/s or greater than 50 m/s and signal to noise ratio less than 3 dB or greater than 24 dB [*Matthews et al.*, 2006]. The remaining echoes are assumed to represent backscatter from meteor ionization trails and are used to calculate hourly median velocities over the first four range gates. The median line-of-sight velocity for each beam-gate cell is then scaled by the elevation angle to obtain horizontal velocities. The analysis assumes that the same neutral wind vector is present over the entire area covered by the radar beams and the wind has a well defined average velocity within the one-hour UT intervals. Hourly median horizontal velocities in the first four range gates are averaged for each beam resulting in 16 velocity values for every hour. These azimuthally distributed velocities are then fit using least squares singular value decomposition over all radar beam azimuth angles [*Press et al.*, 1992]. The total number of meteor echoes including all beams and first four range gates, range between tens (local noon) to thousands (local dawn) per hour. The fitting is performed for those hours having data in at least five radar beams. The standard errors in the wind velocities are determined from the covariance matrix of errors. The extent of uncertainties largely depend on the number of meteors detected and the spread in azimuth of the beams used for the final two component horizontal wind fit. Previous studies have used a similar technique to derive mesospheric winds from the SuperDARN radars [*Jenkins et al.*, 1998; *Jenkins and Jarvis*, 1999; *Bristow et al.*, 1999; *Hussey et al.*, 2000; *Malinga and Ruohoniemi*, 2007; *Hibbins et al.*, 2007].

The last step is to produce a daily zonal wind using a technique similar to that used by *Hibbins and Jarvis* [2008]. Specifically, hourly zonal winds are split into 4-day segments and a running non-linear least squares fit analysis (centered on the third day) is done to remove the high frequency components of terdiurnal (8 hour), semidiurnal (12 hour), diurnal (24 hour) tides and the quasi two day (48 hour) planetary wave. To ensure a good fit, only those data segments having more than half (>48) of the hourly winds are used. This running fit analysis is successively stepped by one day to create a time series of the daily zonal winds. Monthly mean winds are then calculated by averaging the daily zonal winds if the number of daily zonal wind measurements are greater than 15 in a month. The uncertainties are determined by standard errors around the mean. The measurements span the 2002-2014 interval. For this entire duration, there were no months for which monthly mean winds could not be determined.

Previous studies have compared the winds derived from SuperDARN radars with measurements of other co-located instruments and found good agreement at mesospheric altitudes of ~95 km [*Bristow et al.*, 1999; *Hussey et al.*, 2000]. Over the past decade, the SuperDARN radars have been used to study several prominent mesospheric phenomena such as the Quasi Two Day planetary wave [*Malinga and Ruohoniemi*, 2007], polar mesospheric summer echoes [*Ogawa et al.*, 2004], long-period planetary waves [*Espy et al.*, 2005; *Hibbins et al.*, 2009; *Kleinknecht et al.*, 2014] and semidiurnal tides [*Hibbins et al.*, 2007; *Hibbins and Jarvis*, 2008].

2.2. ERA Interim-ECMWF: Mid-Latitude Stratospheric Winds

To assess the QBO signature in the mid-latitude stratosphere, winds are specified using monthly mean zonal wind data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Re-Analyses (ERA) Interim data set. This global atmospheric reanalysis data set began in 1979, is constantly updated in real time, and has a spatial resolution of 0.75°. It uses the ECMWF Integrated Forecasting System (IFS), which incorporates a model with three fully coupled components for the atmosphere, land surface, and ocean waves [*Dee et al.*, 2011]. All observations used in ERA-Interim are subject to a suite of quality control and data selection steps [*Dee et al.*, 2011]. The forecast model, data assimilation method and input data sets used to produce ERA-Interim are described in detail by *Berrisford et al.* [2009] and *Dee et al.* [2011]. For the purposes of this study, we use the zonal winds for 2002-2014 obtained from pressure levels 1 to 70 hPa at 53°N and -106°E as an approximate measure of winds in the stratosphere over Saskatoon.

2.3. Singapore Radiosonde Station: Equatorial Stratospheric Winds

Winds in the equatorial stratosphere are specified using monthly mean zonal wind data obtained by the Singapore radiosonde station (1°N, 104°E). These measurements are commonly used as a proxy for the equatorial Quasi Biennial Oscillation (QBO). The data were downloaded from http://www.geo.fu-berlin.de/met/ag/strat/produkte/qbo/singapore.dat provided by Free University of Berlin. This data set has been produced since 1987 from the Singapore radiosonde measurements by using the daily vertical wind profiles. This data set is representative of the entire equatorial belt since longitudinal differences in the phase of QBO are known to be small [*Belmont and Dartt*, 1968]. The limitation of this data set is that the uncertainties in the wind velocities are not provided. For the purposes of this study, we use the zonal winds for 2002-2014 obtained from pressure levels 10 hPa to 100 hPa.

3. Results

In this section, we present evidence of a QBO signature in the mid-latitude mesospheric winds measured by the Saskatoon HF radar and show that it has a significant correlation with the equatorial QBO measured in the Singapore radiosonde data, and investigate the relationship with the mid-latitude stratospheric winds derived from the ECMWF data set.

3.1. Zonal Wind Observations

Saskatoon Mesospheric Winds: Monthly mean zonal winds measured by the mid-latitude Saskatoon radar for 2002-2014 are presented in Figure 1a. A persistent seasonal cycle is apparent along with year-to-year variations. To isolate this interannual variability, the winds are first de-seasonalized in Figure 1b by subtracting the average climatology from the time-series in Figure 1a, and then a Lomb-Scargle analysis is performed to examine the frequency components in the residual winds. Figure 1c shows the Lomb Scargle periodogram obtained. The black horizontal dotted line indicates the 90% confidence level. Several peaks are visible. Of particular note for this study is the peak at 27.6 months which can be associated with the Quasi Biennial Oscillation (QBO) and the peaks around 8 and 22 months could be attributed to a non-linear interaction between the seasonal (12 month) cycle and the QBO, suggesting that the QBO signal is preferentially carried in one season.

Singapore Equatorial QBO: Quasi-biennial oscillation is often seen at the equator as downward propagating bands of alternating westerly and easterly winds. These features are illustrated in Figure 2a which shows height-resolved stratospheric monthly mean zonal winds at the Singapore equatorial radiosonde station for 2002-2014. The contour interval is 10 m/s with positive (negative) representing westerly (easterly) winds. Year labels on the horizontal axis at dashed lines show start of the year. Figure 2b shows the zonal winds at Singapore equatorial radiosonde station at 50 hPa and Figure 2c shows their Lomb Scargle periodogram with a peak at 27.3 months (red line). A cycle of ~28 months can be clearly seen in Figure 2b along with pronounced asymmetry between the two phases such that easterly phases tend to have higher intensity and shorter duration than westerly phases at 50 hPa. This is especially evident from 2009 onwards. At 50 hPa, most of the phase transitions occur in Northern spring-summer months (Mar-Aug) suggesting QBO is synchronized with the annual cycle at this altitude. By contrast, at about 100 hPa (∼15-20 km) in Figure 2a, QBO is much less apparent and there is instead a steady layer of easterly winds. Therefore, for further analysis, we consider the equatorial QBO between 10-70 hPa, as the QBO is strongest at these altitudes.

Comparison of Figure 2b to Figures 1a and 1b shows that the late winter (Jan-Feb) peaks in westerly mesospheric winds (e.g. during 2004, 2006 and 2013) typically occur during easterly phases of the 50 hPa QBO. There is some evidence to suggest that the mesospheric zonal wind anomalies at mid-latitudes are related to the phase of the equatorial stratospheric QBO.

QBO-ordered Climatology of Mid-Latitude Mesospheric winds: To further study the possibility of QBO influences in the mid-latitude Saskatoon mesospheric winds, we divide the monthly mean wind data shown in Figure 1a according to QBO phase to produce a climatology of the mid-latitude zonal winds for when the QBO phase is positive at 50 hPa and when the QBO phase is negative at 50 hPa. Figure 3a shows the result. The blue curve is the climatology for time periods when QBO was easterly while the red curve is the climatology for the time periods when QBO was westerly. The average climatology obtained by averaging all time periods, is identified by the green curve. The data points used for plotting the two QBO climatologies are also shown for each month, with blue (red) points representing the average wind velocities during QBO easterly (westerly) phases. It is evident from the green curve that the mid-latitude mesospheric winds at Saskatoon are dominated by easterlies (negative values) from Mar to Jun and westerlies (positive values) during rest of the year. During winter (Nov-Feb), the prevailing winds at Saskatoon are generally westerlies and dramatically reverse to easterlies between Feb and Apr. These winds then reverse back to westerlies in Jun reaching high magnitudes of around ∼15 m/s in Aug. The winds decrease to low magnitudes of ~ 5 m/s in Sep and of $\sim 2-3$ m/s in Oct, however, they do not reverse direction. These westerly winds start increasing in magnitude from Oct and persist for the entire winter. This climatology agrees well with that described by *Manson and Meek* [1986] and *Portnyagin and Solovjova* [2000] at ∼95 km at mid-latitudes.

It can also be observed that although the mean directions of the winds remain the same, the difference between the winds of the two QBO climatologies ranges between 0 m/s and 8 m/s. Figure 3b shows the difference between the QBO and the average climatologies. The blue curve shows the difference between the QBO easterly and the average climatology (blue curve-green curve of Figure 3a), whereas the red curve shows the difference between the QBO westerly and the average climatology (red curve-green curve of Figure 3a). From Figure 3b, during early winter (Nov-Dec), no statistically significant QBO modulation is present as the error bars (or even means) overlap. However, in late winter (Jan-Feb), a statistically significant modulation is seen such that the easterly phase (blue) of QBO increases the magnitude of the Saskatoon mesospheric winds relative to the westerly phase (red). The effect of QBO after the spring reversal, during Apr and May, is such that the easterly (westerly) phase of QBO increases (decreases) the magnitude of the easterly wind velocities, whereas during Aug it decreases (increases) the magnitude of westerly wind velocities. In Sep, the effect of QBO flips again and is similar to that observed in late winter. It should be noted in Figure 3a that the green curve does not exactly lie between the blue and red curves. This is because the number of points are unequal in the two QBO climatologies owing to asymmetry between the two phases as noted previously in Figure 1b. It can be observed from panels a, b and c that the QBO differences are largest during late winter (Jan-Feb).

3.2. Correlative Analysis: All Months

Saskatoon Mesospheric Winds vs. Singapore Stratospheric QBO: To further examine the characteristics of the QBO signal in the Saskatoon monthly mean mesospheric zonal winds (∼95 km), a height resolved correlation analysis is performed against the Singapore stratospheric QBO spanning all pressure levels (10-70 hPa), for each month. The results are shown as a correlation contour plot in Figure 4 with an interval of 0.1 and colors representing the Pearson correlation magnitudes. White contours identify correlations having significance>90%. Significance is calculated from the p-value which roughly indicates the probability of an uncorrelated system producing datasets that have a Pearson correlation at least as extreme as the one computed from these datasets. Each data point on this contour plot represents the correlation between two data series of 13 points (for 13 years). A feature of particular interest is the relatively high negative correlation which occurs during late winter (Jan-Feb) corresponding to the lower stratospheric QBO (40-70 hPa), whereas a positive correlation is observed at the higher altitudes (10-20 hPa). Thus, there is a sharp altitude gradient in the correlation during these months at ∼25-30 hPa. This indicates that the QBO during these months reverses its phase at these altitudes. In Mar, the positive correlation with the upper stratospheric QBO continues. From Apr to May, the region of positive correlation with QBO moves to lower altitudes of 40-70 hPa. This is followed by negligible to slightly negative correlation in Jun-Jul and hence no discernible QBO influence on the Saskatoon mesospheric winds in early summer. In Aug, the correlation of the winds with lower stratospheric QBO (30-50 hPa) flips again and becomes positive, with significance greater than 90%. This is opposite to that observed in late winter at lower altitudes. In Sep, the Saskatoon mesospheric winds exhibit negative correlation with Singapore lower stratospheric QBO followed by negligible correlation in early winter (Oct, Nov, Dec) at all altitudes of QBO. This figure implies that the Saskatoon mesospheric winds are significantly correlated with the equatorial QBO during Jan, Feb, Mar and Aug.

From Figures 3 and 4, we conclude that the Saskatoon mesospheric winds exhibit the largest QBO signal in the radar data during late winter (Jan-Feb). We therefore investigate the winds during this time in more detail through time series analysis.

3.3. Correlative Analysis: Late Winter

Saskatoon Mesospheric Winds vs. Singapore Stratospheric QBO:

Figure 5a shows the time series of averaged late winter QBO zonal winds measured by the equatorial Singapore radiosonde at 50 hPa and Figure 5b shows mesospheric zonal winds measured by the mid-latitude Saskatoon radar from 2002 to 2014 through the late winter period. The error bars in Figure 5b represent the standard errors of the mean. The positive velocities indicate westerly winds and negative velocities indicate easterly winds. The designation of all positive values in Figure 5b indicates that the mesospheric winds are consistently westerly during Jan-Feb, as observed before in Figure 3, whereas QBO in Figure 5a alternates between its westerly and easterly phases. The main feature of interest in Figure 5b is the approximately two-year periodicity in the Saskatoon mesospheric winds. The Pearson correlation coefficient between the two time series is -0.61 with a significance of ∼97.4%. This corresponds to the blue colored area on the bottom left (during Jan-Feb) of Figure 4. The dominant feature in this figure is that the mesospheric winds tend to strengthen (weaken) and hence become more (less) westerly when QBO at 50 hPa is easterly (westerly). However, there are some years when the variations are less distinct and this general trend is not so apparent, for example, 2009-2012 corresponds to a change in QBO structure in Figure 5a. This feature can also be identified in Figure 2a and 2b. Both data sets exhibit more irregular behavior through these years. It should also be noted that before 2009, QBO is largely synchronized with the annual cycle (Figure 2b). When these two cycles decouple after 2009, the correlation between the Saskatoon mesospheric winds and the QBO breaks down in Figure 5.

Saskatoon Stratospheric Winds vs. Singapore Stratospheric QBO:

Unlike its influence on the mid-latitude mesosphere, the QBO is widely known to modulate the stratospheric polar vortex winds and planetary wave fluxes in the winter hemisphere [*Holton and Tan*, 1980; *Anstey and Shepherd*, 2014], although the consistency of the HT relationship over time has been found to be variable [e.g., *Naito and Hirota*, 1997; *Lu et al.*, 2008] especially over late winter. It is also widely known that the mesospheric circulation is primarily driven by momentum flux deposition of a spectrum of near-vertically propagating gravity waves filtered by the stratospheric winds [*Holton*, 1983]. It is therefore possible that some of the QBO signature seen in the Saskatoon mesospheric winds is linked to the stratospheric dynamics at Saskatoon.

To investigate the possibility that the QBO signature in Saskatoon mesospheric winds might be mediated through the underlying stratosphere and to confirm that the HT relationship holds for Saskatoon over the time period we are investigating, late winter monthly mean winds spanning pressure levels from 1 to 70 hPa derived from the ERA-Interim data set at Saskatoon are differenced with respect to the phase of the Singapore equatorial QBO at 50 hPa. The results are presented in Figure 6. The vertical axis shows the height in hPa and horizontal axis shows the difference between 50 hPa QBO westerly and QBO easterly conditions in m/s. The positive difference indicates that the winds below 7 hPa in the Saskatoon stratosphere strengthen when the equatorial QBO (50 hPa) is westerly, consistent with the HT relationship. This modulation of the late-winter stratospheric winds maximizes at 10 m/s at around 10 hPa consistent with the results of *Dunkerton and Baldwin* [1991]. The error bars represent the standard error of the mean and demonstrate that the wind difference is statistically greater than zero between 7 and 70 hPa. We note that this relationship between Saskatoon lower stratospheric winds and QBO at 50 hPa during late winter is opposite to that of the Saskatoon mesospheric winds (∼95 km) and QBO at 50 hPa as discussed in connection with Figure 5.

Saskatoon- HF Radar Mesospheric Winds vs. ECMWF Stratospheric Winds. To further investigate the relationship between the mid-latitude mesosphere and stratosphere, a correlation analysis is performed between the Saskatoon HF radar mesospheric winds and the Saskatoon ECMWF stratospheric winds. Figure 7 shows the result. It should be noted that the HF radar mesospheric winds are obtained at a constant altitude of ∼95km, whereas the stratospheric winds derived from ECMWF span the altitudes from 1 to 70 hPa. The vertical axis shows the ECMWF wind height in hPa and horizontal axis shows the Pearson correlation magnitudes. A negative correlation below 2 hPa, maximizing to ∼-0.49 (∼91% significant) at ∼7-10 hPa, indicates that mesospheric winds are negatively correlated with the stratospheric winds at Saskatoon below 2 hPa.

This negative correlation between the stratospheric and mesospheric winds at Saskatoon provides a basis for concluding that the QBO signature in Saskatoon mesospheric winds is indeed mediated through the underlying stratosphere. In the next section, we discuss a plausible mechanism based on vertical coupling.

4. Discussion

In this study we have identified a Quasi-Biennial signature in mesospheric winds measured by the Saskatoon HF radar, that is correlated with the equatorial QBO (Figure 3, 4). This feature is strongest during late winter (Jan-Feb) when winds in the Saskatoon mesosphere are negatively correlated with the QBO (∼45-50 hPa) such that when QBO is easterly (westerly), Saskatoon mesospheric winds tend to become more (less) westerly (Figures 3, 4, 5). By contrast, the Saskatoon ECMWF stratospheric winds become less (more) westerly during easterly (westerly) QBO (Figure 6). The stratospheric and mesospheric winds at Saskatoon are thus anti-correlated during late winter (Figure 7). In this section we discuss these results in the context of previous studies and search for a mechanism which may provide a causative explanation for the correlations we have identified linking the equatorial QBO to the Saskatoon mesospheric winds.

Previous observational and modeling studies have reported a disturbed, warmer polar vortex during the easterly phase of QBO (∼50 hPa) as opposed to a stable, colder polar vortex during its westerly phase [*Holton and Tan*, 1980, 1982; *Baldwin et al.*, 2001; *Anstey and Shepherd*, 2014]. This is sometimes referred to as the HT effect [*Garfinkel et al.*, 2012; *Lu et al.*, 2014] after *Holton and Tan* [1980], who first explained it in terms of QBO influence on winter planetary wave activity. Previous studies have reported that the HT effect is generally felt throughout the winter, although the relationship is more robust in early winter than in late winter [*Dunkerton and Baldwin*, 1991; *Lu et al.*, 2008]. The difference climatology presented in Figure 6 indicates that the weakening of winter westerly winds during easterly phase of QBO, holds true for the mid-latitude Saskatoon stratosphere during Jan-Feb between 2002 and 2014 as well. How this influence becomes manifested in the Saskatoon mesosphere is the next question that needs to be considered.

Figure 7 shows a clear anti-correlation between Saskatoon mesospheric and stratospheric winds which could conceivably be explained by gravity wave coupling between the two regions. It is well established that as a spectrum of atmospheric gravity waves propagates upwards and is filtered by stratospheric zonal winds, the waves become unstable, depositing net wave momentum flux to the mesosphere that is in the opposite direction to the stratospheric winds [e.g., *Fritts and Alexander*, 2003]. Whether, this gravity wave momentum flux will accelerate or retard the flow in mesosphere, should depend on the relative direction of the stratospheric and mesospheric winds. It is possible that the QBO signature in Saskatoon mesospheric winds seen in Figure 5 is a result of a similar process. Namely, when the stratospheric winds at mid-latitudes are anomalously easterly during easterly QBO (HT effect), the westward gravity waves are filtered out leaving anomalous eastward momentum carried into the mesosphere, causing an enhanced eastwards forcing in the mesosphere as they break and deposit their momentum. The opposite would happen when stratospheric winds are anomalously westerly during westerly QBO (i.e., the eastward gravity waves are filtered out resulting in anomalous westwards forcing in the mesosphere). Thus, the opposite phase relationship between the equatorial QBO and QBO signal seen in the mid-latitude mesosphere provides strong evidence that the QBO signal seen in the Saskatoon upper mesosphere is due to QBO modulation of the gravity wave momentum flux by the mid-latitude stratospheric winds. The QBO modulation of the stratospheric vortex through the HT effect has previously been used to provide observational support for interhemispheric coupling theory as outlined in *Karlsson et al.* [2007], *Karlsson et al.* [2009] and *Körnich and Becker* [2010]. For example, *Espy et al.* [2011] have shown that a QBO signal in the high latitude summer mesopause temperatures can be coupled to the state of the winter stratosphere. They explained that the mechanism for this requires a QBO modulation of the gravity wave momentum flux in the winter hemisphere which in turn modulates the meridional pole-to-pole circulation in the mesosphere [*Murphy et al.*, 2012; *de Wit et al.*, 2015]. Our results show that the QBO modulation seen in the summer polar mesosphere is indeed present in the winter mesosphere, and the phase relations are as expected, thus providing additional evidence for the interhemispheric coupling mechanism.

The timing of the mesospheric QBO signal varies between low and high latitudes. At the equator, QBO signature in the mesosphere is generally observed during northern spring equinox (Mar) [*Burrage et al.*, 1996; *Garcia et al.*, 1997; *Venkateswara Rao et al.*, 2012]. The mesospheric QBO signal at high southern latitudes is observed to be present throughout the winter [*Ford et al.*, 2009] whereas the QBO signature in the Saskatoon mesosphere identified in this study is most pronounced during late winter. Thus, further modeling work is required to understand the interplay between the seasonal cycle and the global mesospheric QBO signal.

In summary, we postulate that the QBO signature we have identified in the Saskatoon late-winter mesosphere is most likely to be explained by forcing of gravity wave spectrum that has been filtered through QBO-modulated stratospheric winds. These results provide additional evidence of extratropical QBO signal at mesospheric heights and offer supporting evidence that the QBO perturbations to the winter stratosphere can potentially be coupled to the summer hemisphere. We note that long-term observations of mid-latitude mesospheric gravity wave momentum flux spanning several cycles of QBO are required to confirm and extend these findings.

5. Summary and Conclusions

In this study, we have used 13 years of data (2002-2014) from the mid-latitude Saskatoon SuperDARN radar to identify a QBO signature in the Saskatoon mesospheric winds. This QBO signature in the mesospheric winds is such that, when QBO ~50 hPa is easterly during late winter, the Saskatoon mesospheric winds become more westerly. We observed that the largest QBO effect in the Saskatoon mesosphere is observed during late winter. We also consider the Saskatoon stratospheric winds and found that when the equatorial QBO ~50 hPa is easterly, the stratospheric winds become less westerly in agreement with previous studies and the HT effect. This hints at vertical coupling between the two regions via gravity wave filtering. Namely, when the Saskatoon stratospheric winds are anomalously easterly during easterly QBO (HT effect), the spectrum of gravity waves having westward momentum is filtered out, leading to the deposition of anomalous eastward momentum in the mesosphere as the waves propagate upwards. This results in increased westerly mesospheric winds at Saskatoon. The opposite happens when the equatorial QBO is westerly.

The QBO signal in the mid-latitude mesosphere reported here is a remarkable example of the coupling between the equatorial stratosphere and the mid-latitude mesosphere via meridional effects of equatorial QBO and vertically propagating gravity waves at mid-latitudes. Future studies need to be done to completely understand the dynamic effects of equatorial QBO in the mid- and high- latitude mesospheres.

Acknowledgments. This work is supported by National Science Foundation grants AGS-1341918 and AGS-1150789. Additional support is provided by the Research Council of Norway/COE under contract 223252/F50 (REH). The authors acknowledge the use of Saskatoon SuperDARN radar data. SuperDARN is a network of radars funded by national scientific funding agencies of Australia, Canada, China, France, Japan, South Africa, United Kingdom, and the United States of America. SuperDARN data can be downloaded from the Virginia Tech data server, http://vt.superdarn.org/tiki-index.php. Specifically, for the wind velocity data, the readers are encouraged to contact the authors. We also acknowledge the use of ECMWF ERA Interim data set from their website http://apps.ecmwf.int/datasets/data/interim-full-moda/levtype=pl/ for the Saskatoon stratospheric winds and the QBO data set provided by FU Berlin at their website http://www.geo.fu-berlin.de/en/met/ag/strat/produkte/qbo/.

References

Anstey, J. A., and T. G. Shepherd (2014), High-latitude influence of the quasi-biennial oscillation, *Quarterly Journal of the Royal Meteorological Society*, *140*(678), 1–21, doi:10.1002/qj.2132.

Baldwin, M. P., and T. J. Dunkerton (1998), Quasi-biennial modulation of the southern hemisphere stratospheric polar vortex, *Geophysical Research Letters*, *25*(17), 3343–3346, doi:10.1029/98GL02445.

Baldwin, M. P., L. J. Gray, T. J. Dunkerton, K. Hamilton, P. H. Haynes, W. J. Randel, J. R. Holton, M. J. Alexander, I. Hirota, T. Horinouchi, D. B. A. Jones, J. S. Kinnersley, C. Marquardt, K. Sato, and M. Takahashi (2001), The quasi-biennial oscillation, *Reviews of Geophysics*, *39*(2), 179–229, doi:10.1029/1999RG000073.

Baumgaertner, A., A. McDonald, G. Fraser, and G. Plank (2005), Long-term observations of mean winds and tides in the upper mesosphere and lower thermosphere above Scott base, Antarctica, *Journal of Atmospheric and Solar-Terrestrial Physics*, *67*(16), 1480 – 1496, doi:http://dx.doi.org/10.1016/j.jastp.2005.07.018.

Belmont, A. D., and D. G. Dartt (1968), Variation with longitude of the Quasi-Biennial Oscillation, *Mon. Weather Rev.*, *96*, 767–777.

Belmont, A. D., and G. D. Nastrom (1979), Long-period waves in mesospheric winds at Saskatoon (52°N), *Journal of Geomagnetism and Geoelectricity*, *31*, 165–171.

Berrisford, P., D. Dee, K. Fielding, M. Fuentes, P. Kallberg, S. Kobayashi, and S. Uppala (2009), The Era-Interim Archive, *ERA Report Series,No.1. ECMWF: Reading, UK.*

Bristow, W. A., J.-H. Yee, X. Zhu, and R. A. Greenwald (1999), Simultaneous observations of the July 1996 2-day wave event using the Super Dual Auroral Radar Network and the High Resolution Doppler Imager, *Journal of Geophysical Research: Space Physics*, *104*(A6), 12,715–12,721, doi:10.1029/1999JA900030.

Burrage, M. D., R. A. Vincent, H. G. Mayr, W. R. Skinner, N. F. Arnold, and P. B. Hays (1996), Long-term variability in the equatorial middle atmosphere zonal wind, *Journal of Geophysical Research: Atmospheres*, *101*(D8), 12,847–12,854, doi:10.1029/96JD00575.

Chisham, G., et al. (2007), A decade of the Super Dual Auroral Radar Network (SuperDARN): Scientific achievements, new techniques and future directions, *Surv. Geophys.*, *28*, 33–109, doi:10.1007/a10712-007-9017-8.

De Wit, R. J., R. E. Hibbins, P. J. Espy, and N. J. Mitchell (2013), Interannual variability of mesopause zonal winds over Ascension Island: Coupling to the stratospheric QBO, *Journal of Geophysical Research: Atmospheres*, *118*(21), 12,052–12,060, doi: 10.1002/2013JD020203.

De Wit, R. J., R. E. Hibbins and P. J. Espy (2015), The seasonal cycle of gravity wave momentum flux and forcing in the high latitude northern hemisphere mesopause region, *Journal of Atmospheric and Solar-Terrestrial Physics*, doi: http://dx.doi.org/10.1016/j.jastp.2014.10.002.

Dee, D. P., S. M. Uppala, A. J. Simmons, P. Berrisford, P. Poli, S. Kobayashi, U. Andrae, M. A. Balmaseda, G. Balsamo, P. Bauer, P. Bechtold, A. C. M. Beljaars, L. van de Berg, J. Bidlot, N. Bormann, C. Delsol, R. Dragani, M. Fuentes, A. J. Geer, L. Haimberger, S. B. Healy, H. Hersbach, E. V. Hlm, L. Isaksen, P. Kllberg, M. Khler, M. Matricardi, A. P. McNally, B. M. Monge-Sanz, J.-J. Morcrette, B.-K. Park, C. Peubey, P. de Rosnay, C. Tavolato, J.-N. Thpaut, and F. Vitart (2011), The ERA-interim reanalysis: configuration and performance of the data assimilation system, *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597, doi:10.1002/qj.828.

Dunkerton, T. J. (1997), The role of gravity waves in the quasi-biennial oscillation, *Journal of Geophysical Research: Atmospheres*, *102*(D22), 26,053–26,076, doi: 10.1029/97JD02999.

Dunkerton, T. J., and M. P. Baldwin (1991), Quasi-biennial Modulation of Planetary-Wave Fluxes in the Northern Hemisphere Winter, *Journal of the Atmospheric Sciences*, *48*(8), 1043–1061.

Ebdon, R. A. (1960), Notes on the wind flow at 50 mb in tropical and sub-tropical regions in January 1957 and January 1958, *Quarterly Journal of the Royal Meteorological Society*, *86*(370), 540–542, doi:10.1002/qj.49708637011.

Espy, P. J., J. Stegman, and G. Witt (1997), Interannual variations of the quasi-16-day oscillation in the polar summer mesospheric temperature, *Journal of Geophysical Research: Atmospheres*, *102*(D2), 1983–1990, doi:10.1029/96JD02717.

Espy, P. J., R. E. Hibbins, D. M. Riggin, and D. C. Fritts (2005), Mesospheric planetary waves over Antarctica during 2002, *Geophysical Research Letters*, *32*(21), doi:10.1029/2005GL023886, l21804.

Espy, P. J., S. Ochoa Fernández, P. Forkman, D. Murtagh, and J. Stegman (2011), The role of the QBO in the inter-hemispheric coupling of summer mesospheric temperatures, *Atmospheric Chemistry and Physics*, *11*(2), 495–502, doi:10.5194/acp-11-495-2011.

Ford, E. A. K., R. E. Hibbins, and M. J. Jarvis (2009), QBO effects on Antarctic mesospheric winds and polar vortex dynamics, *Geophysical Research Letters*, *36*(20), doi:10.1029/2009GL039848, l20801.

Fritts, D. C., and M. J. Alexander (2003), Gravity wave dynamics and effects in the middle atmosphere, *Reviews of Geophysics*, *41*(1), doi:10.1029/2001RG000106, 1003.

Garcia, R. R., T. J. Dunkerton, R. S. Lieberman, and R. A. Vincent (1997), Climatology of the semiannual oscillation of the tropical middle atmosphere, *Journal of Geophysical Research: Atmospheres*, *102*(D22), 26,019–26,032, doi:10.1029/97JD00207.

Garfinkel, C. I., T. A. Shaw, D. L. Hartmann, and D. W. Waugh (2012), Does the Holton-Tan Mechanism Explain How the Quasi-Biennial Oscillation Modulates the Arctic Polar Vortex?, *Journal of the Atmospheric Sciences*, *69*(5), 1713–1733, doi:10.1175/JAS-D-11-0209.1.

Gray, L. J., E. F. Drysdale, B. N. Lawrence, and T. J. Dunkerton (2001a), Model studies of the interannual variability of the northern-hemisphere stratospheric winter circulation: The role of the quasi-biennial oscillation, *Quarterly Journal of the Royal Meteorological Society*, *127*(574), 1413–1432, doi:10.1002/qj.49712757416.

Gray, L. J., S. J. Phipps, T. J. Dunkerton, M. P. Baldwin, E. F. Drysdale, and M. R. Allen (2001b), A data study of the influence of the equatorial upper stratosphere on northern-hemisphere stratospheric sudden warmings, *Quarterly Journal of the Royal Meteorological Society*, *127*(576), 1985–2003, doi:10.1002/qj.49712757607.

Gray, L. J., S. Crooks, C. Pascoe, S. Sparrow, and M. Palmer (2004), Solar and QBO Influences on the Timing of Stratospheric Sudden Warmings, *Journal of the Atmospheric Sciences*, *61*(23), 2777–2796, doi:10.1175/JAS-3297.1.

Greenwald, R. A., K. B. Baker, R. A. Hutchins, and C. Hanuise (1985), An HF phased-array radar for studying small-scale structure in the high-latitude ionosphere, *Radio Science*, *20*(1), 63–79, doi:10.1029/RS020i001p00063.

Groves, G. V. (1973), Zonal wind quasi-biennial oscillations at 25-60 km altitude, 1962-69, *Quarterly Journal of the Royal Meteorological Society*, *99*(419), 73–81, doi:10.1002/qj.49709941907.

Hall, G. E., J. W. MacDougall, D. R. Moorcroft, J.-P. St.-Maurice, A. H. Manson, and C. E. Meek (1997), Super Dual Auroral Radar Network observations of meteor echoes, *Journal of Geophysical Research: Space Physics*, *102*(A7), 14,603–14,614, doi:10.1029/97JA00517.

Hibbins, R., O. Marsh, A. McDonald, and M. Jarvis (2010), Interannual variability of the S=1 and S=2 components of the semidiurnal tide in the Antarctic MLT, *Journal of Atmospheric and Solar-Terrestrial Physics*, *72*(910), 794 – 800, doi: http://dx.doi.org/10.1016/j.jastp.2010.03.026.

Hibbins, R. E., and M. J. Jarvis (2008), A long-term comparison of wind and tide measurements in the upper mesosphere recorded with an imaging Doppler interferometer and SuperDARN radar at Halley, Antarctica, *Atmospheric Chemistry and Physics*, *8*(5), 1367–1376, doi:10.5194/acp-8-1367-2008.

Hibbins, R. E., P. J. Espy, and M. J. Jarvis (2007), Quasi-biennial modulation of the semidiurnal tide in the upper mesosphere above Halley, Antarctica, *Geophysical Research Letters*, *34*(21), doi:10.1029/2007GL031282, l21804.

Hibbins, R. E., M. J. Jarvis, and E. A. K. Ford (2009), Quasi-biennial oscillation influence on long-period planetary waves in the Antarctic upper mesosphere, *Journal of Geophysical Research: Atmospheres*, *114*(D9), doi:10.1029/2008JD011174, d09109.

Holton, J. R. (1983), The Influence of Gravity Wave Breaking on the General Circulation of the Middle Atmosphere, *Journal of the Atmospheric Sciences*, *40*(10), 2497–2507.

Holton, J. R., and R. S. Lindzen (1972), An Updated Theory for the Quasi-Biennial Cycle of the Tropical Stratosphere, *Journal of the Atmospheric Sciences*, *29*(6), 1076–1080.

Holton, J. R., and H.-C. Tan (1980), The Influence of the Equatorial Quasi-Biennial Oscillation on the Global Circulation at 50 mb, *Journal of the Atmospheric Sciences*, *37*(10), 2200–2208.

Holton, J. R., and H.-C. Tan (1982), The Quasi-Biennial Oscillation in the Northern Hemisphere Lower Stratosphere, *Journal of the Meteorological Society of Japan. Ser. II*, *60*(1), 140–148.

Hussey, G. C., C. E. Meek, D. Andr, A. H. Manson, G. J. Sofko, and C. M. Hall (2000), A comparison of northern hemisphere winds using SuperDARN meteor trail and MF radar wind measurements, *Journal of Geophysical Research: Atmospheres*, *105*(D14), 18,053–18,066, doi:10.1029/2000JD900272.

Jarvis, M. J. (1996), Quasi-Biennial Oscillation effects in the semidiurnal tide of the Antarctic lower thermosphere, *Geophysical Research Letters*, *23*(19), 2661–2664, doi: 10.1029/96GL02394.

Jenkins, B., and M. Jarvis (1999), Mesospheric winds derived from SuperDARN HF radar meteor echoes at Halley, Antarctica, *Earth, Planets and Space*, *51*(7-8), 685–689, doi: 10.1186/BF03353226.

Jenkins, B., M. J. Jarvis, and D. M. Forbes (1998), Mesospheric wind observations derived from Super Dual Auroral Radar Network (SuperDARN) HF radar meteor echoes at Halley, Antarctica: Preliminary results, *Radio Science*, *33*(4), 957–965, doi: 10.1029/98RS01113.

Kane, R. P., C. E. Meek, and A. H. Manson (1999), Quasi-biennial and higher-period oscillations in the mean winds in the mesosphere and lower thermosphere over Saskatoon, 52°N, 107°W, *Journal of Geophysical Research: Space Physics*, *104*(A2), 2645–2652, doi:10.1029/1998JA900066.

Karlsson, B., H. Körnich, and J. Gumbel (2007), Evidence for interhemispheric stratosphere-mesosphere coupling derived from noctilucent cloud properties, *Geophysi-*

cal Research Letters, *34*(16), doi:10.1029/2007GL030282, l16806.

Karlsson, B., C. McLandress, and T. G. Shepherd (2009), Inter-hemispheric mesospheric coupling in a comprehensive middle atmosphere model, *Journal of Atmospheric and Solar-Terrestrial Physics*, *71*(34), 518 – 530, doi: http://dx.doi.org/10.1016/j.jastp.2008.08.006.

Kawatani, Y., and K. Hamilton (2013), Weakened stratospheric quasibiennial oscillation driven by increased tropical mean upwelling, *Nature*, *497*(7450), 478–481, letter.

Kleinknecht, N. H., P. J. Espy, and R. E. Hibbins (2014), The climatology of zonal wave numbers 1 and 2 planetary wave structure in the MLT using a chain of Northern Hemisphere SuperDARN radars, *Journal of Geophysical Research: Atmospheres*, *119*(3), 1292–1307, doi:10.1002/2013JD019850.

Körnich, H., and E. Becker (2010), A simple model for the interhemispheric coupling of the middle atmosphere circulation, *Advances in Space Research*, *45*(5), 661 – 668, doi:http://dx.doi.org/10.1016/j.asr.2009.11.001.

Kürschner, D., and C. Jacobi (2003), Quasi-biennial and decadal variability obtained from long-term measurements of nighttime radio wave reflection heights over Central Europe, *Advances in Space Research*, *32*(9), 1701 – 1706, doi:http://dx.doi.org/10.1016/S0273-1177(03)90465-0.

Labitzke, K., and H. V. Loon (1988), Associations between the 11-year solar cycle, the QBO and the atmosphere. Part I: the troposphere and stratosphere in the northern hemisphere in winter, *Journal of Atmospheric and Terrestrial Physics*, *50*(3), 197 – 206, doi:http://dx.doi.org/10.1016/0021-9169(88)90068-2.

Lindzen, R. S., and J. R. Holton (1968), A Theory of the Quasi-Biennial Oscillation, *Journal of the Atmospheric Sciences*, *25*(6), 1095–1107.

Lu, H., M. P. Baldwin, L. J. Gray, and M. J. Jarvis (2008), Decadal-scale changes in the effect of the QBO on the northern stratospheric polar vortex, *Journal of Geophysical Research: Atmospheres*, *113*(D10), doi:10.1029/2007JD009647, d10114.

Lu, H., L. J. Gray, M. P. Baldwin, and M. J. Jarvis (2009), Life cycle of the QBO-modulated 11-year solar cycle signals in the Northern Hemispheric winter, *Quarterly Journal of the Royal Meteorological Society*, *135*(641), 1030–1043, doi:10.1002/qj.419.

Lu, H., T. J. Bracegirdle, T. Phillips, A. Bushell, and L. Gray (2014), Mechanisms for the Holton-Tan relationship and its decadal variation, *Journal of Geophysical Research: Atmospheres*, *119*(6), 2811–2830, doi:10.1002/2013JD021352.

Malinga, S. B., and J. M. Ruohoniemi (2007), The quasi-two-day wave studied using the Northern Hemisphere SuperDARN HF radars, *Annales Geophysicae*, *25*(8), 1767–1778, doi:10.5194/angeo-25-1767-2007.

Manson, A., and C. Meek (1986), Dynamics of the middle atmosphere at Saskatoon (52°N, 107°W): a spectral study during 1981, 1982, *Journal of Atmospheric and Terrestrial Physics*, *48*(1112), 1039 – 1055, doi:http://dx.doi.org/10.1016/0021-9169(86)90025-5.

Manson, A. H., C. E. Meek, and J. B. Gregory (1981), Long-Period Oscillations in Mesospheric and Lower Thermospheric Winds (60-110km) at Saskatoon (52°N, 107°W, L=4.3), *Journal of geomagnetism and geoelectricity*, *33*(12), 613–621, doi: 10.5636/jgg.33.613.

Matthews, D., M. Parkinson, P. Dyson, and J. Devlin (2006), Optimising estimates of mesospheric neutral wind using the TIGER Superdarn radar, *Advances in Space Re-*

search, *38*(11), 2353 – 2360, doi:http://dx.doi.org/10.1016/j.asr.2005.07.046.

Mayr, H. G., J. G. Mengel, C. O. Hines, K. L. Chan, N. F. Arnold, C. A. Reddy, and H. S. Porter (1997), The gravity wave Doppler spread theory applied in a numerical spectral model of the middle atmosphere: 1. Model and global scale seasonal variations, *Journal of Geophysical Research: Atmospheres*, *102*(D22), 26,077–26,091, doi:10.1029/96JD03213.

Mayr, H. G., J. G. Mengel, and F. T. Huang (2009), Modeling the temperature of the polar mesopause region: Part I- Inter-annual and long-term variations generated by the stratospheric QBO, *Journal of Atmospheric and Solar-Terrestrial Physics*, *71*(34), 497 – 507, doi:http://dx.doi.org/10.1016/j.jastp.2008.09.033.

Middleton, H. R., N. J. Mitchell, and H. G. Muller (2002), Mean winds of the mesosphere and lower thermosphere at 52°N in the period 1988-2000, *Annales Geophysicae*, *20*(1), 81–91, doi:10.5194/angeo-20-81-2002.

Murphy, D. J., S. P. Alexander, and R. A. Vincent (2012), Interhemispheric dynamical coupling to the southern mesosphere and lower thermosphere, *Journal of Geophysical Research: Atmospheres*, *117*(D8), doi:10.1029/2011JD016865, d08114.

Naito, Y., and I. Hirota (1997), Interannual variability of the northern winter stratospheric circulation related to the QBO and the solar cycle, *J. Meteor. Soc. Japan*, *75*, 925–937.

Namboothiri, S., A. Manson, and C. Meek (1993), Variations of mean winds and tides in the upper middle atmosphere over a solar cycle, Saskatoon, Canada, 52°N, 107°W, *Journal of Atmospheric and Terrestrial Physics*, *55*(10), 1325 – 1334, doi:http://dx.doi.org/10.1016/0021-9169(93)90101-4.

Namboothiri, S., C. Meek, and A. Manson (1994), Variations of mean winds and solar tides in the mesosphere and lower thermosphere over time scales ranging from 6 months to 11 yr: Saskatoon, 52°N, 107°W, *Journal of Atmospheric and Terrestrial Physics*, *56*(10), 1313 – 1325, doi:http://dx.doi.org/10.1016/0021-9169(94)90069-8.

Naoe, H., and K. Shibata (2010), Equatorial quasi-biennial oscillation influence on northern winter extratropical circulation, *Journal of Geophysical Research: Atmospheres*, *115*(D19), doi:10.1029/2009JD012952, d19102.

Naujokat, B. (1986), An Update of the Observed Quasi-Biennial Oscillation of the Stratospheric Winds over the Tropics., *Journal of Atmospheric Sciences*, *43*, 1873–1880.

Neumann, A. (1990), QBO and solar activity effects on temperatures in the mesopause region, *Journal of Atmospheric and Terrestrial Physics*, *52*(3), 165 – 173, doi:http://dx.doi.org/10.1016/0021-9169(90)90120-C.

Ogawa, T., S. Nozawa, M. Tsutsumi, N. F. Arnold, N. Nishitani, N. Sato, and A. S. Yukimatu (2004), Arctic and Antarctic polar mesosphere summer echoes observed with oblique incidence HF radars: analysis using simultaneous MF and VHF radar data, *Annales Geophysicae*, *22*(12), 4049–4059, doi:10.5194/angeo-22-4049-2004.

Pascoe, C. L., L. J. Gray, and A. A. Scaife (2006), A GCM study of the influence of equatorial winds on the timing of sudden stratospheric warmings, *Geophysical Research Letters*, *33*(6), doi:10.1029/2005GL024715, l06825.

Plumb, R. A., and R. C. Bell (1982), Equatorial waves in steady zonal shear flow, *Quarterly Journal of the Royal Meteorological Society*, *108*(456), 313–334, doi:10.1002/qj.49710845603.

Portnyagin, Y. I., and T. V. Solovjova (2000), Global empirical wind model for the upper mesosphere/lower thermosphere. I. Prevailing wind, *Annales Geophysicae*, *18*(3), 300–315, doi:10.1007/s00585-000-0300-y.

Press, W. H., B. P. Flannery, S. A. Teukolsky, and W. T. Vetterling (1992), Numerical Recipes in C: The Art of Scientific Computing, 2nd edn., *Cambridge University Press, New York*.

Reed, R. J. (1965), The Quasi-Biennial Oscillation of the Atmosphere Between 30 and 50 km Over Ascension Island, *Journal of the Atmospheric Sciences*, *22*(3), 331–333.

Reed, R. J., W. J. Campbell, L. A. Rasmussen, and D. G. Rogers (1961), Evidence of a downward-propagating, annual wind reversal in the equatorial stratosphere, *Journal of Geophysical Research*, *66*(3), 813–818, doi:10.1029/JZ066i003p00813.

Sprenger, K., and R. Schminder (1968), On the significance of ionospheric drift measurements in the LF range, *Journal of Atmospheric and Terrestrial Physics*, *30*(5), 693 – 700, doi:http://dx.doi.org/10.1016/S0021-9169(68)80025-X.

Sprenger, K., K. Greisiger, and R. Schminder (1975), Evidence of quasi-biennial wind oscillation in the mid-latitude lower thermosphere, obtained from ionospheric drift measurements in the LF range, *Journal of Atmospheric and Terrestrial Physics*, *37*(10), 1391 – 1393, doi:http://dx.doi.org/10.1016/0021-9169(75)90134-8.

Venkateswara Rao, N., T. Tsuda, D. M. Riggin, S. Gurubaran, I. M. Reid, and R. A. Vincent (2012), Long-term variability of mean winds in the mesosphere and lower thermosphere at low latitudes, *Journal of Geophysical Research: Space Physics*, *117*(A10), doi:10.1029/2012JA017850, a10312.

Wallace, J. M. (1973), General circulation of the tropical lower stratosphere, *Reviews of Geophysics*, *11*(2), 191–222, doi:10.1029/RG011i002p00191.

Xu, J., A. K. Smith, H.-L. Liu, W. Yuan, Q. Wu, G. Jiang, M. G. Mlynczak, J. M. Russell, and S. J. Franke (2009), Seasonal and quasi-biennial variations in the migrating diurnal tide observed by Thermosphere, Ionosphere, Mesosphere, Energetics and Dynamics (TIMED), *Journal of Geophysical Research: Atmospheres*, *114*(D13), doi: 10.1029/2008JD011298, d13107.

second_rev2_fig1.pdf

Figure 1. (a) Time series of monthly mean mesospheric zonal winds recorded by the Saskatoon radar for 2002-2014. Positive values indicate westerly (eastward) winds. (b) Time series of de-seasonalized monthly mean mesospheric zonal winds obtained by subtracting the mean climatology at Saskatoon radar from the winds in Figure 1a. (c) Periodogram for the de-seasonalized mesospheric zonal winds at Saskatoon for 2002-2014 (Figure 1b), with a red line identifying a peak at a frequency of 27.6 months. The black horizontal dotted line indicates the 90% confidence level.

second_rev2.pdf

Figure 2. (a) Height resolved stratospheric zonal winds at the Singapore equatorial radiosonde station for 2002-2014. The contour interval is 10 m/s with colors representing wind velocities in m/s. Positive represents westerly winds, whereas negative represents easterly winds. (b) Monthly mean stratospheric zonal winds at 50 hPa measured at the Singapore equatorial radiosonde station for 2002-2014. The vertical axis represents the wind velocities in m/s and horizontal axis represents the years. (c) Periodogram of winds in panel (b) with vertical axis showing the normalised power and horizontal axis representing the corresponding periods. The red line represents the period of 27.27 months having maximum power.

third_rev_fig5climat2.pdf

Figure 3. (a) Climatology of prevailing zonal winds at Saskatoon organized by phases of QBO at 50 hPa. Green represents the climatology obtained by averaging the zonal winds in Figure 3a. Blue (red) represents the climatology for the time periods when QBO is easterly (westerly). Positive velocities indicate westerly winds and negative velocities indicate easterly winds. (b) Difference between the QBO and the average (green in panel a) climatologies. The blue curve indicates the difference between the QBO easterly (blue in panel a) and the average (green in panel a) climatologies and the red curve indicates the difference between the QBO westerly (red in panel a) and the average (green in panel a) climatologies.

corr_sec_rev_70_widt_white.pdf

Figure 4. Correlation of Saskatoon mesospheric zonal winds with QBO spanning all pressure levels on the left vertical axis, for all the months. The contour interval is 0.1 with colors representing correlation magnitudes. White contours identify correlations with significance greater than 90%.

second_rev_fig8.pdf

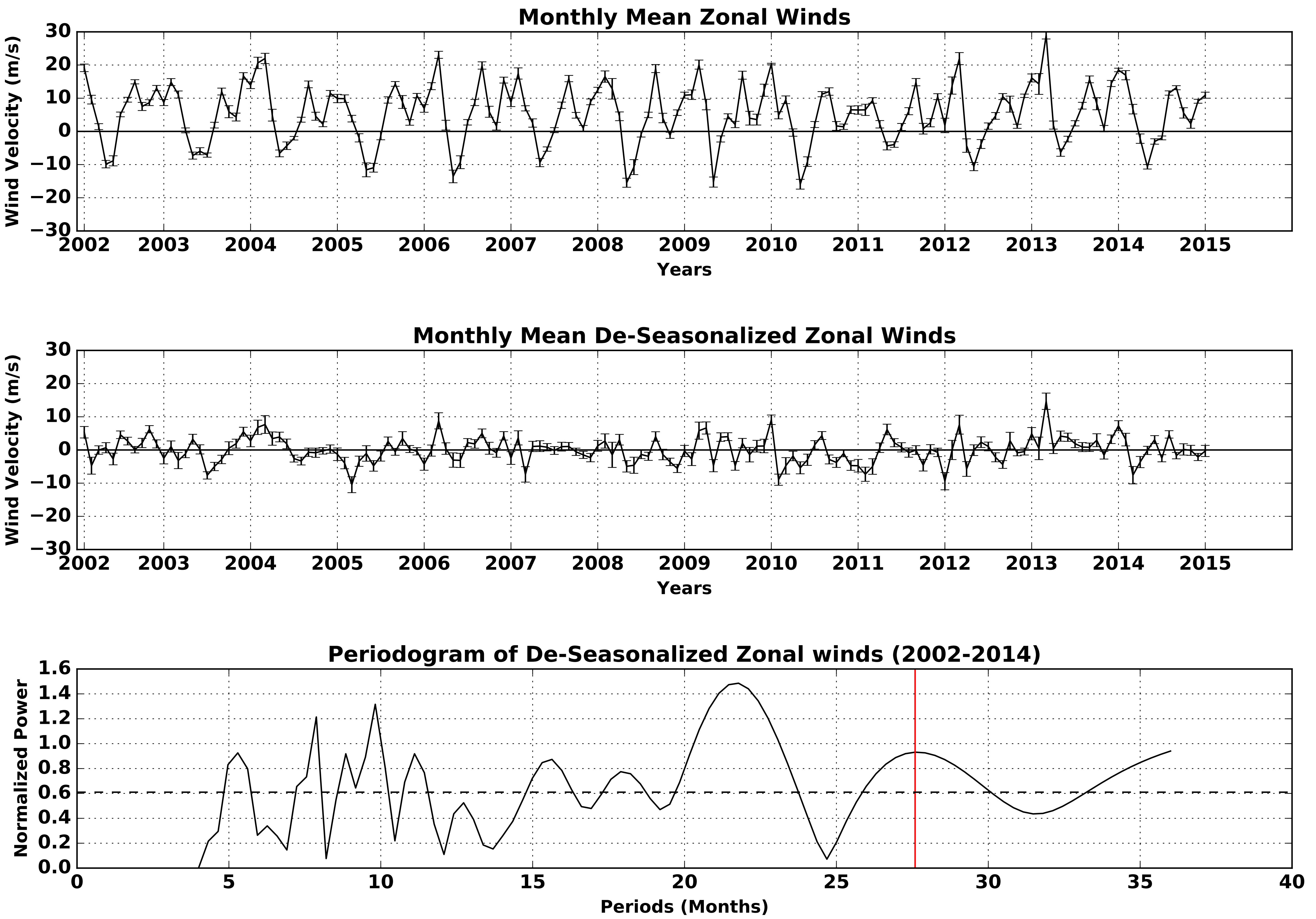
Figure 5. (a) Averaged late winter (Jan-Feb) zonal winds measured by the Singapore radiosonde at 50 hPa for 2002-2014. (b) Averaged late winter (Jan-Feb) mesospheric zonal winds measured by the Saskatoon HF radar for 2002-2014. For both the figures, positive velocities indicate westerly winds and negative velocities indicate easterly winds.

second_rev_diffprof50_2.pdf

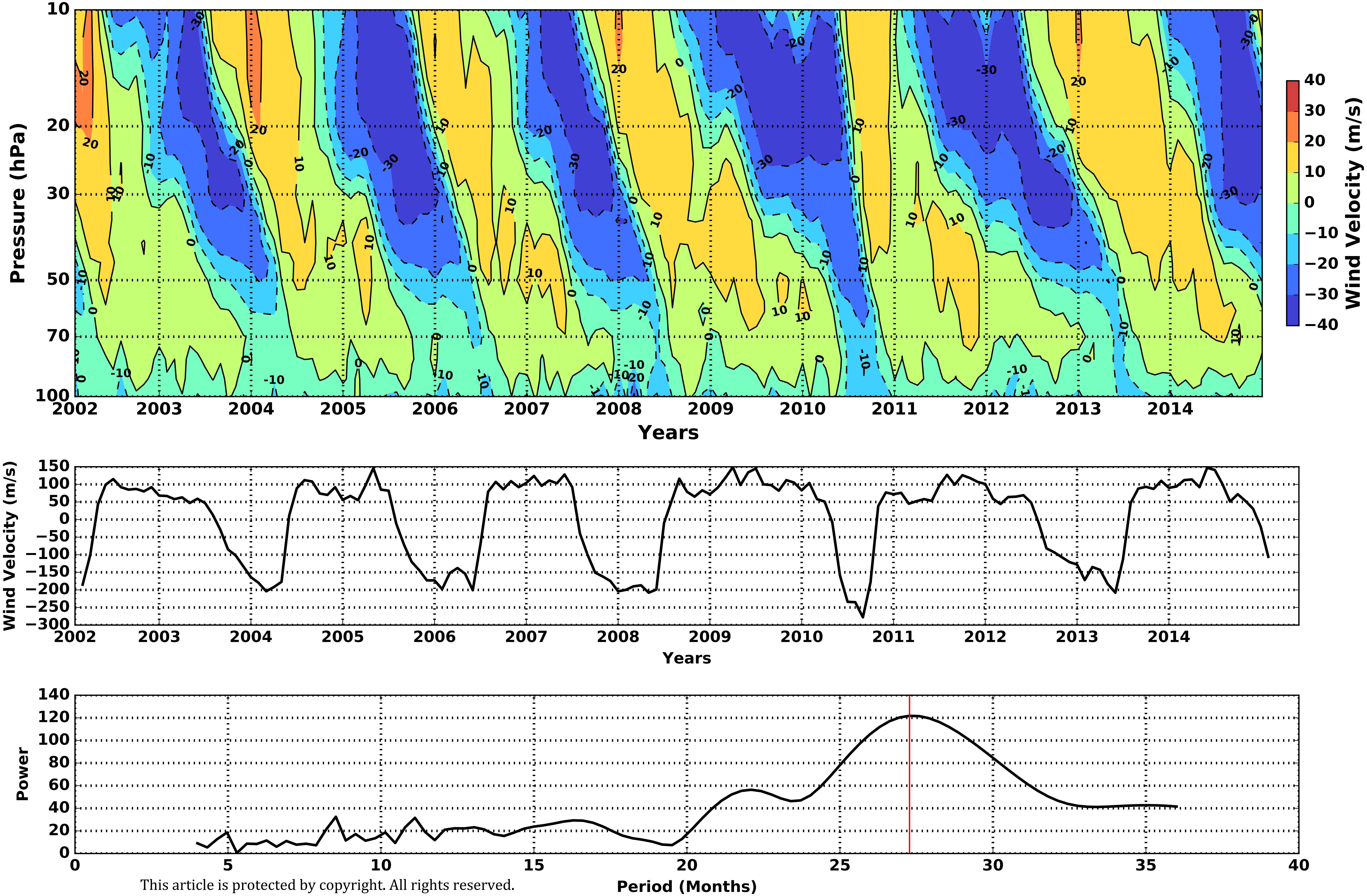
Figure 6. Difference between Saskatoon stratospheric zonal winds of Westerly and Easterly QBO conditions. The Saskatoon winds are derived from the ECMWF ERA-Interim data set and averaged for Jan-Feb for 2002-2014. The QBO phase is defined by the direction of the winds measured by the Singapore radiosonde at 50 hPa. The vertical axis shows the height in hPa in the Saskatoon stratosphere and horizontal axis shows the difference in wind velocities in m/s.

ecmwf_sas_corr.pdf

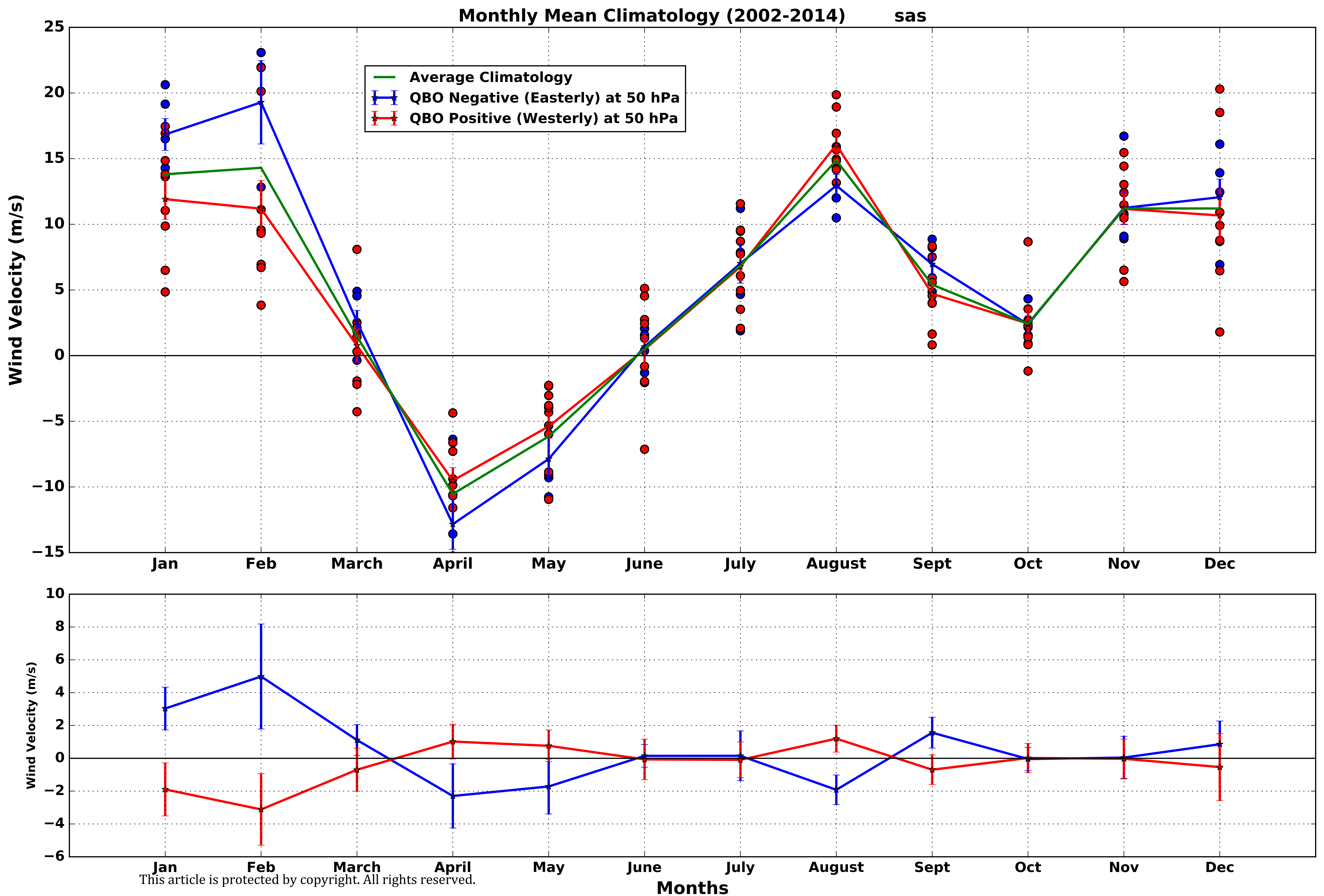
Figure 7. Correlation between averaged late winter (Jan-Feb) mesospheric zonal winds measured by the Saskatoon radar and zonal winds derived from ECMWF at Saskatoon at all the pressure levels identified on the left vertical axis for 2002-2014. The vertical axis shows the height in hPa and horizontal axis shows the correlation magnitudes.



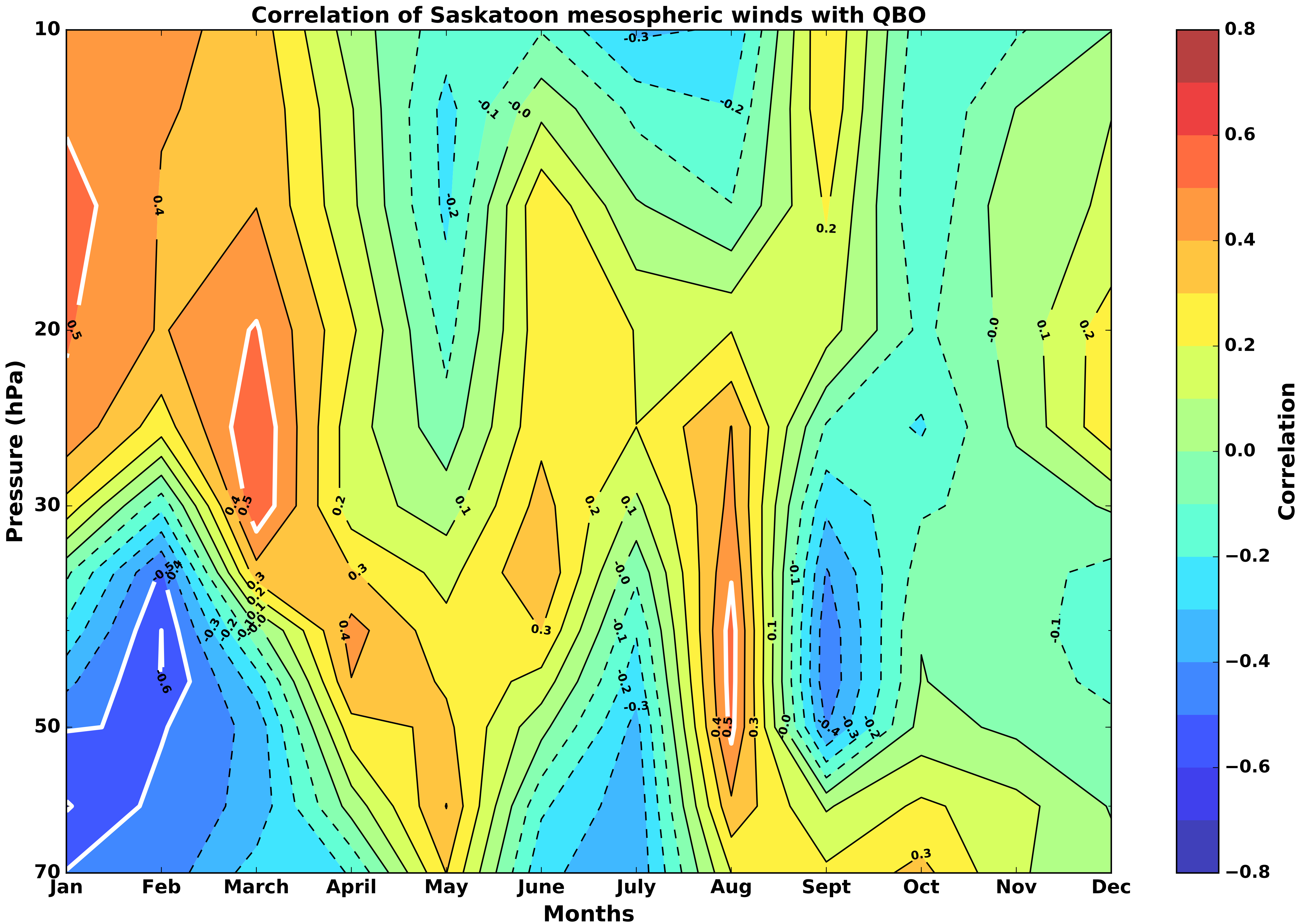
Monthly Mean Zonal Winds
Wind Velocity (m/s)
Years
Monthly Mean De-Seasonalized Zonal Winds
Wind Velocity (m/s)
Years
Periodogram of De-Seasonalized Zonal winds (2002-2014)
Normalized Power
Periods (Months)



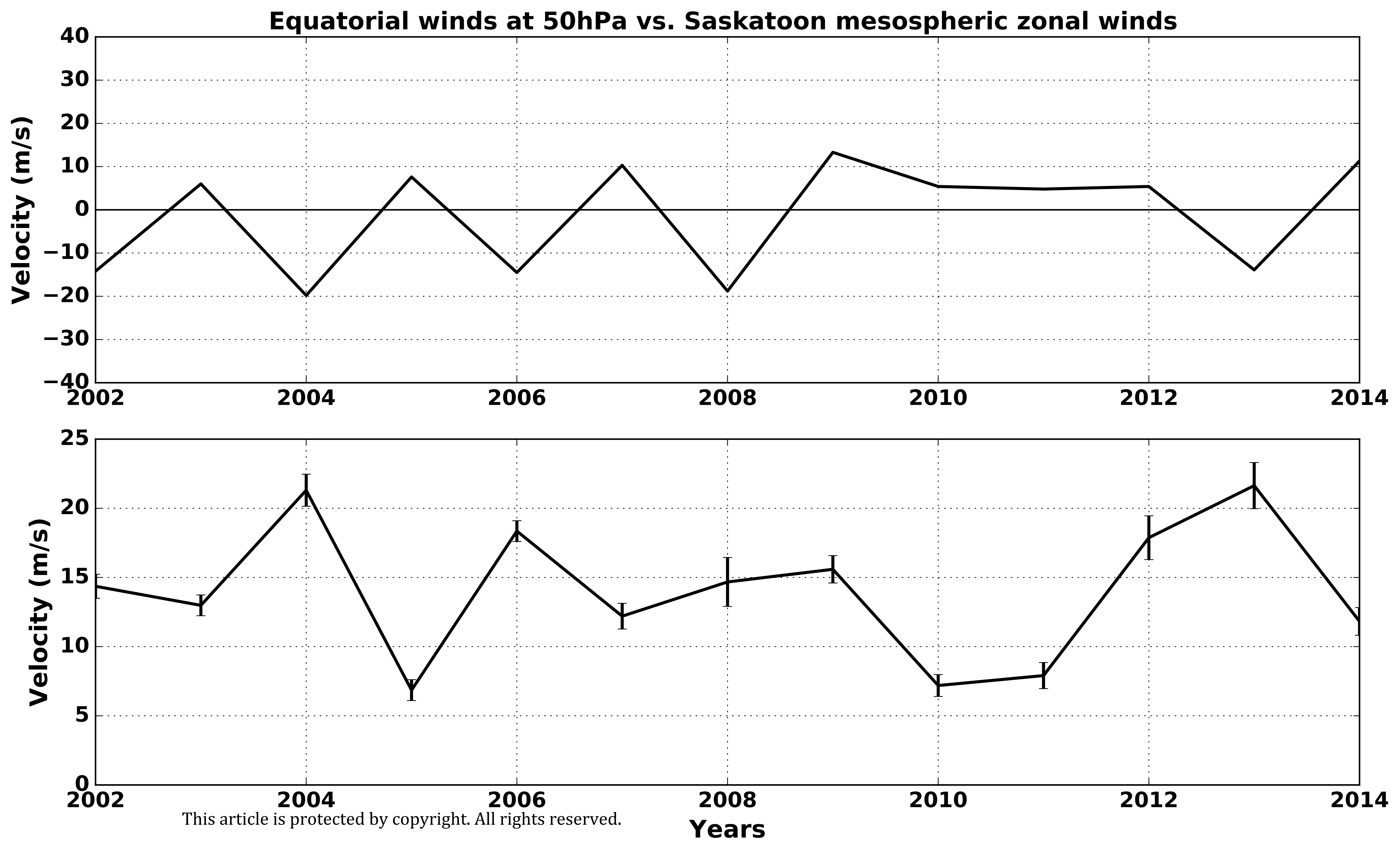
Pressure (hPa)
Years
Wind Velocity (m/s)
Wind Velocity (m/s)
Years
Power
Period (Months)

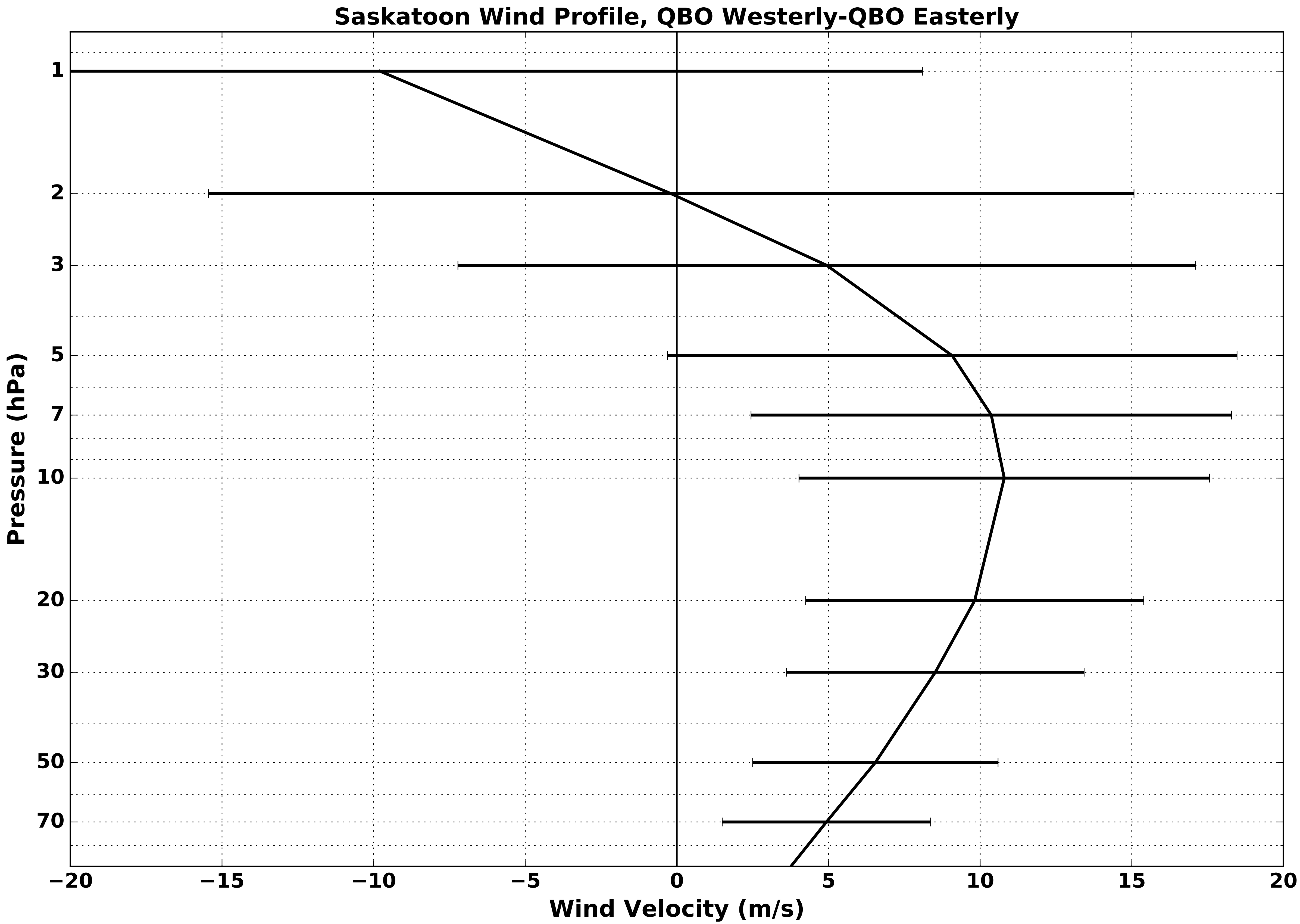


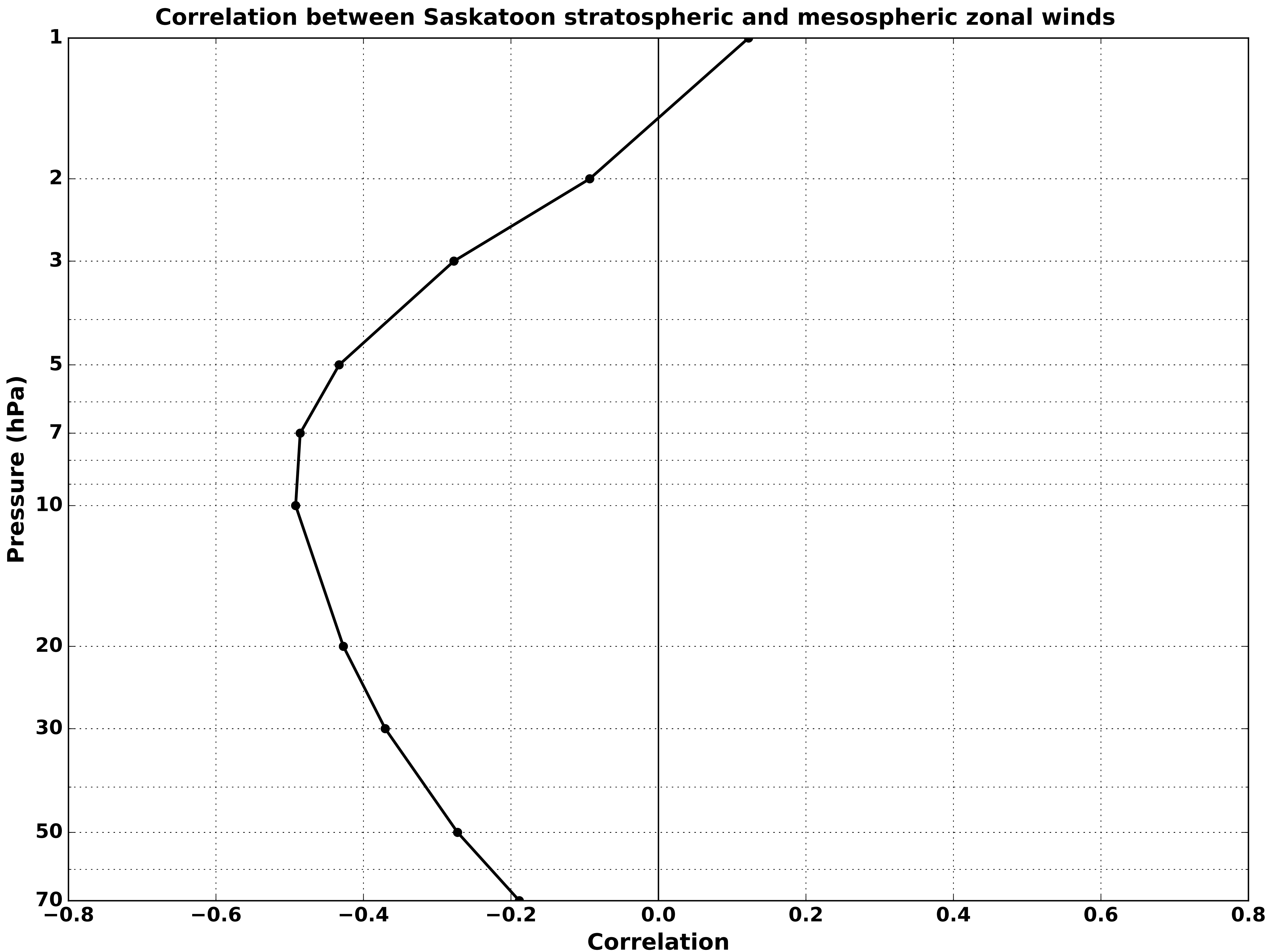
Monthly Mean Climatology (2002-2014) sas
Average Climatology
QBO Negative (Easterly) at 50 hPa
QBO Positive (Westerly) at 50 hPa
Wind Velocity (m/s)
25
20
15
10
5
0
−5
−10
−15
Jan
Feb
March
April
May
June
July
August
Sept
Oct
Nov
Dec
Wind Velocity (m/s)
10
8
6
4
2
0
−2
−4
−6
Jan
Feb
March
April
May
June
July
August
Sept
Oct
Nov
Dec
Months



Correlation of Saskatoon mesospheric winds with QBO
Pressure (hPa)
10
20
30
50
70
Jan
Feb
March
April
May
June
July
Aug
Sept
Oct
Nov
Dec
Months
Correlation
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
−0.8


Equatorial winds at 50hPa vs. Saskatoon mesospheric zonal winds
Velocity (m/s)
40
30
20
10
0
−10
−20
−30
−40
2002
2004
2006
2008
2010
2012
2014
Velocity (m/s)
25
20
15
10
5
0
2002
2004
2006
2008
2010
2012
2014
Years


Saskatoon Wind Profile, QBO Westerly-QBO Easterly
Pressure (hPa)
1
2
3
5
7
10
20
30
50
70
−20
−15
−10
−5
0
5
10
15
20
Wind Velocity (m/s)


Correlation between Saskatoon stratospheric and mesospheric zonal winds
Pressure (hPa)
1
2
3
5
7
10
20
30
50
70
−0.8
−0.6
−0.4
−0.2
0.0
0.2
0.4
0.6
0.8
Correlation