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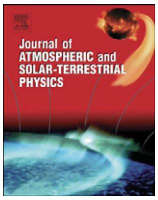

A study of temperature and meridional wind relationships at high northern latitudes

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ABSTRACT

MLT (Mesosphere and Lower Thermosphere) temperatures were measured using ground-based instruments at two high latitude stations over several winters. Warmer temperatures in wintertime are known to arise from the large-scale hemispheric circulation that drives downwelling and upwelling in the MLT region, leading to accompanying adiabatic heating and cooling. Although a relationship between temperature and meridional wind is expected, it has not yet been properly demonstrated. The OH airglow temperatures measured with a SATI (Spectral Airglow Temperature Imager) instrument and a Michelson interferometer are compared with co-located radar wind measurements at Resolute Bay (75°N, 95°W) and Esrange (68°N, 21°E), respectively. The temperature and meridional wind have a positive relationship that is consistent with the large-scale circulation, but the zonal wind is only weakly correlated.

1. Introduction

During wintertime, the temperature in the mesosphere and the MLT (Mesosphere and Lower Thermosphere) region is warmer than in summertime as a result of the large-scale meridional circulation, in contrast with the seasonal temperature variation in the stratosphere (Espy and Stegman, 2002; French et al., 2005). This large meridional circulation is coupled to the Earth circulation which is in turn is driven by the deposition of momentum from breaking gravity waves, as illustrated in Fig. 1 (Andrews et al., 1987). It is of interest that in this work the zonal wind is more weakly correlated with the temperature than is the meridional wind and this result is discussed later. As a result the winter pole experiences downwelling accompanied by adiabatic heating (Garcia and Solomon, 1985). This downwelling is also expected to bring down air having a higher mixing ratio of atomic oxygen, thereby increasing the oxygen airglow emission rate. Liu et al. (2008) showed with WINDII satellite observations that the airglow emission rates were enhanced at high latitudes during winter. The same result was observed as a strong correlation of airglow temperatures and emission rates from ground-based SATI observations at Resolute Bay (74°N) (Cho and Shepherd, 2006). In addition, satellite data confirm this correlation with the integrated emission rate as shown by Shepherd et al. (2007), who suggested that the positive relationship of the airglow temperature and emission rate could be explained by the large-scale circulation.

Although it is not obvious that the meridional circulation can be directly observed against its variability, it may be seen with the 2007 Horizontal Wind Model—HWM07 (Drob et al., 2008). This is an empirical model of the horizontal wind fields of the Earth's atmosphere from the ground to 500 km altitude. The wind model uses over 50 years of data from 35 instruments including satellite, rocket, and ground-based wind measurements.

Fig. 2 presents the daily averaged meridional winds at 75°N and 0°E derived from the HWM07 model. The dashed lines with shaded contours indicate the negative (southward) meridional winds, and the solid contour lines are for the northward winds. The northward (positive) meridional winds are predominant from the altitude 80 to 100 km in wintertime, and southward in summertime. As shown in Fig. 2, the winds are very large at high latitudes in winter, 30 m/s or so; these large winds are comparable to the ground-based radar measurements. Based on these high values the transit time from the equator to the pole is rapid. The HWM07 model was run for mid-latitudes (45°N) to compare the results with those of high latitude (not shown here). The winter winds at 87 km at high latitude(75°N) are 32 m/s

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compared with 10.5 m/s at mid-latitude (45°N). This difference is roughly consistent with the high/mid latitude ratio of the Coriolis force, a factor of 1.36 and a latitudinal convergence factor of 2.72. Also, the HWM07 model shows a significant meridional wind variation. For example, longitudinal variations of meridional wind at 87 km altitude are from −50 to 52 m/s on 0 UT, January 1st, for 75°N latitude.

Espy et al. (2003) compared the OH airglow temperature from the peak altitude of about 87 km with the meridional wind measured by an MF radar in the Antarctic region. They showed that the meridional wind is highly correlated to the airglow temperature in the MLT region. The correlation coefficient of the temperature and meridional wind was −0.63 at Rothera (67°S) for the 2002 winter season. Here, the negative meridional wind values indicate southward wind (negative is poleward) values which are related to the warmer temperature. The large-scale circulation is also expected to be seen in the Arctic. In this presentation, the OH airglow temperatures from the SATI (Spectral Airglow Temperature Imager) and a Michelson interferometer are compared with radar wind measurements at high northern locations, Resolute Bay and Esrange, respectively, in order to investigate the relationship of the meridional wind to the mesospheric temperature at high latitudes and to compare the relationship observed at different latitudes. A strong correlation between the two is found, but it is stronger at the higher latitude of Resolute Bay, 75°N than it is at Esrange, at 68°N.

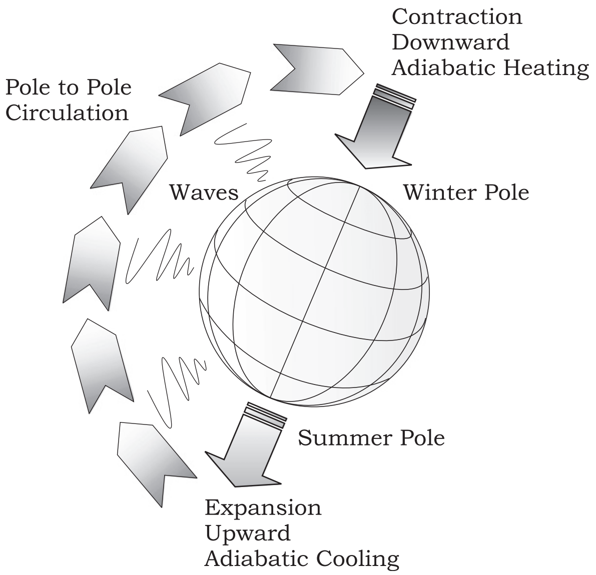


Fig. 1. An illustration of the large-scale circulation.

2. Observations

2.1. Temperature using optical instruments

2.1.1. SATI at Resolute Bay (75°N, 95°W)

A SATI (Spectral Airglow Temperature Imager) instrument was installed at Resolute Bay, in November, 2001 to monitor the MLT temperature. The SATI instrument is a spatial scanning Fabry–Perot spectrometer. It measures OH and O_2 airglow emission at altitudes perturbed from the normal peak altitudes of 87 and 94 km, respectively (Liu and Shepherd, 2006). The rotational temperature is derived from the ratios of the lines of the airglow spectrum. The exposure time for each measurement of the OH and O_2 emission is about 2 min, but the interval of individual measurements is about 9 min due to extra measurements using two additional OH filters after November, 2003. The uncertainty of the relative temperature measurements for both emissions, OH and O_2, is about 1.7 K standard deviation, and for the emission rate about 2% (Sargoytchev et al., 2004).

2.1.2. Michelson interferometer at Esrange (68°N, 21°E)

A Michelson interferometer (MI) was installed to measure OH Meinel bands in the MLT region at Esrange, October, 2001. The MI employs a thermo-electrically cooled InGaAs detector with

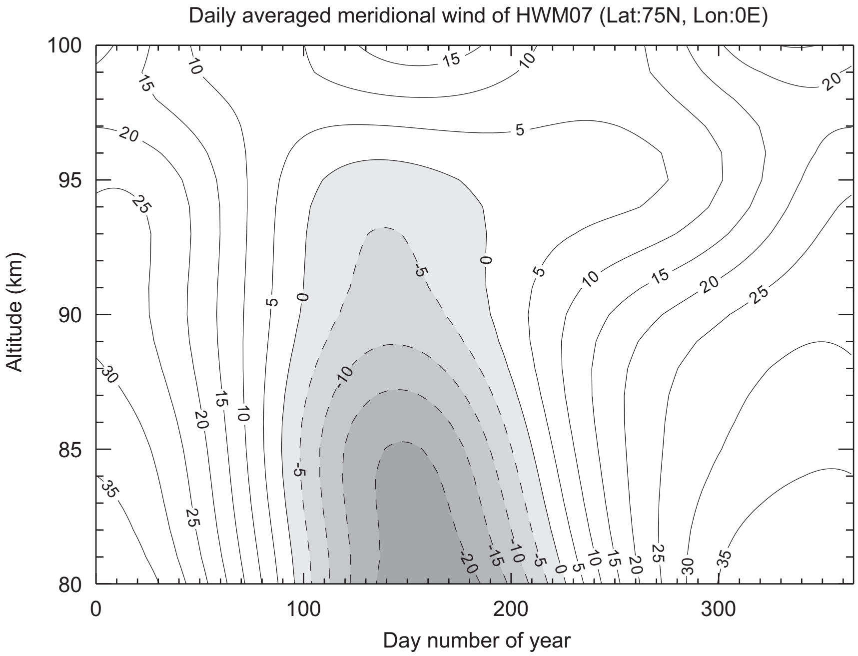


Fig. 2. Daily averaged meridional wind at the location (75°N, 0°E) from the HWM07 model result. The solid contour line represents the positive (northward) meridional wind, and the dashed line with shaded colours is for the southward meridional wind.

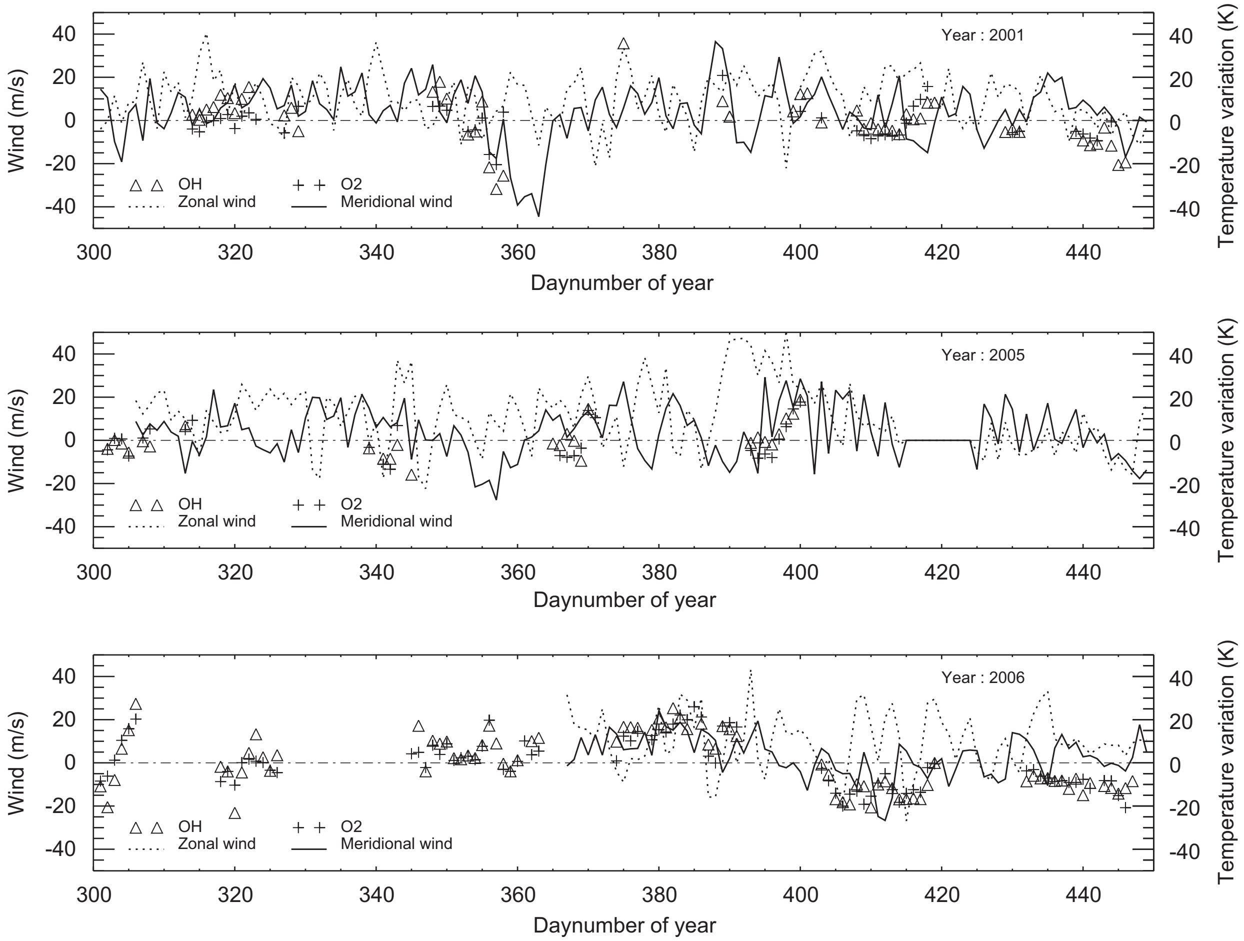


Fig. 3. The daily variations from the MLT temperature of the SATI instrument and the meridional wind at the 88 km altitude layer from the meteor radar at Resolute Bay (75°N, 95°W). The unit of the temperature variation is K on the right side vertical axis, and m/s for the wind on the left side. The data are plotted in daynumber of year and run from day 300 (late October) to 450 (late March). The triangles indicate SATI OH temperature, and the crosses are for the O_2 temperature. For the wind measurements, the solid line represents the meridional wind, and dotted line for the zonal wind. The upper panel shows the daily variation of the temperature and wind for the 2001–2002 winter season, the middle panel is for the winter of 2005–2006, and the lower panel is for the winter season 2006–2007. These years were chosen because they provided the greatest overlap of temperature and wind data.

maximum sensitivity in the wavelength region from 1.0 to 1.7 μm. The system provides choices of spectral resolution and has been operated at 4 cm^{-1} wavenumber resolution. Co-addition of interferograms up to about 5 min was used to increase the signal-to-noise ratio, so the temporal resolution of the data is ~5 min (Won et al., 2003). Continuous measurements of the NIR airglow spectra have been taken during the dark Arctic nights when the local solar depression angle exceeds 4°. The error for the temperature is about 10 K or less.

2.2. *Wind using radar*

2.2.1. *Meteor radar at Resolute Bay*

A meteor radar was installed to measure horizontal winds at Resolute Bay. It has been operated since 1997. The radar is a 51.5 MHz interferometric system, and the winds are measured at different altitudes from 80 to 98 km in height. The transmitted radio pulses are scattered from the atmosphere by various electron density perturbation including meteor trails, and some of the backscattered signal returns to the receiver antennas (Hocking, 2001). By combining the line-of-sight velocities observed from meteor trails in different directions the meridional and zonal winds can be determined. The daily averaged winds for this study are calculated from 2-hour bins.

2.2.2. *Meteor radar at Esrange*

Another meteor radar used in this study is located at Esrange near Kiruna, Sweden. Operating at 32.5 MHz, a single Yagi aerial is used for the transmitter, and five separate aerials are used as receivers. The vertical resolution is less than 2 km covering the altitude range from 78 to 100 km. Velocities from individual meteor trails are combined into 2-hour bins, incremented through the data set in steps of 1 h in order to derive meridional and zonal winds (Mitchell et al., 2002; Hocking, 2001).

3. Results and discussion

The SATI instrument has been used to measure MLT temperature at Resolute Bay since November, 2001, and these temperatures are compared with radar wind measurements. SATI is an optical instrument measuring the night airglow of OH and O_2, and observation is only possible during the winter season in the polar region. Fig. 3 shows the daily variations of the OH temperature from the SATI instrument and the wind from the meteor radar at Resolute Bay for the winters of 2001–2002 (upper), 2005–2006 (middle), and 2006–2007 (lower). The daily variations are calculated by subtracting the winter mean value from the daily average. The winter mean temperature is 226 K for the 2001–2002 winter season, 224 K for the 2005–2006 winter

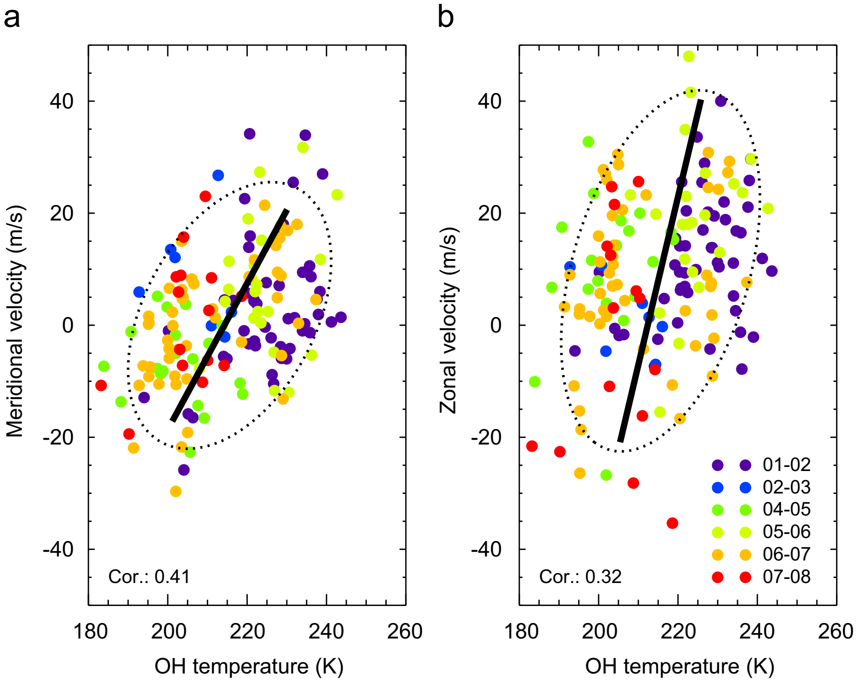


Fig. 4. Scatter plots of daily averaged temperature and wind at Resolute Bay for 169 day observations from the 2001–2002 winter season to 2007–2008 winter season. The correlation coefficient of the meridional wind and the OH temperature is 0.41 as shown in the left panel. Right panel is for the zonal wind and OH temperature, and the correlation coefficient is 0.31. The confidence level is 0.99 calculated by using the number of data points and the correlation coefficient.

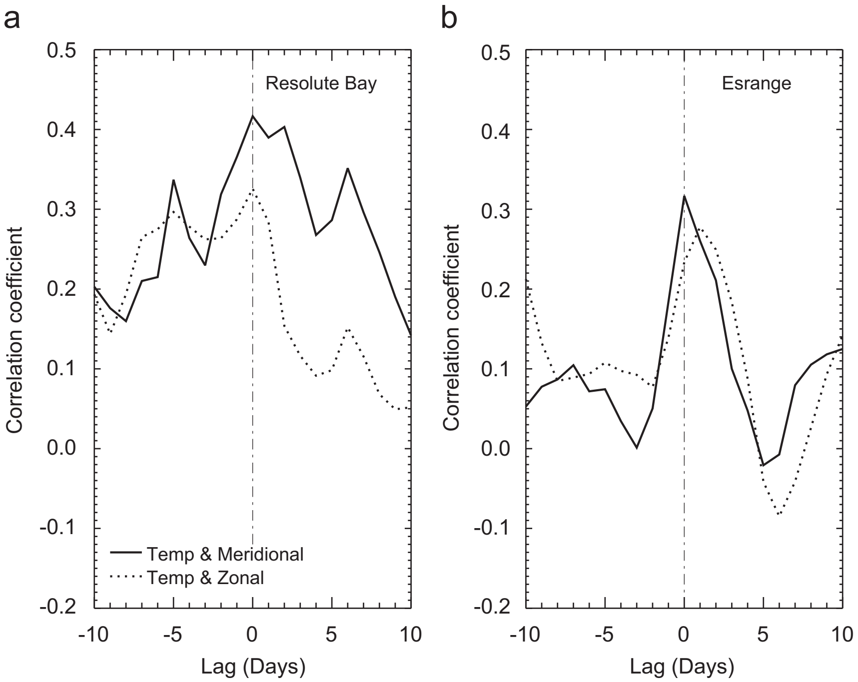


Fig. 5. The cross-correlation plot of temperature and wind at Resolute Bay for the same data set used in Fig. 4 on left panel. The lag is defined as temperature minus wind, and the unit of lag is a day. A peak in the positive lag days means that temperature is leading wind. Right panel is same as left panel, but for Esrange.

season, and 212 K for the 2006–2007 winter season. The atmospheric tides having periods of 24, 12, 6 h are canceled out using daily averages. These three winter seasons provide the best overlap of data for the two data sets.

The overall pattern of the winter temperature variation can be described in terms of two features, a winter maximum interspersed with shorter periods of MLT cooling. First, the MLT temperatures are warmer in the middle of winter than in early or later winter except around daynumber 350 of the 2001–2002 winter season. On the other hand, the meridional wind is mostly northward in the middle of the winter season. The warmer MLT temperatures are coincident with the northward meridional wind as shown in these years. The second feature is the MLT cooling around daynumber 350 of the 2001–2002 winter related to a stratospheric sudden warming (SSW) (Cho et al., 2004). During the period of the MLT cooling-SSW, the positive relationship of temperature and meridional wind continues, with the meridional wind reversing to southward as the temperature decreases below

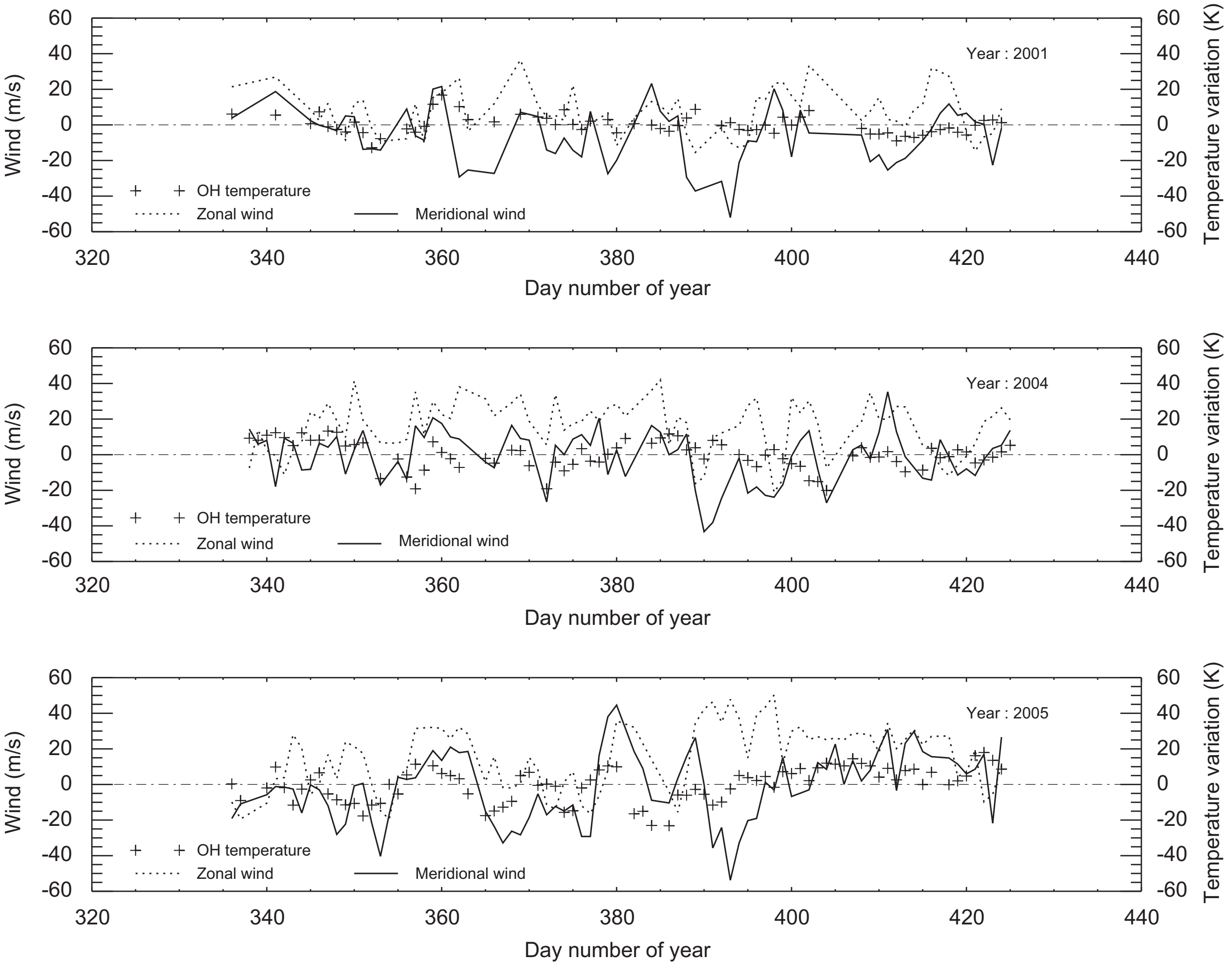


Fig. 6. The daily variations from the OH temperature of the Michelson interferometer and the horizontal wind at the 87.5 km altitude layer from the meteor radar at Esrange (68°N, 21°E). The crosses indicate the OH temperatures. The solid line represents the meridional wind, and dotted line for the zonal wind. The upper panel shows the daily variation of the temperature and wind for the 2001–2002 winter season, the middle panel is for 2004–2005, and the lower panel for 2005–2006.

its mean value for the winter. In contrast to the meridional wind, the mesospheric zonal wind is not influenced by the SSW, although the stratospheric zonal wind should reverse according to the definition of the major SSW. This could indicate a difference between the stratosphere and the mesosphere. In addition, the strong zonal wind reversal appears in UKMO assimilation data around 60°N, near the polar vortex edge. Thus, the zonal wind reversal may not be observed at high latitudes (Chshyolkova et al., 2007). This would also explain the low correlation of the zonal wind and the temperature.

Fig. 4 shows the relationship between the wind and the OH temperature at Resolute Bay for 169 days of observations from the 2001–2002 winter season to 2007–2008. The left panel shows the correlation of the meridional wind and the OH temperature, and the correlation coefficient is about 0.4. On the other hand, the correlation coefficient of the zonal wind and the OH temperature is about 0.3 as shown in the right panel. Although the zonal and meridional winds have a positive relationship with the OH temperature, the OH temperature has a stronger relationship with the meridional wind than with the zonal wind. The slope of the fitted line from the elliptical fit corresponds to about 0.8 K/ms^{-1}, which is close to the value of -0.7 K/ms^{-1} (for southward wind) found by Espy et al. (2003) in the Antarctic, showing that the coupling of meridional wind to temperature is similar in both hemispheres. However, the Antarctic data set from Rothera showed a higher correlation coefficient, -0.63 compared to 0.41 for Resolute Bay. Espy et al. (2003) also found a low correlation coefficient for the zonal wind, 0.29 compared with 0.32 for Resolute Bay. We used the fitting routine MPFITELLIPSE which fits a closed elliptical or circular curve to a two dimensional set of data points. The MPFITELLIPSE routine needs the MPFIT function that uses the Levenberg–Marquardt technique to solve the least-squares problem. The routine MPFITELLIPSE is a public-domain IDL program written by C. Markwardt; it is available from his Web site, http://cow.physics.wisc.edu/~craigm/idl/fitting.html.

In Fig. 5, the cross-correlation plot shows a clear relationship between the wind and the temperature at Resolute Bay in the left panel. The data set in this figure is the same as in Fig. 4. The lag is defined as temperature minus wind, and the lag unit is a day. Thus, a peak in the positive lag days means temperature is leading wind. The correlation coefficient is maximum around lag 0. This means that meridional wind and temperature correlate well without a lag. However, the correlation coefficient of zonal wind and temperature is weaker than that of the meridional wind and the temperature. The right panel is same as the left panel, but for Esrange. More details about Esrange data follow in the next paragraph. The correlation coefficients are lower than those for Resolute Bay. The meridional wind and temperature peak at zero lag while the temperature and zonal wind correlation coefficient peaks near +1 day which means the temperature is slightly leading the zonal wind, although we cannot be certain that this is statistically significant.

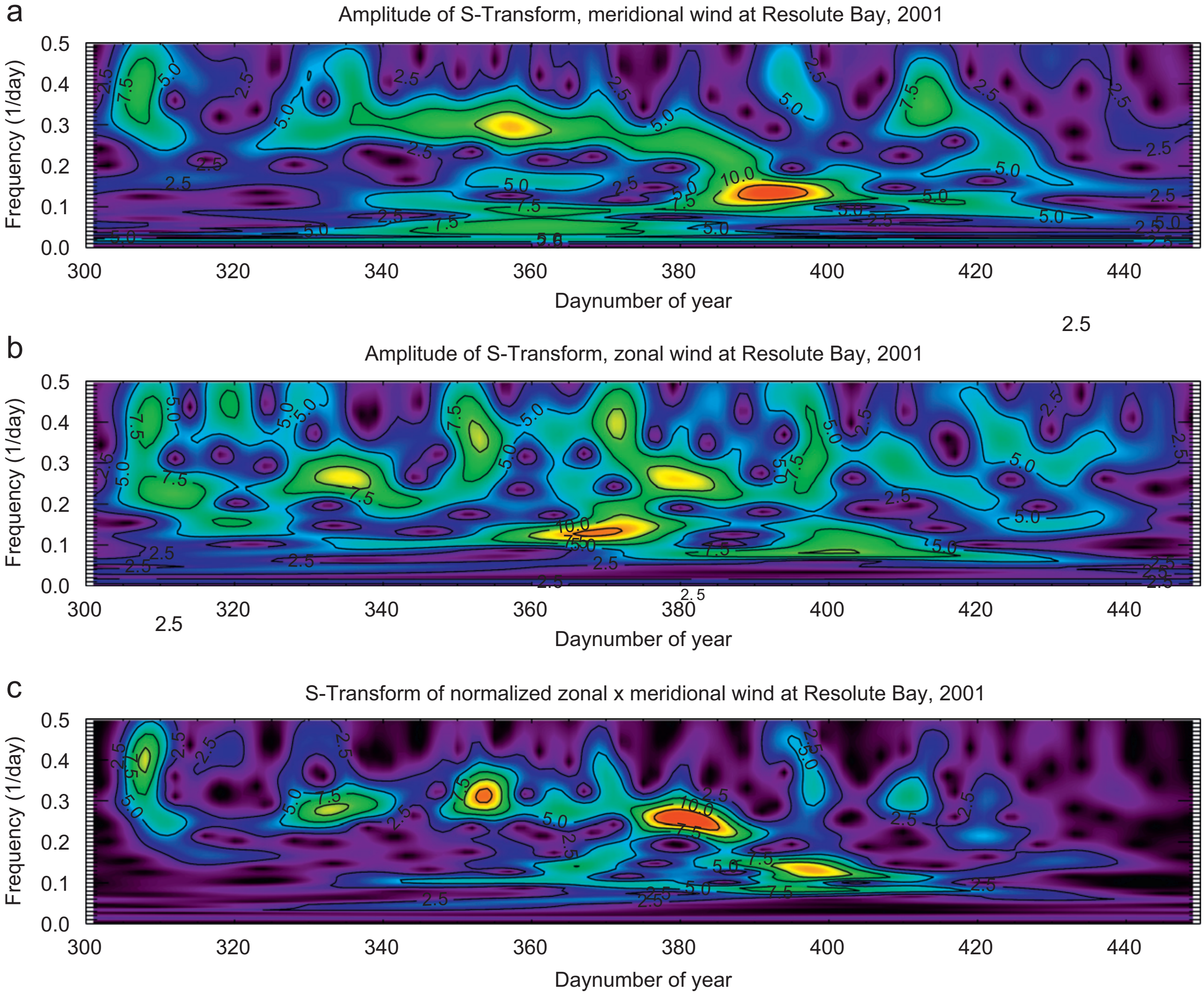


Fig. 7. The local amplitude spectrum of daily averaged winds at Resolute Bay for the 2001–2002 winter season. Panel (a) represents the local amplitude spectrum of the meridional wind, and panel (b) for the zonal wind. The bottom panel is the product of N and E spectral amplitudes to see simply co-exisiting frequencies for both zonal and meridional winds. The horizontal axis is daynumber of year, and the vertical axis is frequency (1/day).

The Esrange data set of wind and temperature was subjected to a similar analysis. Fig. 6 presents the daily variations for the OH temperature from the Michelson interferometer and wind of the meteor radar for the winter seasons of 2001–2002, 2004–2005, and 2005–2006. The temperature and the meridional wind have a similar pattern, and it is comparable to the result at Resolute Bay. However, the winter maximum in temperature is barely seen at Esrange for these three winter seasons. In addition, the meridional winds are not always northward during the wintertime.

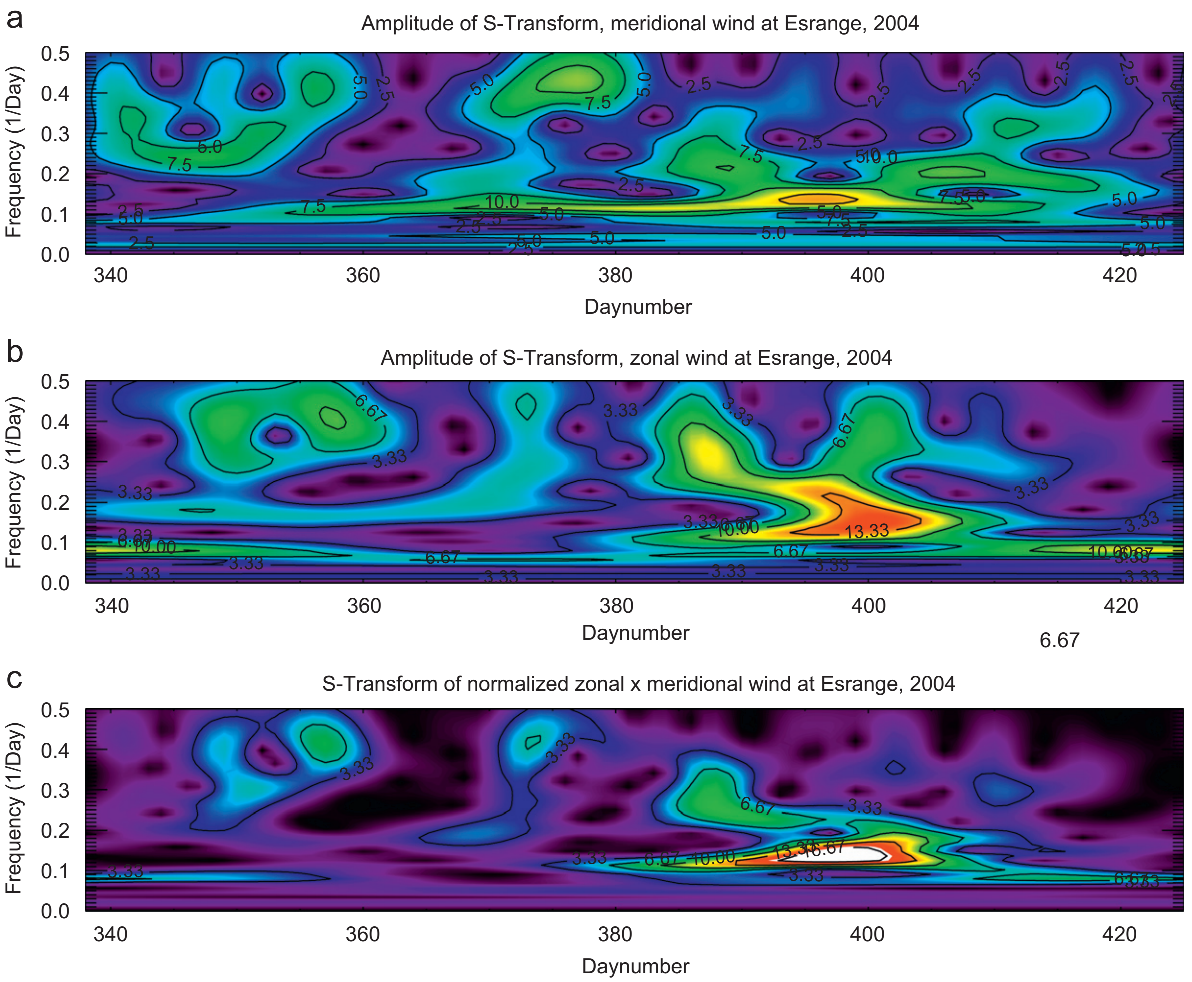
We expected that the Esrange data would show a similar correlation of the temperature and the meridional wind, but the relationship at Esrange is weaker than that of Resolute Bay. Although both locations, Resolute Bay (75°N) and Esrange (68°N), are at high latitude, the latitude difference between two locations may result in a difference rate of downwelling. In other words, the pole to pole circulation must cause some vertical wind shear as one approaches the pole. Thus, Esrange may be located on the boundary of the vertical wind shear while Resolute Bay is located in a more polar region of stronger downwelling.

A local spectral analysis of the wind time series was performed to search for planetary waves. A novel time series analysis, called the S-transform, was used in this study; the S-transform gives the absolute amplitude and phase of the local spectra. For more details about the S-transform, see Stockwell et al. (1996). Fig. 7 shows the local spectrum amplitude of the daily averaged wind at Resolute Bay for the 2001–2002 winter season. Panel (a) is for meridional wind, and panel (b) for zonal wind. The horizontal axis is a daynumber of year, and the vertical axis is frequency (1/day). The bottom panel is the spectrum of the product of the two, which identifies the frequencies that exist for both meridional and zonal winds, as shown in panel (c). Thus, the meridional wind direction could be either north and south during the wintertime as the result of the planetary waves.

Fig. 8 is the same as Fig. 7, but is for Esrange for the 2004–2005 winter season. The wave features of the meridional wind are similar to those of the zonal wind, occurring at the same frequencies.

4. Summary

The seasonal variation of MLT temperature has been attributed to the large-scale circulation from hemisphere to hemisphere. If so, this feature should also be apparent in the meridional wind. In this study, both physical parameters, temperature and wind from different installations were compared at two Arctic stations, Resolute Bay (75°N) and Esrange (68°N) in order to determine if their behavior was consistent with concept of the large-scale mesospheric circulation. Table 1 provides the summary of the comparisons. A total of 169 daily measurements from several



a Amplitude of S-Transform, meridional wind at Esrange, 2004

b Amplitude of S-Transform, zonal wind at Esrange, 2004

c S-Transform of normalized zonal x meridional wind at Esrange, 2004

Fig. 8. This figure is same as Fig. 7, but at Esrange for the 2004–2005 winter season. (a) Amplitude of S-transform, meridional wind at Esrange, 2004, (b) amplitude of S-transform, zonal wind at Esrange, 2004 and (c) S-transform of normalized zonal *x* meridional wind at Esrange, 2004.

Table 1
Correlation coefficient of OH temperature and wind.

Location	# of days	T-meridional	T-zonal	Zonal-meridional
Resolute Bay	169	0.41	0.32	0.19
Esrange	302	0.31	0.27	0.40

winter seasons were used at Resolute Bay, and 302 days at Esrange. The correlation of temperature and meridional wind is about 0.41 at Resolute Bay, and 0.31 at Esrange. While these values are low, a cross-correlation analysis showed strong peaks near zero lag, confirming the reality of the correlation. The convergence of the meridional wind flow is a strong function of latitude and the differences between the two sets of observations may result from this relatively small latitude difference. The correlation coefficient between temperature and meridional wind is higher than that with the zonal wind even though the two wind components are thought to be coupled. Also, the correlation coefficient between the zonal and meridional wind is 0.19 at Resolute Bay, and 0.40 at Esrange. The higher correlation coefficient of zonal and meridional wind at Esrange could be a result of planetary waves. The results also show that the large-scale circulation at Resolute Bay dominates over planetary wave features. A comparison with similar results obtained by Espy et al. (2003) shows almost the same responsivity of temperature to meridional wind, about 0.8 K/ms^{-1}.

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