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Article

All Sky Camera and Fabry-Perot Interferometer Observations in the Northern Polar Cap

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Abstract : We report all sky camera and Fabry-Perot interferometer (FPI) observations of mesospheric gravity waves and a 12-hour wave at Resolute (75°N) and a joint observation of 10-hour wave with Eureka (80°N). All sky camera observations showed a low occurrence of mesosphere gravity waves during equinoxes, which is similar to the mid-latitude region. A slightly higher occurrence near solstice appears to indicate that gravity waves are not filtered out by the neutral wind in the winter. The FPI observation of a 12-hour wave showed amplitude variations from day to day. The phase of the wave is mostly stable and consistent with the GSWM prediction in the winter. The phase shifts with season as predicted by the GSWM. Four events of the 12-hour wave were found in spring with amplitudes larger than the GSWM predictions. The FPIs at Resolute and Eureka also observed a wave with period close to 10 hours. The 10-hour wave maybe the result of the non-linear interaction between the semi-diurnal tide and the quasi-two day wave. Further studies are under way. Overall, the combined Resolute and Eureka observation have revealed some new features about the mesospheric gravity wave, tidal wave, and other oscillations.

Key words : gravity wave, 12-hour wave, 10-hour wave, polar mesosphere, migrating semi-diurnal tide.

1. Introduction

Since the establishment of the Early Polar Cap Observatory at Resolute Bay in 1995, an all sky camera and a Fabry-Perot interferometer have been making continuous measurements of the polar mesospheric region during northern winter seasons. One of natural phenomena of interest is the occurrence of mesospheric gravity waves. Gravity waves originate in the lower atmosphere as disturbances. As gravity waves propagate upward, some can reach mesospheric heights, if the conditions are favorable. The amplitude of the wave grows exponentially with increasing altitude as the air density decreases. Since gravity waves can transfer momentum from the lower atmosphere to the mesosphere, they play an important role in the global circulation. An all sky camera can detect gravity wave activity during nighttime by imaging wave induced structures in the nightglow emissions (Wu and Killeen 1996). One of the mostly used nightglow emission is the OH emission, which peaks at 87 km (Witt *et al.* 1979). Compared to the mid-latitude regions (Wu and Killeen 1996), polar region gravity wave observations have been lacking. Because of the influence of gravity waves on the global circulation, a better understanding of gravity waves can lead to a better understanding of the polar mesospheric dynamics. Not all gravity waves can reach mesospheric altitudes. Some are filtered out by neutral winds while others break before reaching high altitudes. The gravity wave activity has a strong seasonal trend in the mid-latitude region. Wu and Killeen (1996) suggested that the gravity wave propagation has a preference for the eastward direction in the northern

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hemisphere mid-latitude region. Because of the mid-latitude strong westerly neutral wind at 60 km altitude in the winter season and easterly in the summer, gravity waves can easily propagate to the mesosphere in the summer and are mostly filtered out in the winter season. Consequently, the mesospheric gravity wave activity in the mid-latitude region has a strong seasonality. It is impossible to obtain a complete polar seasonal trend of the gravity wave occurrence because of the lack of observation during the summer season and short observations during the spring and fall seasons. However, even incomplete monthly statistics are still useful.

Another instrument at Resolute is a Fabry-Perot interferometer (FPI), which measures the neutral wind in the mesosphere by monitoring the Doppler shift of the OH Meinel (7-3) band. Commonly observed features in the mid-latitude region at mesospheric heights are tidal waves. One of the most frequently observed tides is the 12-hour migrating semi-diurnal tide. At high latitudes, however, the classical tidal theory predicts the semi-diurnal tide to be weak, because of the zero amplitude of at the pole (Longuet-Higgins 1968). Mathematically, the semi-diurnal tide is a combination of many modes, which are solutions to the Laplace's equation (Longuet-Higgins 1968; Forbes 1995). However, more recent simulations of the tidal waves based on solar forcing calculations have predicted sizable semi-diurnal tide amplitudes at relatively high latitudes during winter season. The Global Scale Wind Model (GSWM) has been used for these kind of calculations (Hagan *et al.* 1995; Hagan *et al.* 1999). Nevertheless, the amplitude of the semi-diurnal tide is always zero at the pole. The nonzero solution at the pole for the Laplace's equation has a zonal wavenumber one. The zonal wavenumber is the number of cycles of a wave around the globe in the longitudinal direction. The migrating semi-diurnal tide has a zonal wavenumber two because it is sun-synchronous. What is interesting is that 12-hour oscillation (same period as semi-diurnal tide) is observed in the mesospheric winds near the pole (Hernandez *et al.* 1993; Forbes *et al.* 1995; Portnyagin *et al.* 1993). The FPI at Resolute observed the12-hour wave frequently. It is possible that the 12-hour oscillation is the result of either the semi-diurnal tide or the zonal wavenumber one ($s = 1$) oscillation. In this study, we do a survey of the 12-hour oscillation to examine variations of amplitude and phase with time. Furthermore, we will compare the observational results with GSWM predictions. While it is impossible to determine the zonal wavenumber from one station, we intend to provide a general picture of the 12-hour oscillation occurrence.

Besides the tidal waves, oscillations with periods, which are not a harmonic of 24 hours, are also observed in the mesospheric neutral wind. Manson *et al.* (1982) and Manson and Meek (1990) observed waves with oscillation periods close to 10 hours in the mesospheric neutral wind at 52°N. Sivjee *et al.* (1994) also recorded waves in mesospheric temperature with similar period. They all suggested that the wave might be the result of a non-linear interaction between the semi-diurnal tide and the quasi-two day wave. The quasi-two day wave is a free oscillation of the atmosphere, which requires no forcing (Muller 1972). The wave has a zonal wavenumber 3 (Glass *et al.* 1975). The wave does not propagate vertically, implying a very long vertical wavelength. A non-linear interaction between the quasi-two-day and 12-hour waves will result an oscillation with period close to 10 hours and 16 hours. The zonal wavenumber for the 10-hour oscillation will be close to 5. The vertical wavelength will be similar to that of the semi-diurnal tide. In the high latitude region, the vertical wavelength may range from 30 to 50 km based on estimated values of the semi-diurnal tide modes (Forbes 1995). The Resolute FPI also observed the 10-hour wave and so has an FPI at Eureka. The Eureka FPI monitors multiple nightglow emissions and one of them is the O (^{1}S) 5577 Å emission, which peaks at 97 km altitude (Donahue 1972). While the future goal is to use the two-station observation to study the zonal wavenumber and vertical wavelength of the 10-hour wave, we will limit ourselves to show one example of the wave in this paper.

This paper covers the three areas of the polar mesosphere research: 1) all sky camera observations of gravity waves; 2) FPI observations of the 12-hour wave in the neutral winds; 3) FPI observations of the 10-hour wave. These observational results show some new features of gravity waves, the 12-hour wave, and the 10-hour wave.

2. All sky camera observation

All sky cameras have been used to observe gravity waves for a long time (Taylor *et al.* 1993). The Resolute camera is based on an earlier design (Mende *et al.* 1977) and capable of detecting OH emission variations greater than 5% (Wu and Killeen 1996). An example of a gravity wave observed by the all sky camera is shown in Fig. 1. The all sky camera makes routine daily nighttime observations. Because cloud and moonlight can have an adverse effect on observations, only data taken during

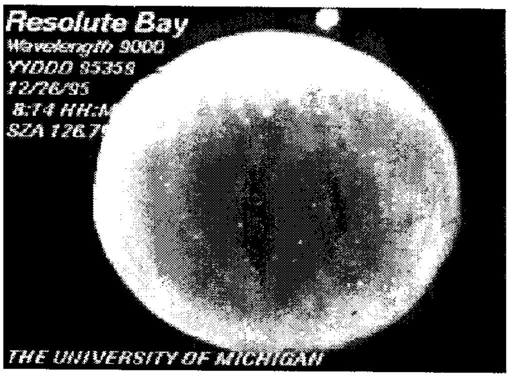

Fig. 1. Example of gravity wave image at Resolute.
(The OH emission shows the gravity wave induced wave structures recorded by the all sky camera at Resolute. The image has 329 × 258 pixels and was taken with an exposure of 9 seconds. Several stars are visible in the image indicating a clear sky. From the center to the upper bright spot (a beacon light) is the westward direction. The north direction is towards right slightly lower. The orientation of the wave front is from southwest to northeast. The wave was moving towards north slightly westward.)

nights with a moonless, clear sky were used. The data set used in the study was recorded from October 1995 to March 1996. The local time coverages of all sky camera observations are plotted in Fig. 2 on a monthly basis. The charts show the number of hours with a moonless clear sky. The figure shows a relative low coverage in February 1996. The local time coverage is very limited in March 1996 due to the shortened nighttime in the spring season. The coverage is reasonably good for the other months. The image data were examined visually. Since the same instrument used in this study and that of Wu and Killeen (1996), the same statistical method and criteria were used here. The hours with gravity waves present were counted and divided by the total number of moonless clear sky hours. The monthly occurrences of gravity waves are illustrated in Fig. 3. The figure shows a very low occurrence (< 0.1) in October. The occurrence is higher in November and January. The February occurrence is high, but it has a large uncertainty due to the low coverage time. There were no gravity waves observed in March. Because the local time coverage is not the same during different months, differences in the monthly occurrence ratio might be related to local time distribution of gravity wave occurrence. To reduce that possibility, we also examined the local time variation of gravity wave occurrences. The local time occurrences for all the months are displayed in

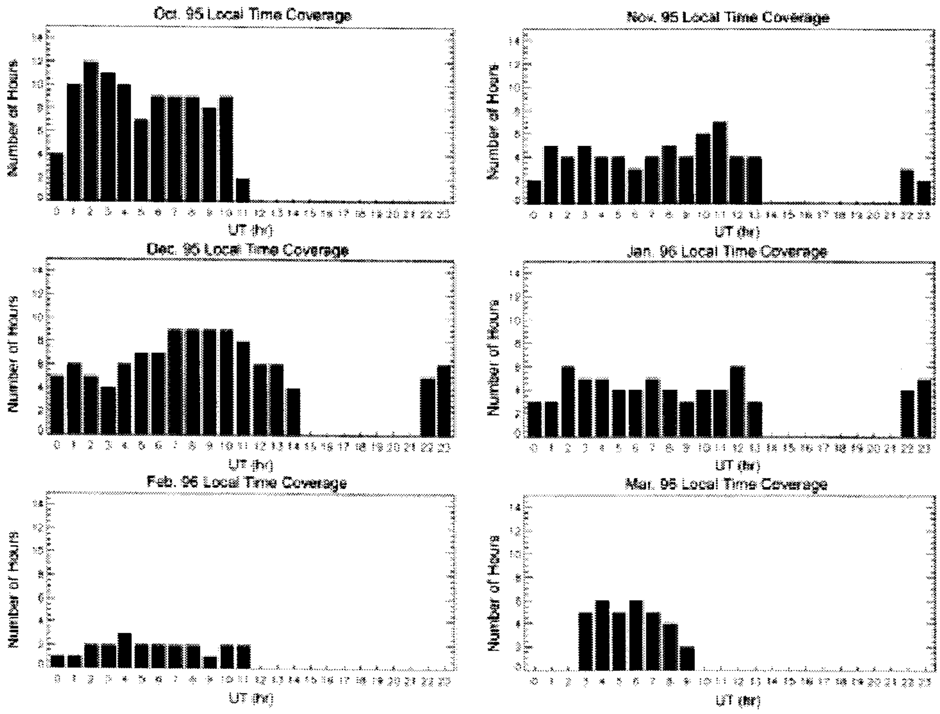

Fig. 2. Image data monthly local time coverage.
(The numbers of hours with moonless clear sky are counted at every local time hour for each month. Shortened local time coverages during March and October are due to the short nighttime for the spring and fall season.)

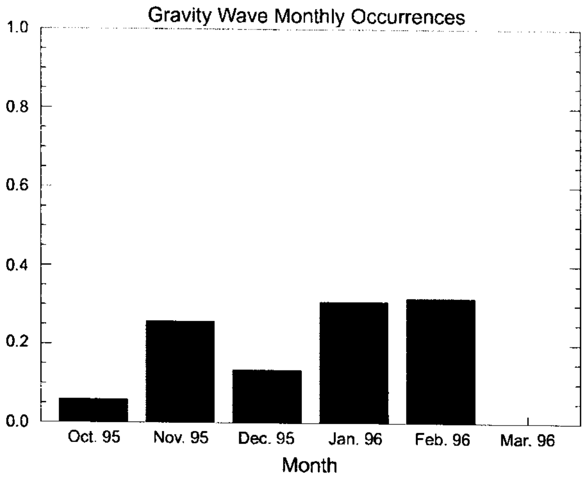

Fig. 3. Gravity wave monthly occurrences.
(The occurrences for each month are calculated including all local times during moonless sky nights.)

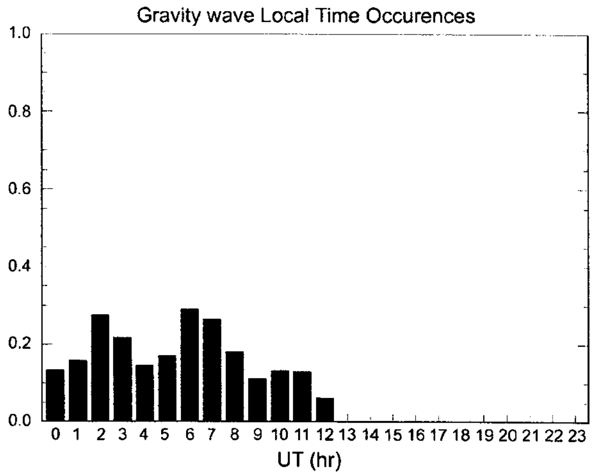

Fig. 4. Gravity wave local time occurrences.
(The occurrences are calculated for all months at each local time hour.)

Fig. 4. The gravity wave local time occurrences do not show any large variations, which would have affected the monthly occurrences. Therefore, the observed monthly occurrence of gravity waves can be considered a good representation of the monthly variation of gravity wave activity. The occurrence appears to be small in the fall (October) and spring (March) with some enhancement during the winter months (November, December, and

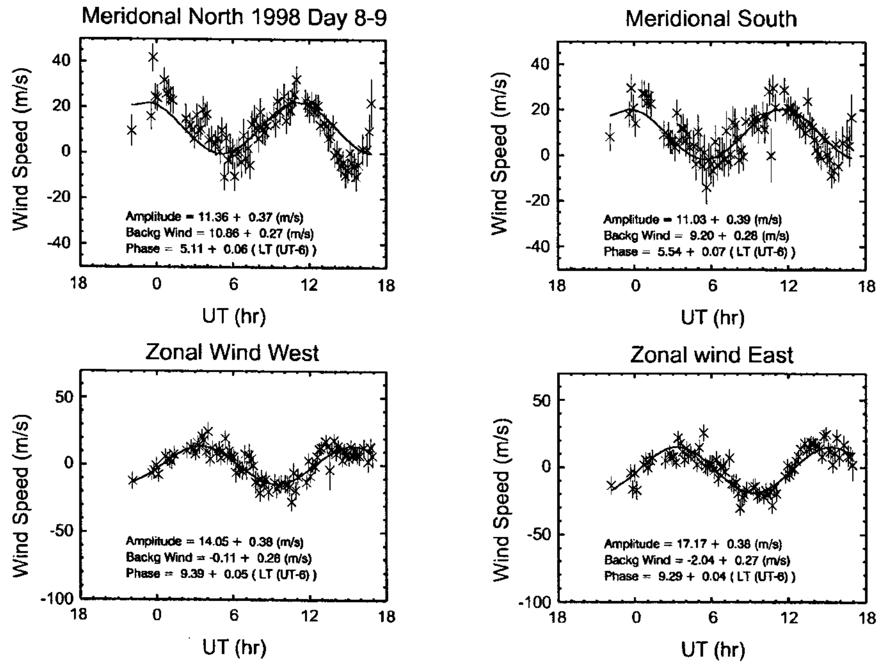

Fig. 5. A 12-hour wave example.
(The neutral wind measured using OH 8920 emission on 1998 January 8-9. The winds are divided into four directions and the 12-hour wave is prominent in all four components. The least squares fit curves for each component and the results are also shown.)

January) season. However, there is no single peak occurrence in the winter season. Overall, the gravity wave features are much weaker and less frequent in the polar region than in the mid-latitude region (Wu and Killeen 1996). Wu and Killeen (1996) reported 70% occurrence rate of gravity waves during the summer at 40°N. While the all sky camera is ideal for examining short time variations like gravity wave, other slower variations are best examined with an FPI.

3. FPI observations of the 12-hour wave

The FPI installed at Resolute measures mesospheric winds by monitoring the Doppler shift of the OH Meinel (7-3) emission line in nightglow. The instrument is equipped with a Circle-to-Line-Interferometer Optics (CLIO) conical mirror, which was invented by Hays (1990). The CLIO system greatly reduces the readout noise of the CCD detector. Consequently, it increases the sensitive of the instrument. More information about the system is provided in a paper by Wu *et al.* (1994). The wind measurement error is on the order of 8 m/s. The 12-hour wave is a commonly observed feature of the mesospheric winds above Resolute. Fig. 4 shows an example of the 12-hour wave. The wind data are divided into four cardinal directions. The four-direction measurement cycle is designed to calculate the zero wind. An FPI can measure only relative changes in the wind. By measure of the same wind component in opposite directions, one can determine the zero wind position of the instrument. Moreover, the two measurements of the same component can also be used to check the consistence of the data. The winds shown in the figure are horizontal winds. The least squares fit results for each component are also shown in the figure. We used least squares fit to select of the 12-hour wave events. The following criteria are used in selecting the 12-hour wave events: 1) the data sequence is longer than 12 hours; 2) data were taken under relatively clear sky; 3) wave amplitude is larger than 10 m/s in the zonal wind; 4) the phase error for the zonal wind is less than 12 minutes; 5) the goodness of the least squares fit (Q) is higher than 0.1 (Press *et al.* 1992). The wind measurement error is the limiting factor for the wave amplitude criterion. The requirements for the zonal components are applied to both the eastward and westward directions. The clear sky is determined by the comparing the intensity of the OH nightglow taken at the zenith and at 45° zenith angle. If the sky is cloudy, the intensity will be the same at all directions due to scattering. If the sky is clear the OH nightglow at 45° zenith angle will be stronger than that observed at the zenith due to the van Rhijn effect, which states that the airglow layer is optically and linearly thin at the zenith. We compute the ratio of the OH nightglow intensities at the two directions. If the ratio is greater than 0.8, then we consider the sky to be cloudy. The data used for this study were collected during the '97-'98 winter season from October 8, 1997 to March 6, 1998. The observational period is limited by the requirement for 12 hours or longer of nighttime. The amplitudes for the selected 12-hour wave events are plotted in Fig. 6. The upper panel is for the meridional wind and the lower for the zonal wind. The dashed-lines are the predicted amplitudes of the semi-diurnal tide by the GSWM for the fall, winter, and spring seasons (Hagan *et al.* 1995; Hagan *et al.* 1999). The meridional wind showed mostly consistent results between the northward and southward directions. The zonal winds showed the same consistency. In spite of low predicted amplitudes (~3 m/s) by the GSWM and the relatively high amplitude selection criterion (10 m/s), several events have been selected in the fall and spring seasons. In the winter season, the selection criterion is comparable with the predicted amplitudes of the GSWM and four events were selected. Since only the selected events are plotted, the gaps between the selected events are an indication of some variability of the 12-hour wave amplitude in the polar region. Because of the selection criterion, the observed events tend to have larger amplitudes than the model predictions.

It is somewhat surprising, however, that four events with amplitudes greater than 10 m/s were selected in the spring season, while the predicted amplitude is very low. The phases for those events are plotted in Fig. 7, which is the local time for the positive peak. The upper panel is for the meridional wind and the lower for the zonal. The dashed-lines are the predicted phases of the semi-diurnal tide by the GSWM for the fall, winter, and spring seasons. The observed phases in of the two components in the fall and winter seasons match well with the predictions. The observed phases in the spring season show a gradual shift towards the predicted spring value. They are, however, still off the model spring prediction by a few hours at the end of the study period. Since the model run is for the equinox, these differences are probably expected. The 12-hour wave in the meridional and zonal components is supposed to have a quadrature phase difference according to the Laplace's equation solution (Forbes 1995). To verify the consistency of the phases of the two components,

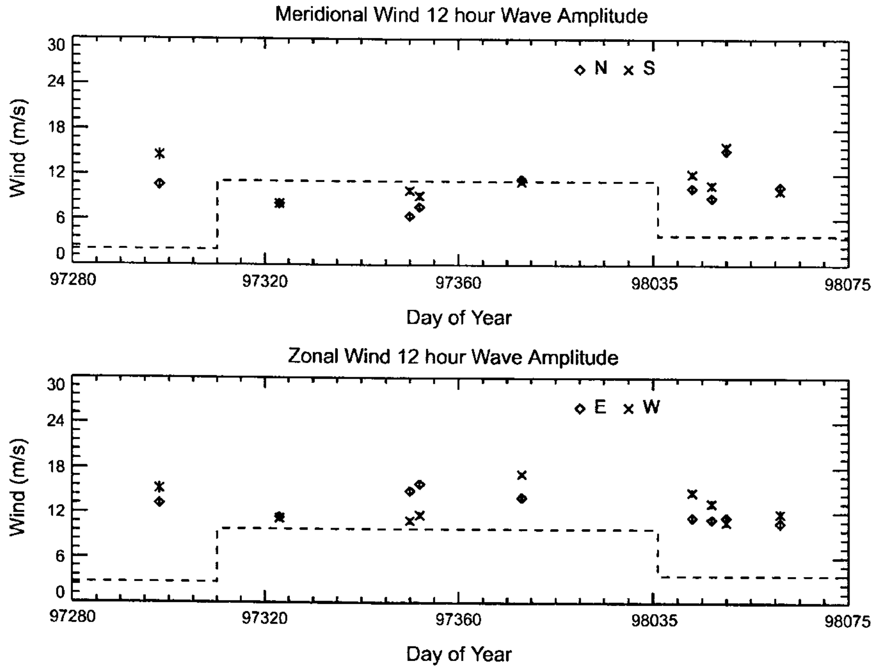

Fig. 6. 12-hour wave amplitudes.

(The amplitudes are for the selected event. The upper panel is for the meridional component and lower for the zonal. The dashed-line in each panel represents the GSWM predictions of the semi-diurnal tide for the fall, winter, and spring seasons.)

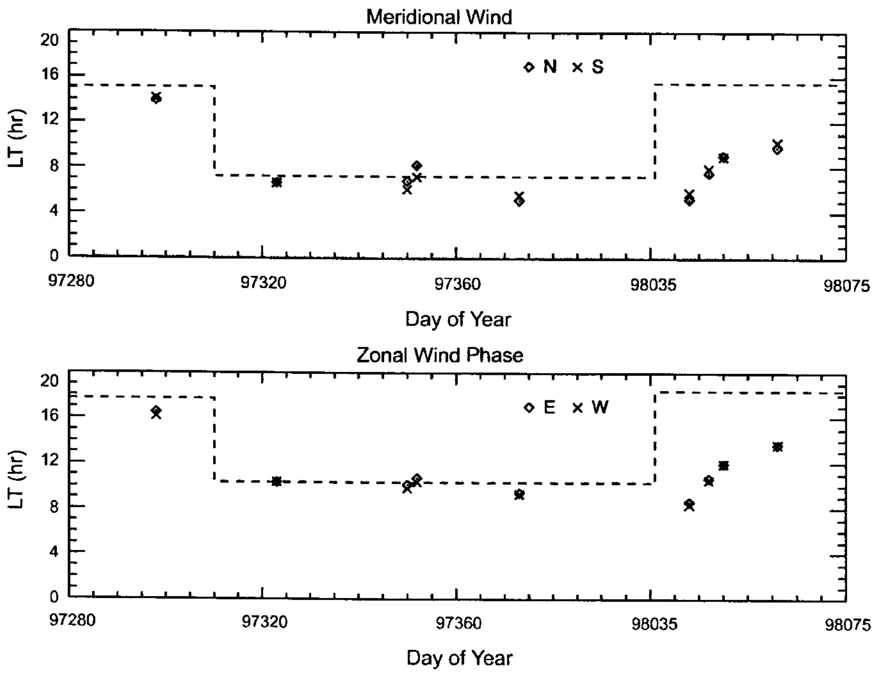

Fig. 7. 12-hour wave phases.

(Same for format as Fig. 6 for the 12-hour wave phases.)

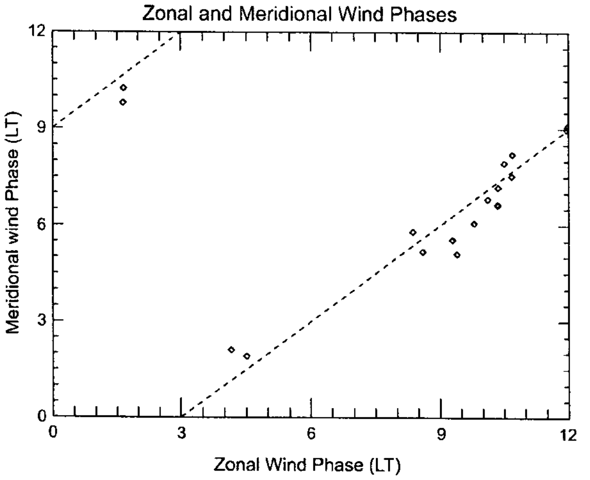

Fig. 8. 12-hour zonal phase vs. meridional phase.
(The meridional wind phase plotted as a function of the zonal wind phase. The dashed-lines mark a quadrature phase difference.)

the meridional wind phases are plotted as a function of the zonal wind phase in Fig. 8. The dashed-lines mark the location of the 3-hour difference (a quadrature for the 12-hour wave). All events are distributed very close to the dashed-lines indicating a consistent quadrature phase difference throughout. While the 12-hour wave is the most frequently observed wave in the polar mesosphere, occasionally, waves with periods other than harmonics of the 24 hours were also observed. In the next section we will show a case of 10-hour wave.

4. FPI observations of the 10-hour wave

A 10-hour wave was observed on January 21-22, 1998 in the OH emission neutral winds at Resolute as shown in Fig. 9. The upper panel is the meridional wind and the lower zonal wind. The periodograms of the neutral winds are plotted in Fig. 10. Both meridional and zonal wind components show a peak at 10 hours. Since the time sequence of the event is short, there is a large uncertainty about the oscillation period (± 2.6 hours). The wave faded in the next day (data not shown). The Eureka FPI also observed the similar feature. Guo (2000) provided more information about the instrument. The O (^{1}S) 5577 Å emission wind data obtained at Eureka are shown in Fig. 11. The data gap is due to the presence of aurora, which may affect the wind measurements. The wave is apparent in the zonal component. The meridional component

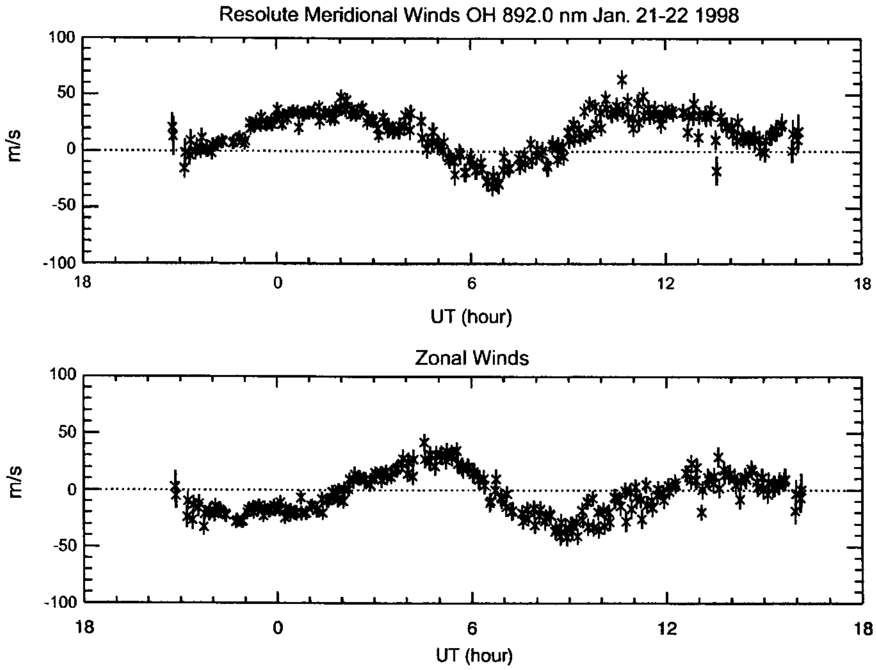

Fig. 9. 10-hour wave in OH emission winds at Resolute.
(The meridional wind is plotted in the upper panel and zonal in the lower panel. The data were taken on January 21-22, 1998.)

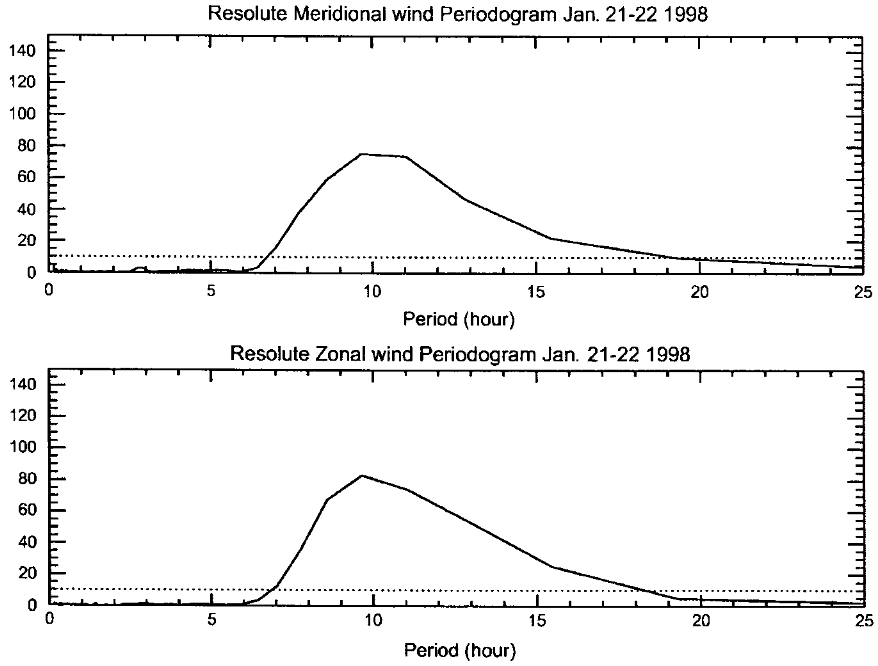

Fig. 10. Periodograms of the OH emission winds at Resolute.

(The periodograms of meridional (upper panel) and zonal wind components show a strong peak centered at 10 hours. Due to the short data sequence, there is a large uncertainty about the wave oscillation period. The dashed-line marks the 99% significance level.)

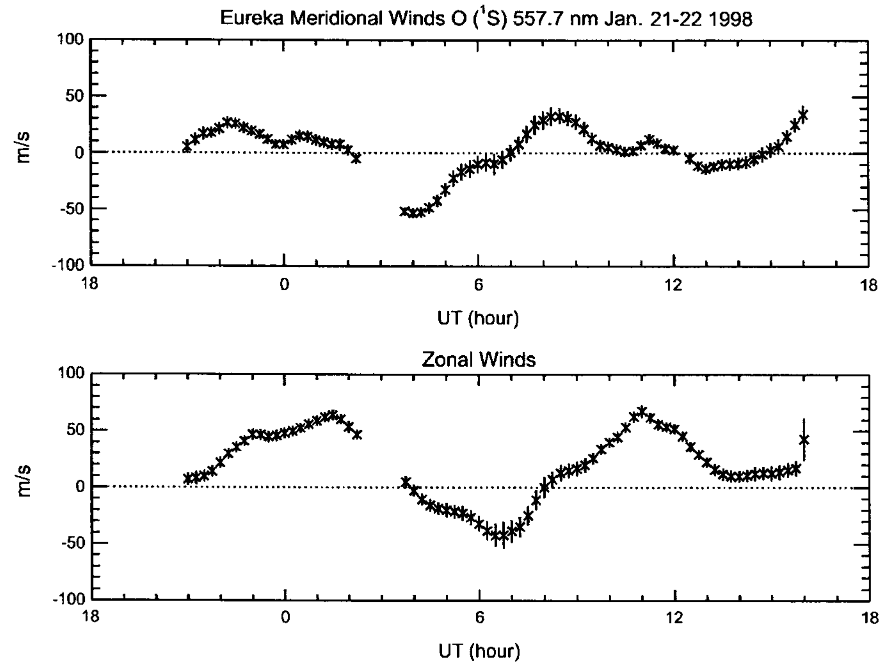

Fig. 11. 10-hour wave in O (^{1}S) emission winds at Eureka.

(Same as Fig. 9 for the Eureka O (^{1}S) emission winds.)

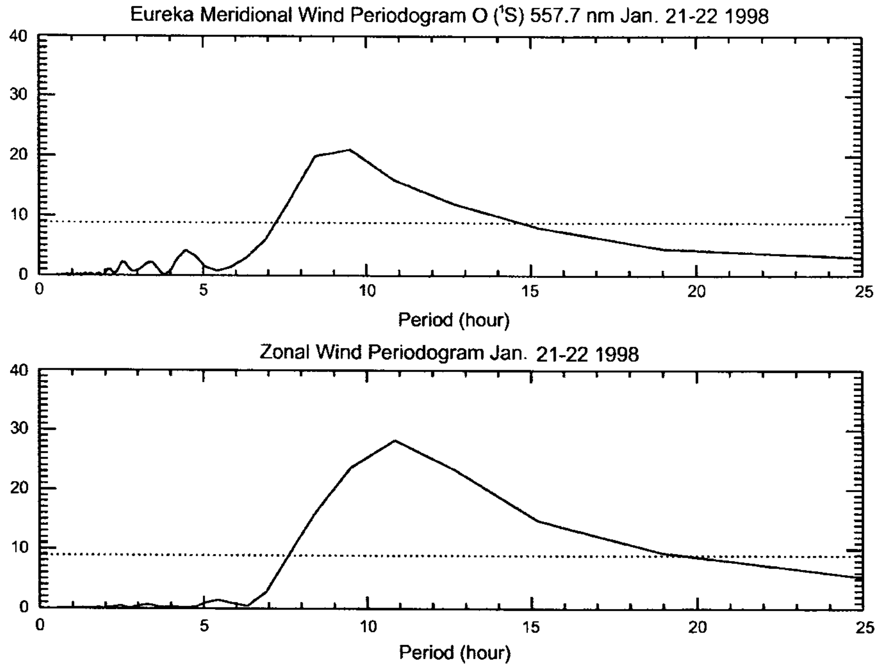

Fig. 12. Periodograms of the O (^{1}S) emission winds at Eureka.
(Same as Fig. 10 for the Eureka O (^{1}S) emission winds.)

shows some other fast oscillations and the 10-hour wave is relatively weak. The periodograms of the Eureka winds are plotted in Fig. 12. The meridional wind shows a peak near 9 hours. The zonal wind has a dominant peak centered close to 11 hours. With the large certainty in the estimation of the oscillation period, it is likely that what we see in Eureka is the same wave appeared in Resolute.

5. Discussions

The gravity wave occurrence at high latitude is obviously different from that at mid-latitude (Wu and Killeen 1996). There is, however, a similar tendency of low occurrences during the equinoxes. During the winter solstice the gravity wave activity increased slightly. Since we do not have the summer season, the annual picture is not clear at this point. Gravity waves in the high latitude are unlikely to be generated by the jet stream, though they may still be weather related. Since there is no strong easterly and westerly wind near 60 km altitude at high latitudes, the source and propagation conditions for gravity waves in the high latitude region are different from that in the mid-latitude region. Consequently, we do not expect the same kind seasonality of gravity waves at high latitudes and the observational results agree with that. The smaller occurrence of gravity waves in the high latitude region, as well as in the mid-latitude region during equinoxes, appears to suggest it is a global phenomenon. We speculate that the low occurrence might be related to gravity wave generating mechanism not its propagation process. The low occurrence in the mid-latitude winter season is thought be related to the filtering out of gravity waves by the neutral winds. Whether the same is true at high latitudes is unclear. Since there is a small increase of the occurrence around the winter solstice, we believe that gravity waves are not filtered in the winter season. A summer observation would have provided a complete annual picture. Unfortunately, this is not possible with an all sky camera observation. Perhaps, future satellite and radar observations may shed some light on the subject. The weaker gravity wave features in the polar region are indicative of weaker gravity wave sources.

The 12-hour wave is the most common observed features in the polar region. The existence of the wave at high latitudes during some seasons is puzzling, because classical tidal theory predicts small amplitudes for the migrating semi-diurnal tide. The proposed zonal wavenumber one 12-hour wave can solve the problem, however, past studies of the subject have been inconclusive (Portnyagin *et al.* 1998; Palo *et al.* 1998; Riggin *et al.* 1999). Most of the studies were based on radar observations in Antarctica. A general picture has emerged, which divides the high latitudes into three regions (Portnyagin *et al.* 1998). The first region is at latitudes above 78°, where the wave is mostly the $s = 1$ type. The second is between 78° and 68°, where a mixture of $s = 1$ wave and the semi-diurnal tide exists. The third is below 68°, where the semi-diurnal tide dominates. Resolute is located in the second region, where a mixture is suppose to exist. It is impossible to determine the zonal wavenumber with a single station of course. The statistically analysis of the wave amplitude and phase can provide some clues to the true nature of the wave. The amplitude of the wave showed some fluctuations. Since the solar forcing used in the GSWM is based on seasonally averaged result, some discrepancy in amplitude is not entirely unexpected. We have seen mostly comparable results in the winter. The phase results are in an agreement with the GSWM, with the exception of the spring season. According to Riggin *et al.* (1999) the zonal wavenumber is closer to 2 (more semi-diurnal-like) during the polar winter and closer to 1 during the polar summer at similar latitudes. It should be pointed out that during the winter, the phases of the two components remain relatively stable. This result appears to support the idea of that these waves are the semi-diurnal tide, which should have a constant phase in local time at any longitudes. The shifting of the phase of the 12-hour wave at Resolute is shown in both the observational and modeling results. Only one event was selected in the fall season, the phases for two components have a good agreement with the GSWM. In the spring season, there are four events selected, their phases appear to be in transition from the winter phase to the spring phase. However, they never reach the spring phase value near the end of the time interval. These 12-hour oscillations in spring season follow the same seasonal phase variations of the semi-diurnal tide, but have larger wave amplitudes than the GSWM predicted. It is uncertain at this point whether they are the semi-diurnal tide or not. It is possible that the GSWM underestimates the semi-diurnal tide amplitude. It also cannot be ruled out that these are zonal wavenumber on ($s = 1$) oscillations. Further studies are needed.

We have just started to examine waves with period close to 10 hours. The hope is that we will be able to use multi-emission wind data at different altitudes to estimate the vertical wavelength, and multi-station observations to calculate the zonal wavenumber. Earlier observations have suggested that the wave might be the result of the non-linear interaction between the semi-diurnal tide and the quasi-two day wave. If that is true, the zonal wavenumber of such wave should be 5. The vertical wavelength should be similar to that of the semi-diurnal tide (30-50 km). Further analysis will be performed on the data set.

6. Summary

This paper summarizes recent all sky camera and Fabry-Perot Interferometer observations at Resolute and a joint observation with a Eureka FPI. All sky camera observations show a low occurrence of gravity waves during equinoxes, which is similar to the mid-latitude region. The slightly higher occurrence near solstice appears to indicate that gravity waves are not filtered in winter, as is suggested in the mid-latitude region. The FPI observations of 12-hour wave show amplitude variations from day to day. The phase of the wave is mostly stable and consistent with the GSWM prediction in winter. The phase shifts with season as predicted by the GSWM. A 10-hour wave was observed in both Resolute and Eureka by the FPI instrument. The oscillation is possibly a result of non-linear interaction between the semi-diurnal tide and the quasi-two day wave. Further analyses are underway.

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