Characteristics of Mesosphere Echoes over Antarctica Obtained Using PANSY and MF Radars

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Abstract

We investigated characteristics of mesosphere echoes over Syowa Station (69S) in the Antarctic, which were detected by the Program of the Antarctic Syowa Mesosphere, Stratosphere and Troposphere/Incoherent Scatter (PANSY) radar (47 MHz) and Medium Frequency (MF) radar (2.4 MHz). Winter echoes from the PANSY radar and low altitude MF echoes below approximately 70−75 km mostly coexisted, appearing during the daytime as well as for a few hours post sunset. Summer echoes in the lower height region were absent in both radar observations, suggesting a close relationship in the generation mechanisms of these two radar echoes. High correlation between local K-index and the occurrence of winter echoes suggested that electron density enhancement due to ionized particle precipitation was one of the triggers of echo generation. Angles of arrival of the MF echoes were more isotropic in winter. Because gravity wave activity is much higher in winter over Syowa, higher turbulence energy caused by gravity wave breaking may also be responsible for the generation of the winter echoes and their isotropic behavior. The horizontal wind velocities of the two systems were further compared and agreed well throughout the height region of 60−90 km.

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1. Introduction

Mesosphere, Stratosphere, and Troposphere (MST) radars are one of the most powerful instruments for the study of the polar mesosphere. Characteristic mesosphere echoes are observed: polar mesosphere summer echoes (PMSEs) and polar mesosphere winter echoes (PMWEs) (e.g., Ecklund and Balsley 1981; Hoppe et al. 1988; Rapp and Lübken 2004; Zeller et al. 2006; Morris et al. 2011). According to turbulence theories, expected turbulence in the polar mesosphere seems too weak to explain the observed strength of both echoes (e.g., Rapp et al. 2013). Recent studies in the Arctic have indicated that ice particles play an important role in increasing the Schmidt number (Sc) and enable the existence of PMSEs (Rapp and Lübken 2004, and references therein). On the other hand, PMWEs are still poorly understood, mostly because they are much weaker and rarer. Nevertheless, extensive radar studies have proposed various generation mechanisms of PMWEs, such as strong turbulence (Lübken et al. 2007), infrasound waves (Kirkwood et al. 2006), and meteor smoke particles that increase the Sc (La Hoz and Havnes 2008). Nishiyama et al. (2015) recently reported height, local time, and seasonal dependence of PMWEs using the PANSY radar at Syowa Station (69°S, 40°E) in the Antarctic. In addition to MST radars, Medium Frequency (MF) radars also have a long history and have greatly contributed to the understanding of the polar mesosphere and lower thermosphere (e.g., Vincent 1994; Murphy et al. 2009).

In the present study, we examine the nature of polar mesosphere echoes, with an emphasis on winter echoes, through a comparison based on two radars employing largely different operation frequencies, that is, the PANSY radar (47 MHz) and the collocated MF radar (2.4 MHz). We also compare horizontal wind velocities of the two radars as a preparatory study for the future work of analyzing atmospheric dynamics using both of them.

2. Experimental setup and observations

The PANSY radar is a large-aperture MST radar (Sato et al. 2014). The radar began continuous MST observations in early 2012 using a partial system (12 groups out of 55) based on a Doppler beam swinging technique. After some full system operation tests from March to May 2015, the radar has been in continuous full system operation since late September 2015.

The Syowa MF radar consists of four dipole antennas (Tsutsumi et al. 2001). Because the antenna pattern is rather broad, horizontal winds are estimated based on a spaced antenna technique, the full correlation analysis (FCA) method (Briggs 1984). Both ordinary (O) and extraordinary (E) polarizations are used, but the O mode data is mostly used for wind analysis because of less radio wave absorption as described later. Winds are estimated on a few min basis for both radars.

3. Results and discussion

We first looked at the seasonal behavior of the mesosphere echoes. A summary plot of echo power in 2015 for the PANSY vertical beam is shown in Fig. 1a. The result is shown for data with a detectability (Fukao and Hamazu 2013) greater than 3 in order to reject noisy estimates. Numbers of individual 2-min echo events integrated for a day at each height are shown in Fig. 1b to better understand their height distributions. Summer echoes in December, January, and February are mostly confined to altitudes of 80−90 km and are rarely seen outside this region, which is a well-known feature of PMSEs (e.g., Sato et al. 2014, 2017). Non-summer echoes between mid-March and mid-November are seen mostly at altitudes of 55−80 km, which is in line with the reported features of PMWEs over Syowa (Nishiyama et al. 2015). Note that there are transient periods from summer to winter in March, and also from winter to summer in October and November, in which echoes are observed in both PMSE and PMWE height regions. The transition period from summer to winter appears shorter, but this might be due to the much-reduced sensitivity caused by partial system operation. The PMSE region echoes during the winter-to-summer transition exhibit an interesting feature; the centroid height of the echoing region gradually rises from approximately 82 km to approximately 85 km with the progress of the season as indicated by the red arrow in Fig. 1b. The coexistence of the PMSE and PMWE region echoes in early

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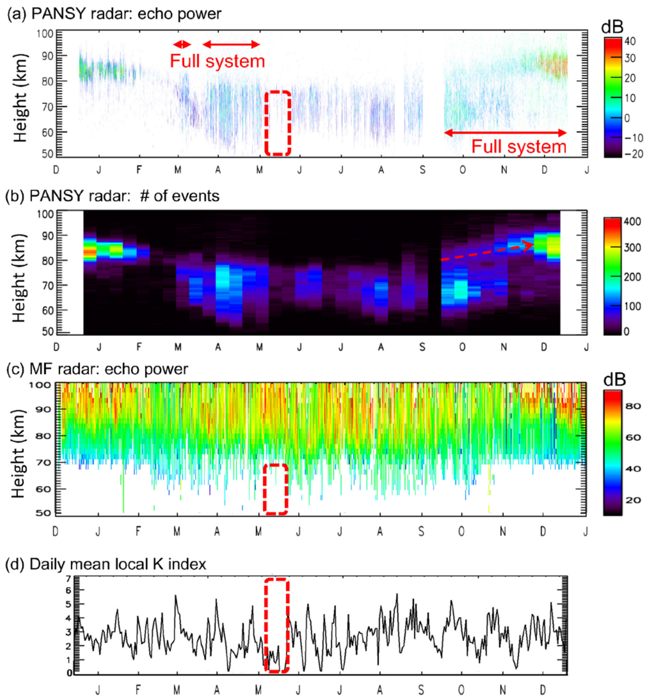

Fig. 1. (a) Time-height section of mesosphere echo power in 2015 for the PANSY radar. The radar was operated largely using a partial system in 2015; the full system periods are indicated by arrows. Data collected during the second half of September is not plotted because its parameter settings were largely different from the other periods. (b) Number of individual 2-min echo events integrated per day at each height bin for the PANSY radar. (c) Same as Fig. 1a but for the MF radar, where the echo power is plotted only for data with which the FCA wind was successfully estimated in order to reduce the effects of radio interference. (d) Daily mean local K-indices at Syowa.

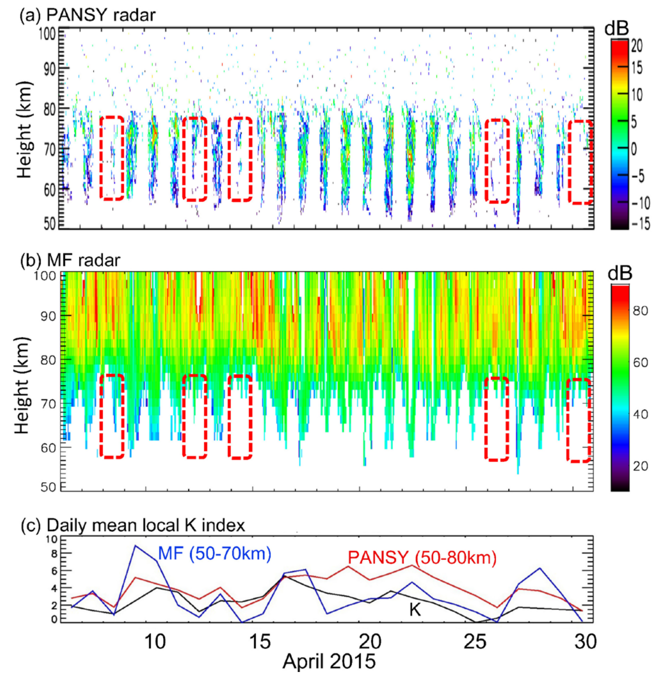

Fig. 2. (a) and (b) Same as Figs. 1a and 1c, respectively, but for the observation period of 6–30 April 2015, when the PANSY radar was operated using its whole system. The local solar noon at Syowa is 09:18 UT. (c) Daily mean local K-indices at Syowa (black), and number of individual echo events per day for PANSY at 50–80 km divided by 1000 (red) and for MF at 50–70 km divided by 100 (blue).

summer has also been reported in the Arctic from MAARSY (69.30°N, 16.04°E) observations (Latteck and Strelnikova 2015). This common feature will be key in understanding their generation mechanism in future studies.

Figure 1c is the same as Fig. 1a but for the MF O mode echoes. The echoes are limited to above approximately 65 km in the summer from November to February while the winter echoes are observed down to 55 km and sometimes down to nearly 50 km. Seasonal transitions of the lowest height limit are seen from February to early March and also in October, occurring at nearly the same time as those of the PANSY echoes. When PMWEs are weak or absent, low altitude MF echoes are also weak, as shown in Fig. 1c in the hatched areas of late May to early June. These results suggest a close relationship between the generation mechanisms of PMWEs and low-altitude MF echoes. To further assess any relationship between these echoes and geomagnetic activity (a measure of electron density (Ne) enhancement in the upper atmosphere), daily mean local K-indices at Syowa are shown in Fig. 1d. Winter time K-indices appear to be positively correlated to PMWEs and MF low-altitude echoes.

Next, we examined day-to-day variations of the winter echoes. Figure 2 is the same as Fig. 1 but for the dates of 6–30 April 2015, when the full system PANSY operation was conducted. Note that PMWEs are observed virtually every day during daylight hours. When PMWEs are weak (hatched area in Fig. 2), low-altitude MF echoes below approximately 75 km are also weak. Hall et al. (2006) reported the coexistence of PMWEs and MF echoes in the Arctic under highly disturbed conditions, such as solar proton events. The results seen in Figs. 1 and 2 indicate that coexistence is a common feature over Syowa in winter, although the large power aperture product of the PANSY radar is thought to facilitate the detection of PMWEs. Figure 2c shows daily mean K-indices together with the number of individual echo events per day for PANSY at 50–80 km and for MF at 50–70 km. Occurrence of these winter echoes is highly correlated with the K-index.

We further investigated the local time dependence of winter echoes. Time-height sections of echo power obtained on 22 April 2015 are shown in Fig. 3 as an example: (a) the PANSY vertical beam, (b) O mode MF data, and (c) the power ratio of E mode to O mode. The PANSY echoes are observed from 55 km to nearly 80 km, mostly during the daytime, with a somewhat anti-symmetric structure about the local noon slightly shifted to post-sunset hours. These features are basically the same as the findings of Nishiyama et al. (2015). Note that low-altitude MF echoes below approximately 70 km exhibit a similar time and height dependence, although the PANSY data demonstrates its much higher range resolution, showing fine wave structures propagating downward with time. On the other hand, the MF echoes above 70 km from 8–12 UT are very weak. Hall et al. (2006) reported similar U-shaped MF echoes over Tromsö (69°N), which were observed during the daytime and isolated to lower altitudes. They investigated the mechanism creating the structure and found that MF radio wave absorption through collisions between plasma and the neutral atmosphere was responsible for the apparent lack of higher altitude signals. The ratio shown in Fig. 3c is a good measure for estimating the degree of absorption (e.g., Manson and Meek 1984), where a large ratio serves as a proxy for low absorption and vice versa. The ratio at 70–80 km altitude is low around mid-day (more absorption) but relatively high in the morning and the evening (less absorption), presenting a reasonable agreement with the MF echo power seen in Fig. 3b. At night, Ne content in the mesosphere decreases because of a lack of insolation, leading to the disappearance of PMWEs and the disclosure of MF echoes above approximately 70 km. In Supplement 1, the local time dependence and its seasonal variation are further investigated based on monthly composite diurnal cycles.

The correlations seen between PMWEs, MF echoes and K-indices in Figs. 2 and 3 are summarized in Fig. 4. The occurrence of PMWEs (number of individual echo events per day at 50–80

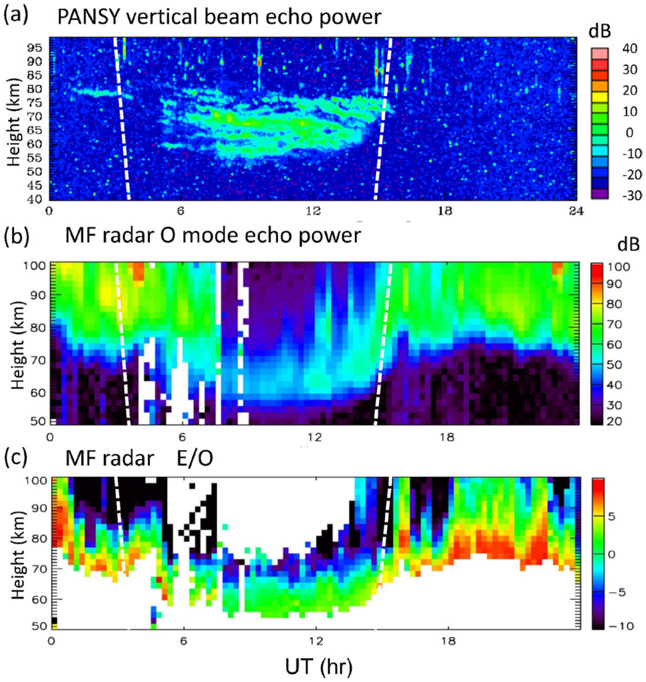

Fig. 3. A typical example of winter echoes, observed on 22 April 2015. (a) The echo power of the vertical beam by the PANSY radar, (b) O mode echo power by the MF radar, and (c) the ratio of E mode echo power to O mode echo power by the MF radar. Sunrise and sunset times at each altitude are indicated by the dashed lines.

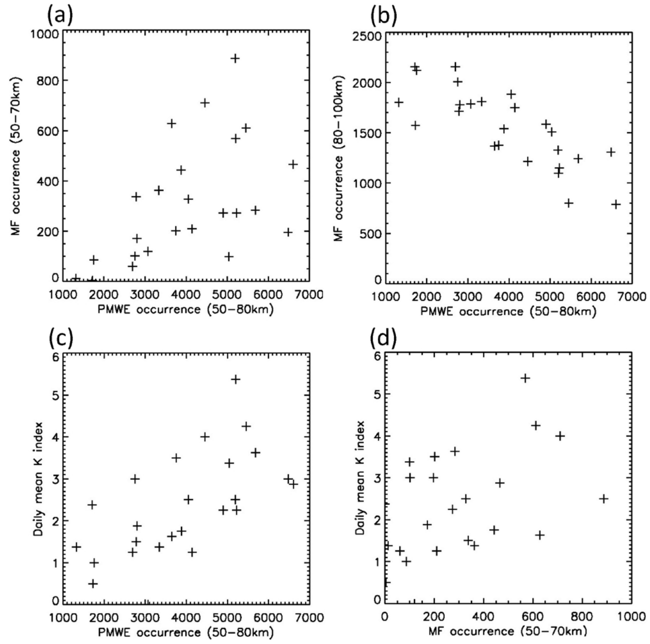

Fig. 4. Correlation plots among numbers of integrated events of MF and PANSY radar echoes per day and local K-indies on 6−30 April 2015. (a) PANSY at 50−80 km vs. MF at 50−70 km. (b) PANSY at 50−80 km vs. MF at 80−100 km at 06−18 UT (09−15 LT). (c) PANSY at 50−80 km vs. daily mean K-indices. (d) MF at 50−70 km vs. daily mean K-indices.

km) shows a clear positive correlation with that of MF low-altitude echoes (50−70 km) as seen in Fig. 4a. The PMWE occurrence is even more correlated, but negatively, with MF high-altitude echoes (80−100 km) during the day time (09−15 LT) as in Fig. 4b, indicative of more MF radio absorption during strong PMWEs because of the higher Ne content. K-indices are also clearly correlated with radar echoes as seen in Figs. 4c and d, consistent with the aforementioned scenario.

Next, we investigated another aspect of MF echoes, that is, their angles of arrival (AOAs). First, the raw time series was cut into 2-sec segments. Secondly, the AOAs were estimated for cases in which the corresponding FCA wind was successfully estimated, in order to eliminate non-atmosphere echoes. Thirdly, high-quality AOAs were selected for further analyses when four AOAs, each of which was estimated using three out of the four antennas, were distributed within a spatial angle of 1°. Obtained AOAs are shown in Figs. 5a, 5b, 5c, and 5d for a typical winter day of 22 April 2015 and Figs. 5e, 5f, 5g, and 5h for a typical summer day of 17 December 2015. The centers of the distributions are almost exactly at the zenith for both days. However, AOAs in winter are distributed much more widely than in summer. Fiftieth percentile zenith angles, within which 50% of AOAs are distributed, are shown as white circles in Fig. 5 for an easier comparison: 7.1° (5.4°) at 60−70 km, 5.9° (4.4°) at 70−80 km, 7.8° (4.6°) at 80−90 km, and 12.1° (5.7°) at 90−100 km for the winter (summer) day. The angles for the range 60−90 km are about 40−60% wider in winter. Monthly averaged values for April and December are almost identical to these values, within approximately a 10% difference. The very wide scatter in the 90−100 km range in winter (Fig. 5d) can be attributed to meteor echoes, as shown by Tsutsumi and Aso (2005). Below 80 km, the scatterers are not meteor trails but are thought to be ionized atmosphere. These results suggest that MF mesosphere echoes, at least below 80 km, are more isotropic (less aspect sensitive) in winter.

Finally, we compared horizontal winds obtained using the two radars. All the hourly mean winds in the year 2015 were used. To adjust the height resolutions, PANSY wind profiles were smoothed by applying a triangle-shaped running window with a full width of 8 km. Scatter diagrams for an altitude of 84 km are shown in Figs. 6a and 6b for zonal (meridional) component. As seen in Fig. 1, the height of 84 km approximately corresponds to the centroid height of the PMSEs and there are only a few PMWEs. On the other hand, Figs. 6c and 6d show that for a height of 70 km, where nearly all the data are PMWEs. Correlation coefficients are generally very high, greater than 0.8 in all the plots. The ratio of MF winds to PANSY winds (Fig. 6e) is close to 1 for the zonal component throughout the height region from 60 to 90 km. The ratio for the meridional component is from approximately 0.85 to 1 above 70 km, but gradually decreases with decreasing height and reaches 0.7 at 60 km. It is known that wide beam MF radars such as the Syowa system tend to underestimate wind velocities (e.g., Manson et al. 2004; Tsutsumi and Aso 2005) and that such radar data should be carefully treated (e.g., Reid 2015). The somewhat reduced Syowa MF meridional winds seem to be at least partly due to the low signal-to-noise ratio of one of the four antennas, at the northernmost corner of the triangle-shaped receiving array, located close to the radar hut. Weak radiation from in-house equipment can interfere with the atmospheric echoes, leading to underestimation in the north-south baseline (e.g., Meek 1990; Holdsworth and Reid 1995). Nevertheless, the overall agreement between the two radars is very good.

4. Summary and conclusions

We investigated the nature of mesosphere echoes in the Antarctic, with more emphasis on the less understood winter echoes. We used two radars that employed significantly different operation frequencies of 47 MHz (PANSY radar) and 2.4 MHz (MF radar).

First, we compared seasonal and day-to-day variations as well as local time dependence of the mesosphere echoes in 2015. PANSY echoes reproduced reported results by Sato et al. (2014, 2017) and Nishiyama et al. (2015): summer echoes (PMSEs) were mostly confined to the height region of 80−90 km, and winter echoes (PMWEs) were mostly below 80 km during the daytime and for a few extended hours after sunset. This somewhat

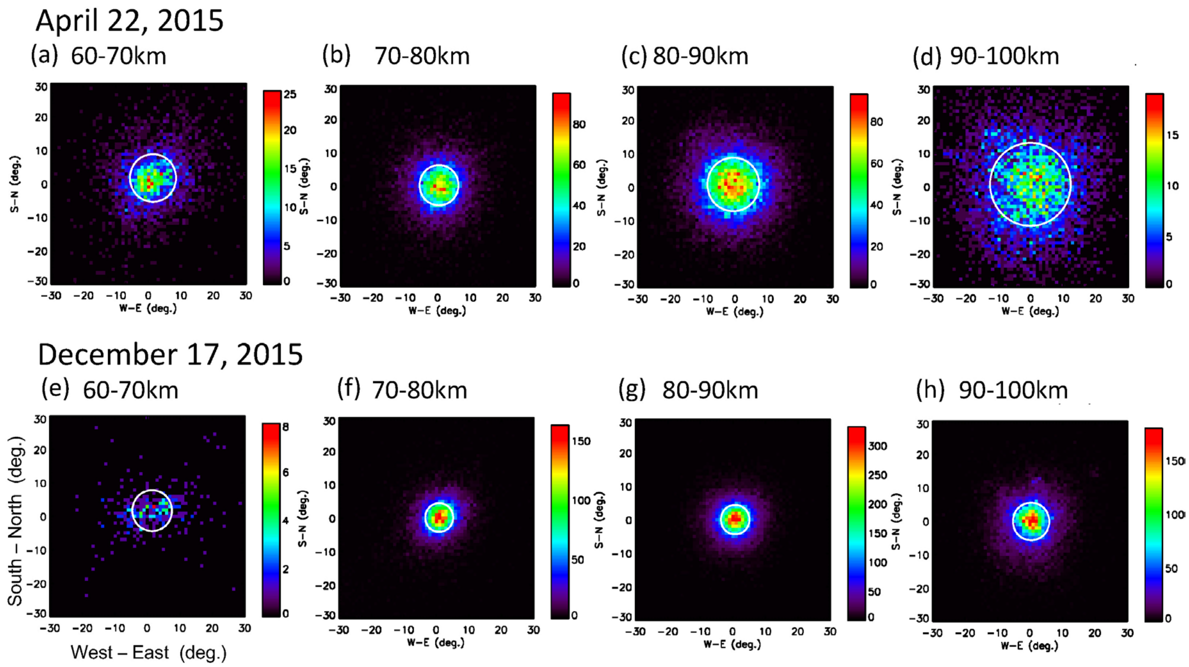

Fig. 5. Probability distribution functions of angles of arrival of MF radar O mode echoes for (a–d) a typical winter day of 22 April 2015 and (e–h) for a typical summer day of 17 December 2015, for every 10-km range step between 60 and 100 km. Fiftieth percentile zones, within which 50% of AOAs were included, are indicated with white circles.

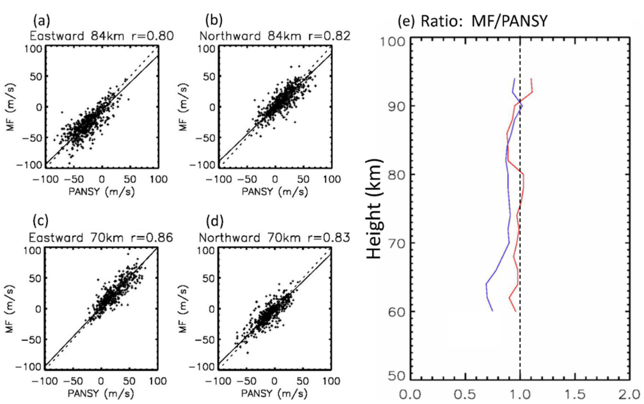

Fig. 6. Summary plots of correlation analysis between PANSY and MF radar horizontal wind velocities observed in 2015. Hourly averaged values were used. Scatter plots of (a) eastward wind velocities at 84 km, (b) northward wind velocities at 84 km, (c) eastward wind velocities at 70 km, and (d) northward wind velocities at 70 km, where dashed lines denote the results of a least square fitting. (e) Ratios of MF winds to PANSY winds, where the red and blue lines represent the zonal and meridional components, respectively.

asymmetric structure about the local noon in winter was also depicted in the MAARSY observations in the Arctic (Latteck and Strelnikova 2015) although not explicitly mentioned. On the other hand, MF echoes above approximately 75 km are observed throughout the year, but those in winter below approximately 70 km mostly appear and disappear simultaneously with PMWEs, implying common generation mechanisms. PMWEs and winter MF echoes were further found to be highly correlated with local K-indices. Electron density enhancement caused by ionized particle precipitation in addition to insolation is thought to be a trigger for mesosphere echo generation, at least in winter.

In addition to ionization, refractive index variations are necessary for radar measurements. Two main scattering mechanisms have been proposed: Bragg scatter from turbulence and Fresnel scatter from the atmosphere with a vertical electron density gradient. The former is thought to be mostly responsible for MST radar echoes and the latter for wide-beam MF radar echoes. However, the mechanisms are still not fully understood, and both scatters are thought to coexist in reality (Hocking and Röttger 2001; Reid 2015). We found that the AOAs of the MF echoes were more widely distributed in winter than in summer, implying more isotropic (less specular) echoes in winter. Gravity wave activity over Syowa has been shown to maximize in winter (Dowdy et al. 2007; Yasui et al. 2016). According to Yasui et al. (2016) the gravity wave activity in winter at an altitude of 75 km is three times as high as that in summer in the wave period of 20 min−24 h, suggesting more turbulence generation in winter.

These results suggest that winter MF echoes below 70−75 km are at least partly of turbulence origin. This may further explain the lack of summer MF echoes in the same altitude region despite higher electron density. Turbulence energy in the mesosphere has been estimated using various techniques (e.g., Thrane et al. 1985; Hall et al. 1999; Hocking et al. 2017). Hall et al. (1999) is one of a limited number of studies on seasonal behavior of mesospheric turbulence in the polar region, although it was completed in the Arctic. They reported enhanced turbulence activity in winter (summer) in the lower (upper) mesosphere, which qualitatively supports the findings in the present study. In a future study, we will more quantitatively examine the relationship among parameters such as PANSY echo power, MF echo power, K-index, gravity wave activity, aspect sensitivity, and turbulence energy to further investigate the origin of these mesosphere echoes, based on PANSY full system data which is being collected.

Finally, we compared horizontal winds observed by the two radars in 2015. They show a very high correlation (> 0.8) in a wide height region of 60−90 km. The velocity ratios of MF versus PANSY are also excellent, especially for the zonal component which was nearly 1. The meridional component of the MF system somewhat underestimated that of the PANSY radar, probably because of radio interference from the radar hut on the north-south antenna baseline. Some adjustment to compensate for this difference is planned. Combining measurements from these two radars will greatly contribute to the further study of atmospheric dynamics by taking advantage of each technique.

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Supplements

Supplement 1 provides monthly mean composite days of winter MF echo acquisition rates to compare with those of the PANSY PMWEs by Nishiyama et al. (2015). In supplement 2, possible height offsets of MF echoes caused by the large off-vertical AOAs seen in Figure 4 are discussed.

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