International Student Center, The University of Electro-Communications, pp. 45-52（2005）〔Regular Paper〕

Statistical Analysis of Polar Mesosphere Summer Echoes with Super Dual Auroral Radar Network

Keisuke Hosokawa*　Tadahiko Ogawa**
Natsuo Sato***　Akira Sessai Yukimatu***

Abstract

Polar Mesosphere Summer Echoes (PMSE), which are regularly observed in summer months at polar latitudes, are strong radar backscatter from the upper mesosphere. They have been studied with ground-based radars whose frequency ranges from VHF to UHF. Recently, peculiar echos, which are interpreted as PMSE, were found to appear in the near range observations of Super Dual Auroral Radar Network (SuperDARN). This suggests a possibility that SuperDARN becomes a powerful tool for studying PMSE as a global scale phenomenon. In this paper, we statistically analysed occurrence frequency of the near backscatter echoes using two years measurements of the SuperDARN radars in Antarctica and Iceland. Occurrence percentage of the near range backscatter is enhanced significantly in summer months. Maximum is located at the summer solstice, where occurrence percentage reaches 80-90 % in Iceland and 70-80 % in Antarctica. Local time distribution of the echo occurrence has its maximum around local noon and minimum at 20LT. These characteristics of the near range echoes are quite similar to those of PMSE at VHF frequencies, which implies that near range observation of SuperDARN contains huge amount of PMSE. Interhemispheric difference of the echo occurrence probabilities are also estimated. Occurrence percentage averaged over summer months is 1.5 times larger in the Northern Hemisphere than that in the Southern Hemisphere, suggesting that occurrence of PMSE has actually an interhemispheric asymmetry. However, degree of interhemispheric asymmetry is much smaller than that predicted from the earlier VHF radar observation.

Keyword: Upper Atmosphere, Radio Observation, Global Climate Change

1 Introduction

The polar mesosphere has become a region of increasing interest in recent years. Temperature at the solstices is significantly different from those expected from radiative equilibrium, which is presumably because of the effect of gravity wave driving pole to pole meridional circulation (e.g., McIntyre, 1989). Temperature measurements by rocket experiment have shown that summer polar mesosphere is the coldest region on the Earth (von Zahn and Meyer, 1989). The cold temperature leads to the formation of ice particles near the mesopause which are visible as noctilucent clouds (NLCs) from the ground. The other important feature that is also associated with the cold polar summer mesospheric temperature is Polar Mesosphere Summer Echoes (PMSE). PMSE are unexpected strong radar backscatters from mesospheric heights which are regularly observed during summer months at polar latitudes. Detail of PMSE is precisely described in reviews by Cho and Röttger (1997) and references therein. The first observations were made by Ecklund and Balsley (1981) with the 50 MHz VHF radar at Poker Flat in 1979. Later on, the Arctic PMSE have been observed at higher frequencies from VHF to UHF.

In contrast to the Arctic PMSE, observational

Received on October 12, 2004
* Department of Information and Communication Engineering, The University of Electro- Communications, Tokyo, Japan.
** Solar-Terrestrial Environment Laboratory, Nagoya University, Toyokawa, Aichi, Japan.
*** National Institute of Polar Research, Tokyo, Japan.

history of the Antarctic PMSE is very short. This could be due to lack of the facilities suitable for the PMSE observation or lower occurrence probability of PMSE itself in the Southern Hemisphere. The first clear observation was made with a 50 MHz radar in 1994 by Woodman et al. (1999). However, the echoes were much weaker than the Arctic PMSE. Huaman and Balsley (1999) discussed this interhemispheric difference in terms of possible difference in temperatures and water vapour concentrations. However, recent rocket measurements in Antarctica (Lübken et al., 1999) pointed out that there is no significant interhemispheric difference in summer mesopause temperatures. Clearly, further detailed analysis is required to estimate the degree to which conditions in the opposite hemispheric polar mesospheres differ. A problem is that only a small number of VHF radar are operative in Antarctica. Alternative way of monitoring the Antarctic mesosphere is indispensable for more detailed understanding of PMSE.

Recently, Ogawa et al. (2002) have identified peculiar backscatter returns in the near range observations of the Super Dual Auroral Radar Network (SuperDARN) Syowa East radar, Antarctica. The echoes appear mostly at slant ranges of 180-225 km (first range gate). The main characteristics of the echoes are as follows: (1) radar echoes continue for about 80 min with intermittent subsidence, (2) echo groups have duration of 5-40 min, (3) they move across the radar beams, (4) velocity and power exhibit quasi-periodic oscillations with periods of 5-20 min, (5) velocities are between -40 to 20 m s^{-1}, spectral widths are less than 40 m s^{-1}, and the power are less than 25 dB, and (6) no particular correlation exists between the power and velocity amplitudes. Relying on the fact that their morphological features are very similar to those of the Arctic PMSE, Ogawa and colleagues concluded that this is the first observation of the Antarctic PMSE by using the SuperDARN HF radars.

Very recently, Hosokawa et al. (2004) looked for such echoes that were observed, under quiet geomagnetic conditions, during 46 months from 1997 until 2000 with the SuperDARN radar at Syowa Station. With some strict criteria for echo selection, they identified 22 events in summer months and 2 events in August and September. Their distinct seasonal variation evidences that these near range echoes in summer months are indeed the Antarctic PMSE. These results suggest that the SuperDARN radars can be used to routinely monitor the activity of PMSE in a wide area of the polar mesosphere in both hemispheres. However, there still remain some questions concerning basic characteristics of PMSE observed with SuperDARN. One of them is "How many backscatter returns associated with PMSE are detected with SuperDARN radars?". The other one is that "Does there exist an interhemispheric difference of PMSE activities?". In order to answer these open questions we have conducted automated estimation of the PMSE occurrence frequency with two SuperDARN radars in both hemispheres. At first, seasonal variation and local time distribution of the echo occurrence are presented. Interhemispheric asymmetry of the PMSE activities is also discussed on the basis of the comparison between two radars in the Northern and Southern Hemispheres.

2 Instrumental Arrangement

Data from the Super Dual Auroral Radar Network (SuperDARN; Greenwald et al., 1995) Syowa East radar at Syowa Station, Antarctica (69.01.S, 38.61°E) and Iceland East radar at Pykkybaer, Iceland (63.77°N, -20.54°W) are employed. The radars of SuperDARN conform to the basic operating design of the first facility which was built at Goose Bay in 1983. A detailed description of the Goose Bay radar was given by Greenwald et al. (1985). The SuperDARN radars comprise two arrays of log-periodic antennas, one is a main array of 16 antennas with both transmit and receive capability and the other is an interferometer array of 4 antennas with receive capability only. The radar frequency could be set anywhere from 8 to 20 MHz, but most often is set to 10 MHz. The radars operate on a 24-hours, 365-days-a-year basis, under the control of the operating program. The operation program is separated into three categories, common time, special time and discretionary time. The data used in the present analysis are taken from periods when the radars were running in the common time normal scan mode (approximately 50% of whole operation time, see Greenwald et al., 1995 in detail). In the current version of the common time normal scan mode, the radar beam is sequentially scanned from beam 0 to beam 15 with a step in azimuth of 3.33° for Syowa East and 3.24° for Iceland East. It takes approximately 7 s to integrate backscatter returns in one direction and about 120 s is needed to do a scan of all directions. 75 range gates are sampled for each beam with a pulse length of 300 μs, which is equivalent to a gate length of 45 km, and a lag to the first gate of 1200 μs (180 km).

Most of PMSE have been detected by using vertical incidence radars with short altitude resolution (minimum ≈ 150 m), which is due to the strong aspect sensitivity and thin layer of PMSE. Range resolution of the SuperDARN radars is set to 45 km, which is obviously thicker than the PMSE layer. However, radars of the SuperDARN employ the oblique sounding system, in which maximum sensitivity occurs at elevation angles of 15°-35° depending on frequency (Greenwald et al., 1985). This oblique incidence enables the radars to detect the echoes at mesospheric altitude in the first range gate (180-225 km in slant range). We have statistically computed the occurrence of the first range gate echoes with two SuperDARN radars and clarify the fundamental characteristics of PMSE in HF frequencies.

3 Method of Statistics

There exist three classes of dominant backscatter target in the near range (say 180-500 km in slant range) observations of the SuperDARN radars. Those are (i) meteor trails, (ii) *E* region backscatter echoes and (iii) PMSE in HF frequencies (hereinafter termed as HF-PMSE). In the course of this research, backscatters from *E* region FAIs and meteor trail must be correctly distinguished from HF-PMSE. Figure 1 shows the typical examples of these three kinds of backscatter features. Left panels show range versus time plots of backscatter power of meteor echoes observed by the SuperDARN Syowa East radar, middle panels of typical *E* region backscatter and right panels of HF-PMSE, in which beams of even number are displayed. The backscatter power is colour-coded with blue representing the smallest and red representing the greatest. Two horizontal dashed lines indicate a band of slant range between 180 and 315 km, where Ogawa et al. (2002) identified HF-PMSE in the Syowa East radar data.

Meteor trails are one of the major targets in near

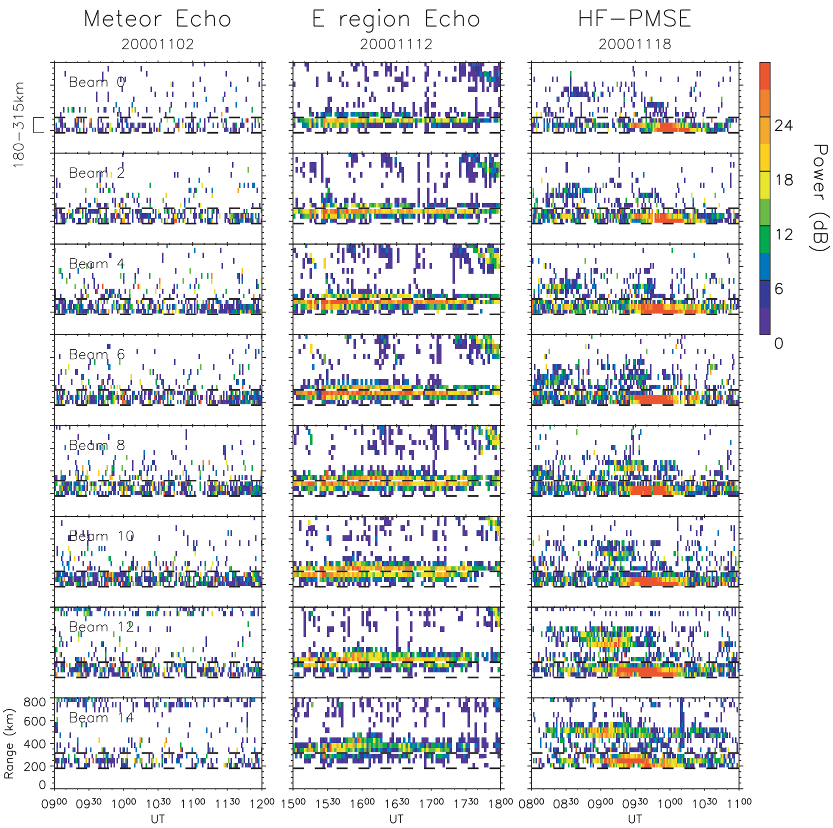

Figure 1 Typical examples of the three dominant backscatter echoes that appear in the near range observations of SuperDARN.

range observations of the SuperDARN radars, which have been used to measure surrounding neutral wind velocity (Hall et al., 1997). The height ranges where they appear (mesosphere to lower *E* region) well overwrap the layer of HF-PMSE. Doppler velocity and spectral width of meteor echoes tend to be less than 50 m s^{-1} (Hall et al., 1997), which is also similar to those of HF-PMSE. However, meteor echoes appear randomly both in time and space because they tend to be short-lived (within 2 min, which is comparable to the scan repeat time of the radar) and then the backscatter power is normally low (most of them are less than 9 dB, see left panels of Figure 1). On the contrary, HF-PMSE last longer than at least 20 minutes in a fixed range and the backscatter power is stronger as presented in the right panels of Figure 1. Meteor echoes can be accurately excluded by setting a selection criterion in the backscatter power.

In general, radars observe *E* region backscatter echoes when their field-ofview intersects the region of auroral electrojet on the nightside ionosphere. They fall into two broad categories, type I and type II, depending on the plasma instability process of the ionospheric field-aligned irregularities (FAIs) from which the radar signal has been scattered (Fejer and Kelley, 1980). Type I echoes that have narrow spectral width with velocities near the local ion-acoustic speed $C_s \approx 400$ m s^{-1} are understood in terms of two-stream instability. Type II echoes that have broad spectral width with slow velocities are thought to be generated by the gradient drift instability (e.g., Milan and Lester, 2001). Hence, we can exclude *E* region backscatter echoes by setting criteria in Doppler velocity and spectral width.

We have computed the occurrence probability of the first range gate backscatter echoes satisfying the following conditions simultaneously: (1) backscatter power is greater than 9 dB, (2) magnitude of Doppler velocity is less than 50 m s^{-1}, and (3) spectral width is less than 50 m s^{-1}. Beams of all directions have been employed in the present statistics. Occurrence percentage has been calculated for each bins with 10 minutes duration. The study period encompasses two years from October 1998 to September 2000 for Iceland East in the Northern Hemisphere and from April 1999 to March 2001 for Syowa East in the Southern Hemisphere.

4 Statistical Results and Discussions

The top two panels of Figure 2 present map of the PMSE occurrence frequency (a) in Iceland East and (b) in Syowa East. In each panel, the vertical axis is the local time from 0 to 24 LT and the horizontal axis is total day from October 1998 to September 2000 for Iceland and April 1999 to March 2001 for Syowa, respectively. The horizontal dotted line indicates local noon. Occurrence percentage of the first range gate backscatter echoes passed the criteria as described in the previous section is colour-coded with blue representing the smallest (0 %) and red representing the greatest (100 %). Gray shows period when the common time mode has not been operated, i.e. no data are available. The two vertical dashed lines indicate the summer solstices. It is clearly found that there exist clear enhancements of occurrence percentage in summer months from beginning of May (November) to end of August (February) in the Northern (Southern) Hemisphere. These distinct enhancements are suspected to correspond to the occurrence of HF-PMSE. Occurrence frequency has its maximum just after the summer solstices, where the occurrence percentage reaches 80-90 % for Iceland and 70-80 % for Syowa near noon meridian. In the following, seasonal variations and local time distributions of these summer time echo enhancements are compared to those derived from the previous measurements with VHF radars. Difference between two hemispheres is also discussed in terms of interhemispheric asymmetry of the mesospheric thermal state.

The bottom panel of Figure 2 displays seasonal trend of the backscatter occurrence percentage of the first range gate echoes passed the criteria. Here, plotted percentages have been averaged for the occurrence within the local time sector between 11 and 13 LT, because echo occurrence has its maximum near local noon. Blue line with open circles indicates the results from Iceland East radar and orange shows those from Syowa East radar. The vertical dashed lines indicate the summer solstices. It is apparent that the occurrence rate of the first range gate echoes is greatly enhanced in summer months. Bremer et al. (2003) have investigated 7 years data of VHF radar in Norway and have reported that averaged date of the first seasonal appearance of

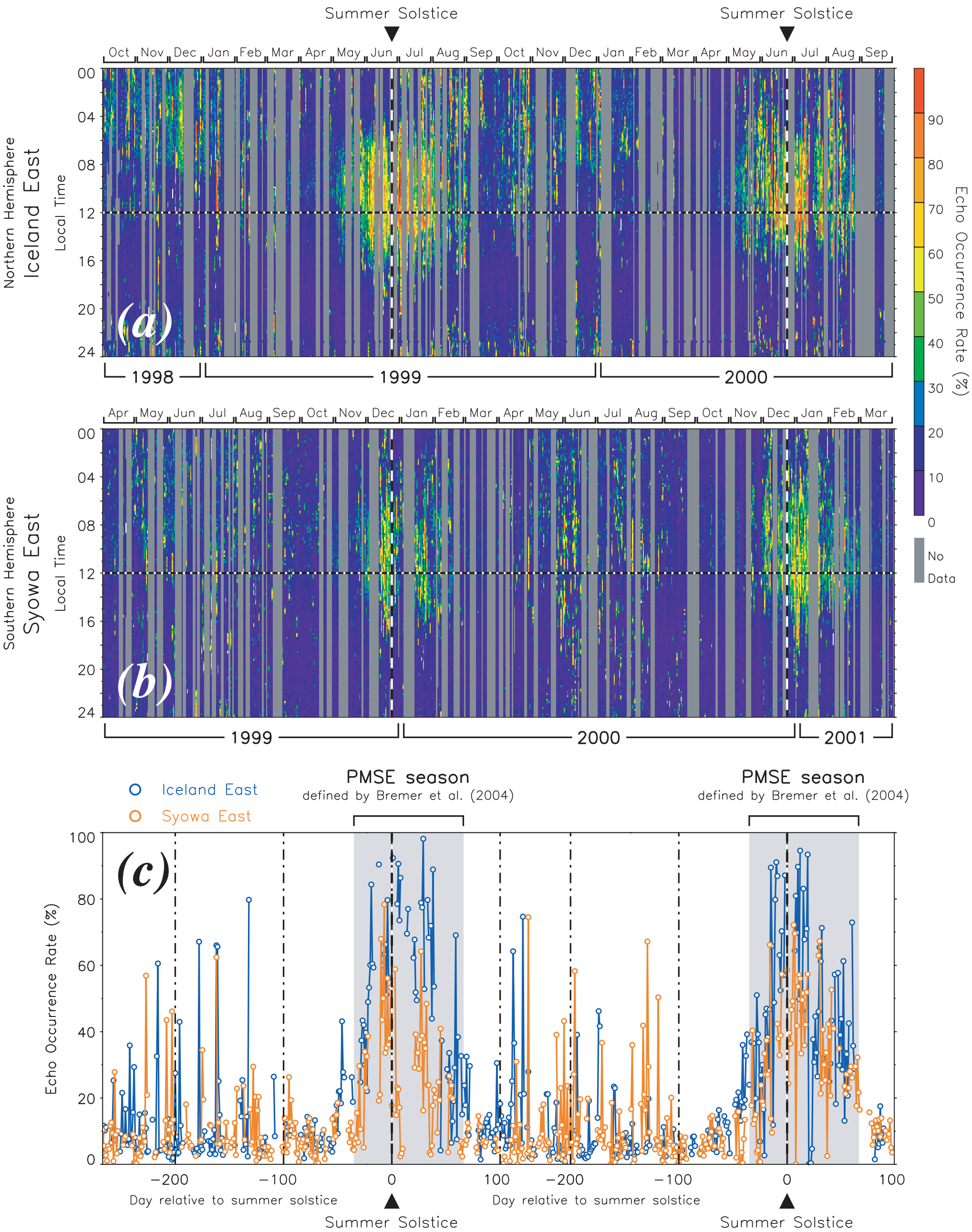

Figure 2 Summary of the statistical analysis.

PMSE is May 19 (Julian day 139), and that of the last appearance is August 28 (Julian day 240). These dates are corresponding to November 19 and February 27 in the Southern Hemisphere, respectively. Light-gray shaded areas show the PMSE seasons which are encompassed by the first and last dates of PMSE appearance defined by Bremer et al. (2003). The enhancements of first range gate echo occurrence are found to be well inside of the PMSE seasons. Hoffmann (1999) have shown that the daily prevalence of PMSE rapidly increases at the beginning of the PMSE season, and maximum occurs some days after the solstice. In contrast, decay of PMSE from maximum values to the end of the season takes approximately two months. Also in the present dataset, the gradient of increase is pronounced than that of decrease, and maximum occurs some days after the solstice. Our statistical result shows features comparable to the previous studies in VHF frequencies despite the differences in location, time and experimental setup of the radars. This again supports that near range observations of SuperDARN radars contain huge amount of PMSE at HF frequencies.

The other important thing to be mentioned in Figure 2 (c) is that some temporally isolated peaks can be identified outside of the PMSE season. Balsley et al. (1983) have identified mesospheric echoes in winter months which appeared to be correlated with the high-energy particle precipitation into the mesospheric altitudes. Recently, Kirkwood et al. (2002) observed winter time mesospheric echoes in the polar region during several recent solar proton events. Then, fraction of the temporally isolated peaks outside of the PMSE season might be due to the high- energy particle precipitations. However, our interest is primarily in the behaviour of the summer time mesospheric echoes thus we do not discuss this issue further in this paper.

Figure 3 presents how the occurrence of the first range gate echoes varies with local time (a) in 1999-2000 and (b) in 2000-2001 PMSE seasons. The blue line with filled circles indicates the results from Iceland East and orange line with open circles does those from Syowa East. According to Palmer et al. (1996), the mean diurnal variations of the PMSE occurrence probability is characterised by a maximum and a deep minimum near 12 LT and 20 LT, respectively. Our result is fairly consistent with the results of the previous studies. In the course of this statistics, we have employed criteria in backscatter power, Doppler velocity and spectral width to exclude possible contaminations of meteor and/or E region echoes into PMSE characteristics. Meteor echoes are generally observed in the dawn hemisphere (Hall et al., 1997). *E* region echoes are predominantly the nighttime phenomena (Milan and Lester, 2001). The local time distribution shown in Figure 3 is quite different from those of the meteor and *E* region echoes. This implies that our selection criteria were successful in eliminating contaminations of meteor and *E* region echoes, and then our estimation of PMSE occurrence probability is quantitatively reliable.

Finally, we will discuss how PMSE activities differ between two hemispheres on the basis of the present statistics. Occurrence percentage averaged over the two entire PMSE seasons is 60 % for Iceland East and 41 % for Syowa East, suggesting that occurrence frequency of PMSE are 1.5 times higher in the Northern Hemisphere than that in the Southern Hemisphere. Woodman et al. (1999) presented that PMSE in the Southern Hemisphere are more sporadic and are at least 34 dB to 44 dB weaker than their counterparts in the Northern Hemisphere. One reason proposed for the weaker and more sporadic

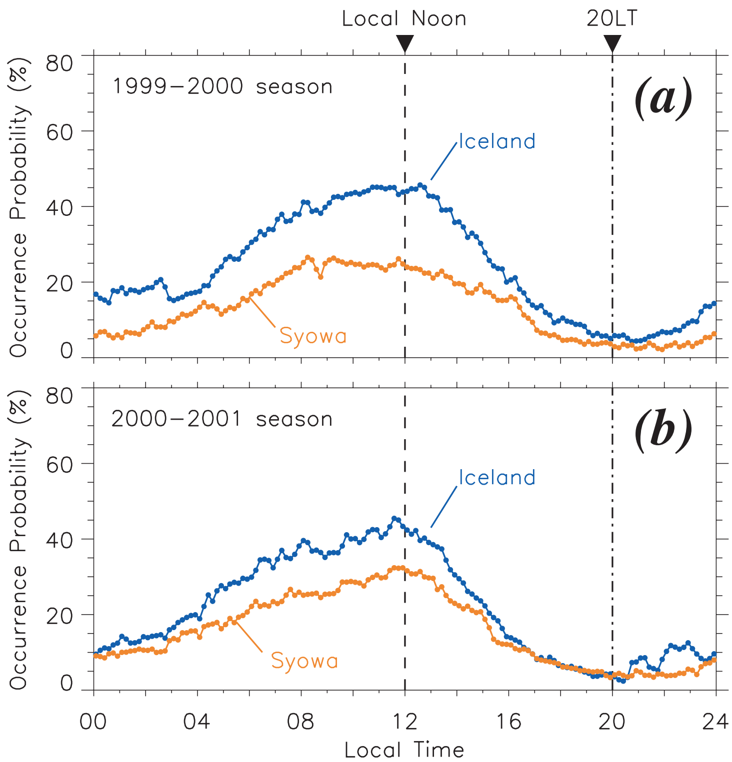

Figure 3 Mean local time distributions of the echo occurrence frequency.

PMSE in the Southern Hemisphere is that the summer upper mesospheric temperatures in that hemisphere are somewhat warmer (Huaman and Balsley, 1999). Since we know that gravity waves play a fundamental role in driving the circulation and therefore in determining the thermal structure of the mesosphere, knowledge on the upper mesospheric winds would be important in studying the causal factors governing PMSE generation. Vincent (1994) have measured reduced mesospheric gravity wave activity in the Southern Hemisphere with Antarctic MF radar. They suggests that reduced PMSE occurrence may be related to reduced gravity wave activity and resulting reduced mesospheric circulation.

Our statistical results show that estimated interhemispheric difference in PMSE occurrence frequency is much smaller than that derived by Woodman et al. (1999). They have carried out their estimation by using VHF radar at King George Island, Antarctica in comparison with earlier Poker Flat VHF radar results in 1981. Their comparison was made in different PMSE seasons with different systems. In contrast, our comparison has been carried out by using the data taken in almost the same interval (just 6 months apart each other) with the same radar systems. This implies that the interhemispheric asymmetry of PMSE activities actually exists, however, the earlier estimation by Woodman and colleagues could be overestimated. Woodman et al. (2000) have estimated a difference in the summer mesospheric temperature between two hemispheres of ≈ 7.5 K. Recent rocket measurements in Antarctica (Lübken et al., 1999) pointed out that there is no significant interhemispheric difference in summer mesopause temperatures. We claim that interhemispheric asymmetry of mesospheric temperature is smaller than expected. Although bias due to an instrumental difference between the radars of SuperDARN might be included in our statistics, our comparison is quantitatively more accurate than that by Woodman et al. (1999). In future, we plan to extend our statistical analysis to all of the SuperDARN radars (9 radars in the Northern Hemisphere and 6 radars in the Southern Hemisphere) and then produce a global map of PMSE activities and mesospheric thermal structure.

5 Summary and Conclusion

In order to clarify fundamental characteristics of PMSE at HF frequencies, we have analysed occurrence probabilities of the first range gate (180 km) backscatter echoes in a statistical fashion. Two years of measurements of the Super Dual Auroral Radar Network (SuperDARN; Greenwald et al., 1995) Syowa East radar at Syowa Station, Antarctica (69.01°S, 38.61°E) and Iceland East radar at Pykkybaer, Iceland (63.77°N, -20.54°W) are employed. As a result, occurrence percentage of the near range backscatter is enhanced significantly in summer months. Maximum is located at summer solstice, where occurrence percentage reaches 80-90 % for Iceland East and 70-80 % for Syowa East near noon meridian. Local time distribution of the echo occurrence has its maximum around local noon and minimum at 20LT. These features of the echoes are quite similar to those of VHF-PMSE, which supports that near range observation of SuperDARN contains significant amount of PMSE. Interhemispheric asymmetry of the echo occurrence probabilities are also estimated. Occurrence percentage averaged over the two entire PMSE seasons is 60 % for Iceland East and 41 % for Syowa East, suggesting that occurrence frequency of PMSE are 1.5 times higher in the Northern Hemisphere than that in the Southern Hemisphere. This implies that the interhemispheric asymmetry of PMSE activities actually exists, however, degree of the interhemispheric asymmetry is found to be smaller than those predicted from the previous studies with VHF radars.

Acknowledgement. The Ministry of Education, Culture, Sports, Science and Technology supports the Syowa HF radar systems. The 39th, 40th, and 41th JAREs (Japanese Antarctic Research Expedition) have carried out the HF radar operations. Iceland East radar is supported by the Particle Physics and Astronomy Research Council (PPARC grant no. PPA/R/R/1997/00256), UK, the Swedish Institute for Space Physics, Uppsala, and the Finnish Meteorological Institute, Helsinki. This study is supported by the Project for Promotion of Research and Education, The University of Electro-Communications.

References

Balsley, B. B., W. L. Ecklund, and D. C. Fritts, Mesospheric radar echoes at Poker Flat, Alaska: Evidence for seasonally dependent generation mechanisms, *Radio Sci., 18*, 1053-1058, 1983.

Bremer, J., P. Hoffmann, R. Lattechk, and W. Singer, Seasonal and long-term variations of PMSE from VHF radar observations at Andenes, Norway, *J. Geophys. Res., 108(8)*, 10.1029/2002 JD002369, 2003.

Cho, J. Y. N., and J. Röttger, An updated review of polar mesosphere summer echoes: Observation, theory and their relationship to noctilucent clouds and subvisible aerosols, *J. Geophys. Res., 102*, 2001-2020, 1997.

Ecklund, W. L., and B. B. Balsley, Long-term observations of the Arctic mesosphere with the MST radar at Poker Flat, Alaska, *J. Geophys. Res., 86*, 7775-7780, 1981.

Fejer, B. G., and M. C. Kelley, Ionospheric irregularities, *Rev. Geophys., 18*, 401, 1980.

Greenwald, R. A., K. B. Baker, R. A. Hutchins, and C. Hanuise, An HF phased-array radar for studying small-scale structure in the high-latitude ionosphere, *Radio Sci., 20*, 63-79, 1985.

Greenwald, R. A., et al., DARN/SuperDARN: A global view of the dynamics of high-latitude convection, *Space Sci. Rev., 71*, 761-796, 1995.

Hall, G. E., J. W. MacDougall, D. R. Moorcroft, J.-P. St.-Maurice, A. H. Manson and C. E. Meek, Super Dual Auroral Radar Network observations of meteor echoes, *J. Geophys. Res., 102*, 14,603-14,614, 1997.

Hoffmann, P., W. Singer, and J. Bremer, Mean seasonal and diurnal variations of PMSE and winds from 4 years of radar observations at ALOMAR, Geophys. *Res. Lett., 26*, 1525-1528, 1999.

Hosokawa, K., T. Ogawa, N. Sato, A. S. Yukimatu, T. Iyemori, Statistics of Antarctic Mesospheric Echoes Observed with the SuperDARN Syowa Radar, *Geophys. Res. Lett., 31*, 10.1029/2003GL 018776, 2004.

Huaman , M. M., and B. B. Balsley, Di.erence in near-mesopause summer winds, temperatures, and water vapour at northern and southern latitudes as possible causal factors for inter-hemispheric PMSE di.erences, *Geophys. Res. Lett., 26*, 1529-1532, 1999.

Kirkwood, S., V. Barabash, E. Belova, H. Nilsson, T. N. Rao, and K. Stebel, Polar mesosphere winter echoes during solar proton events, *Adv. Polar Upper Atmos. Res., 16*, 111-125, 2002.

Lübken, F.-J., M. J. Jarvis, and G. O. L. Jones, First in situ temperature measurements at the Antarctic summer mesopause, *Geophys. Res. Lett., 26*, 3581-3884, 1999.

McIntyre, M. E., On dynamics and transport near the polar mesopause in summer, *J. Geophys. Res., 94,* 14,617, 1989.

Milan, S. E. and M. Lester, A classi.cation of spectral populations observed in HF radar backscatter from the E region auroral electrojets, *Ann. Geophys., 19*, 189- 204, 2001.

Ogawa, T., N. Nishitani, N. Sato, H. Yamagishi, and A. S. Yukimatu, Upper mesosphere summer echoes detected with the Antarctic Syowa HF radar, *Geophys. Res. Lett., 29(7)*, 10.1029/2001GL014094, 2002.

Palmer, J. R., H. Rishbeth, G. O. L. Jones, and P. J. S. Williams, A statistical study of polar mesosphere summer echoes observed by EISCAT, J. Atmos. *Terr. Phys., 58*, 307-315, 1996.

Vincent, R. A., Gravity-wave motions in the mesosphere and lower thermosphere observed at Mawson, Antarctica, J. Atmos. *Terr. Phys., 56*, 593-602, 1994.

von Zahn, U., and W. Meyer, Mesopause temperatures in the polar summer, *J. Geo- phys. Res., 94*, 14,647, 1989.

Woodman, R. F., B. B. Balsley, F. Aquino, L. Flores, E. Vazquez, M. Sarango, M. M. Huaman, and H. Soldi, First observations of polar mesosphere summer echoes in Antarctica, *J. Geophys. Res., 104*, 22,577-22,590, 1999.