· Article ·
Advances in Polar Science
doi: 10.13679/j.advps.2018.1.00034
March 2018 Vol. 29 No. 1: 34-39

Aspect sensitivity of polar mesosphere summer echoes observed with the EISCAT VHF radar

LI Hui[1*], WU Jian [1], TIAN Ruihuan[1,2], JIANG Xiaonan[1,3] & LIANG Yonggan[1,2]

[1] China Research Institute of Radio wave Propagation (CRIRP), Beijing 100041, China;
[2] Department of physics, Harbin Institute of Technology, Harbin 150001, China;
[3] School of Physics and Optoelectronic Engineering, Xidian University, Xi'an 710126, China

Received 1 January 2018; accepted 5 March 2018

Abstract The European Incoherent Scatter Scientific Association (EISCAT) Very High Frequency (224 MHz) Radar has been used to investigate the aspect sensitivity of polar mesosphere summer echoes (PMSE) in the period 13–15 July 2010. The aspect sensitivity of PMSE using this radar and at such a high frequency has not been previously reported. Data concerning the aspect sensitivity of PMSE were collected by traversing the antenna beam from the zenith direction, and comparing the received power. Surprisingly, as the intensity received by the oblique beam was often larger than that of the vertical beam, suggesting the presence of tilted dusty plasma layers as a potential cause, a theoretical model was developed to confirm the existence of these layers and their formation process. The experimental results and theoretical model presented help elucidate the structural properties of the possible generation mechanism of strong radar echoes in the polar summer mesosphere region.

Keywords **polar mesosphere, radar echoes, gravity wave, dusty plasma layers**

Citation: Li H, Wu J, Tian R H, et al. Aspect sensitivity of polar mesosphere summer echoes observed with the EISCAT VHF radar. Adv Polar Sci, 2018, 29(1): 34-39, doi: 10.13679/j.advps.2018.1.00034

1 Introduction

Polar mesosphere summer echoes (PMSE) are extremely strong radar echoes in the polar summer mesopause region, and have been detected in many radar observations during the past decades. Several theories have been put forward to explain PMSE since they were first detected by the Poker Flat 50-MHz radar in 1979 (Hoppe et al., 1988; Röttger et al., 1988; Ecklund et al., 1981). Although charged ice particles in the mesosphere likely play a crucial role in creating PMSE, the actual mechanism is not well understood. The reviews by Cho et al. (1997) and Rapp and Lübken (2004) provide detailed information about the characteristics of PMSE, and their relation to other mesosphere phenomena.

Very high frequency (VHF) radar echoes from the mesosphere can originate from either a turbulent or a non-turbulent medium, whose physics are quite different, but can produce echoes of comparable power. Most investigations of PMSE have applied the theory of scattering from turbulent irregularities to explain the echoes. Indeed, some properties of PMSE can been explained by turbulence scattering theory (La Hoz et al., 2006; Kelley et al., 1990; Ulwick et al., 1988), but some of the echoes are of a non-turbulent type (Belova et al., 2008; Lübken et al., 2002; Blix et al., 1996). A better distinction between these two types of echoes is the consideration of the aspect sensitivity, which describes the relationship between the scattered power and incident angle, and can provide information about the potential scattering processes, as well as the nature of the scatterers. In general, a signal dependence on the tilting angle is usually not attributable to scattering from isotropic turbulence structures. However, a strong signal decreases when increasing the tilting angle,

* Corresponding author, E-mail: lihui_2253@163.com

implying that the observed scatterers operate under an anisotropic scattering mechanism, such as Fresnel reflection or Fresnel scatter. An important feature of PMSE is the aspect sensitivity, which measurements by Czechowsky et al. (1988) first showed is significant in the lower part of PMSE layers. Czechowsky et al. (1997) also reported that, in 90% of their observations, PMSE appeared to have a narrow spectral width and strong aspect sensitivity, whereas in 10% of their measurements, they found turbulence characterized by an extremely broad spectral width in the upper part of the PMSE region. Similar features were later also confirmed by several independent investigators (Smirnova et al., 2012; Zecha et al., 2001; Hoppe et al., 1990). Although there are many experiments concerning the aspect sensitivity of PMSE, no rational theoretical model conforming to observations has yet to be put forward, while the potential scattering processes, as well as the actual scatter structure, are not yet clear.

The European Incoherent Scatter Scientific Association (EISCAT) 224-MHz Radar (peak power: 2 × 1.5 MW, average power: 2 × 0.19 MW, pulse width: 1 μs–2.0 ms, beam width: 0.6ºEW and 1.7ºNS) can be manipulated to collect information about the aspect sensitivity of PMSE by traversing the antenna. However, to our knowledge, no experimental reports of the aspect sensitivity of PMSE from this radar have been published. Additionally, there does not seem to be any experimental measurements of the aspect sensitivity at such a high frequency. Therefore, we report new experiments carried out with the EISCAT 224-MHz Radar during the period from 13–15 July 2010. We then discuss the relationship between the received power and the tilt angle of the radar beam, with the focus on developing a theoretical model to explain the experimental observations. Finally, we summarize the main conclusions, and offer some suggestions for future work.

2 Data presentation

Often used to study PMSE (Röttger et al., 1990, 1988), the EISCAT 224-MHz Radar located in northern Norway (69.6ºN, 19.2ºE) is used here to compare the echo powers between the vertical and oblique beams for examination of the aspect sensitivity of PMSE. Experiments were performed from 13–15 July 2010 for about 3 h each day, during which we traversed the antenna beam from 90º to 84º off the zenith on 13 July, and 90º to 78º on the following two days. Each antenna traversal from the zenith to the respective angle took approximately 6 min, which is a smaller time period than any irregularity variations in time (15 min; Rapp et al., 2004).

To illustrate the credibility and complexity of the observations, Figure 1 shows the mean backscatter power relative to the received power in the vertical beam as a function of the elevation angle for the three different observational periods, where, for example, the average received power by the oblique beams is often larger than the vertical beam. Specifically, according to the data from 13 July, with the increase in elevation, the average intensity of echoes gradually becomes stronger, reaching a peak at 86º, before trending downward, similar to that observed on 15 July. In contrast, the data from 14 July have a smaller relative power for radar-beam traversals from 88º to 82º, since the maximum average echo power actually occurs at 78º. The phenomenon of smaller relative power in the range 82°–88° may be caused by the measurement error of the radar, or some other echo mechanism. We note that identical results were also observed in similar experiments with other VHF radars (Chen et al., 2004; Chilson et al., 2002).

3 Analysis and discussion

Two mechanisms have the potential to explain the aspect sensitivity of PMSE: reflections from a sharp gradient in the refractive index (Alcala et al., 2001), and turbulence anisotropic scattering (Dovika et al., 1984). If the radar echoes were to result from turbulence irregularities, some physical mechanism must exist to cause these anisotropic irregularities, since isotropic irregularities cannot explain the dependence of echo power on the radar zenith angle. Were such anisotropic irregularities to somehow be created, a preferable direction at which the maximum echoes occur would be detected, as evident in the experimental results in Figure 1. However, as turbulence irregularities often exhibit isotropic structures at such small scales, and magnetic field effects can be ignored because of the high collision frequency with neutral particles at this altitude range (PMSE range, 80–90 km), turbulence anisotropic scattering is unlikely the cause of the aspect sensitivity. Therefore, as our experimental results contradict the characteristics of scattering resulting from the turbulence, these features suggest that the strong radar echoes appear to be, at least partially, caused by the reflection from sharp gradients in the refractive index.

In fact, many rocket soundings and radar data have confirmed the existence of electron density depletion layers in this region, with the strong radar echoes often corresponding to the altitudes of these layers (Havens et al., 2001; Havens et al., 1996; Ulwick et al., 1988), which often have very sharp vertical gradients because of the presence of thin ice-particle layers resulting from the scavenging of electrons. Also named a dusty plasma layer, this layer consists of electrons, ions and charged ice particles. In addition, based on the theory of Fresnel reflection, the echo power is largely dependent on the gradients in the refractive index, so the maximum echo power should be in a direction perpendicular to the reflected layers, which, if they are tilted, it is possible for the oblique beams to receive a stronger echo than the vertical beam, as sketched in Figure 2. Moreover, Alcala et al. (2001) have calculated the reflection coefficient of the radar echoes by using rocket data and radar measurements to obtain similar results to that observed here.

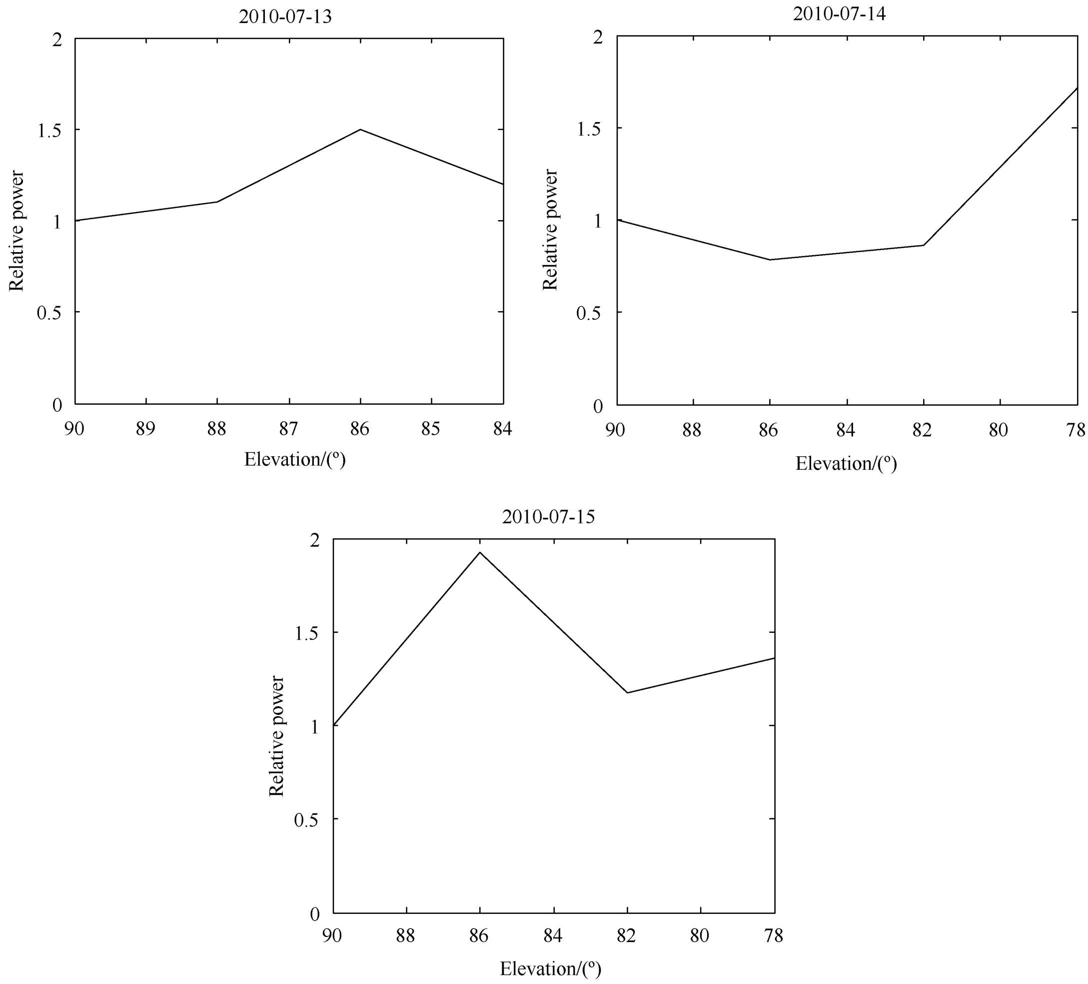

Figure 1 The mean echo power relative to that received in the vertical beam as a function of the elevation angle.

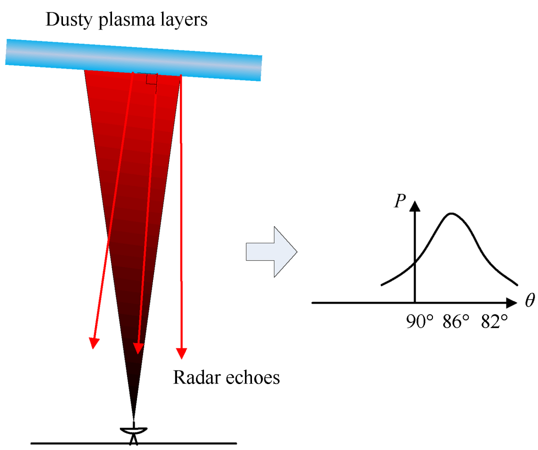

Figure 2 Sketch describing the radar backscatter from the dusty plasma layers.

Although rocket soundings have confirmed the relationship between the dusty plasma layers and PMSE, individual rocket flights have not provided any information about the fully two-dimensional nature of the structure of dusty plasma layers in the mesopause region, and whether their orientation as depicted in Figure 2 is accurate. Were the layers to have a tilt angle, the question would arise as to which mechanism does the tilting, and which factor would control the tilt angles leading to a maximum intensity in the echoes found at angles of 86º or 78º. Therefore, in the next section, we address our understanding of this feature in detail by using a theoretical model.

4 Model description

4.1 Model equation

In an earlier work (Hui et al., 2010), we proposed that the wind-speed variation caused by gravity waves, which can significantly influence the transport of heavy ice particles through collision coupling between the neutral atmosphere and ice particles, ultimately results in their convergence into thin and dense multiple layers. Here, we are particularly interested in studying the effects of gravity waves on the tilting of these layers using a theoretical two-dimensional model to explain the aspect sensitivity of PMSE.

To quantitatively assess whether the motion associated with gravity waves leads to tilting of the dusty plasma layers, density variations of ice particles resulting from gravity-wave activity are described by the continuity equation,

$$\frac{\partial n_d}{\partial t} + \nabla \cdot (n_d u_d) = 0 , \quad (1)$$

where $\nabla = \hat{x}(\partial / \partial x) + \hat{y}(\partial / \partial y)$, n_d and u_d are the ice-particle density and velocity components, respectively. Strictly speaking, the forces acting on the ice particles include the drag force, atmospheric pressure and gravity in the mesopause region. The velocity of the ice-particle is given by the momentum equation as

$$m_d n_d \frac{\partial u_d}{\partial t} = -n_d m_d \upsilon_{dn} (u_d - u_n) - \frac{\partial p_d}{\partial z} + m_d n_d g , \quad (2)$$

where m_d is the ice-particle mass, υ_{dn} is the effective collision frequency, $p_d = n_d k T_d$ is the partial pressure, and g is the acceleration due to gravity. The effective collision frequency υ_{dn} for ice particles is represented by (Lie-svendsen et al., 2003)

$$\upsilon_{dn} = \frac{8}{3\sqrt{\pi}} \frac{n_n m_n}{m_d + m_n} \sqrt{\frac{2k_B T(m_d + m_n)}{m_d m_n}} \pi (r_d + r_n)^2 , \quad (3)$$

where n_n, m_n and r_d are the neutral density, mass and particle radius, respectively. The term $u_n = v(u, w)$ in equation (2) is the velocity of the neutral particles, which is assumed to represent the gravity-wave perturbation velocity, where u and w are its components in the horizontal and vertical directions, respectively. According to linear gravity-wave theory, the horizontal velocity component u and the vertical velocity component w are related to the neutral density n/n_0 by Hines et al. (1960).

$$u = \frac{(n / n_0) \cdot (ik_x g / \omega) \cdot [\omega^2 \gamma H_0 - g(\gamma - 1)]}{[i\omega^2 + g(\gamma - 1)k_z]} , \quad w = \frac{(n / n_0) \cdot [-g\omega(1 - i\gamma H_0 k_z)]}{[i\omega^2 + g(\gamma - 1)k_z]} \quad (4)$$

respectively, where H_0 is the scale height, γ is the ratio of the specific heats, and k_x and k_z are the horizontal and vertical wave numbers, respectively. Finally, the wave-density perturbation n / n_0 is written in terms of the amplitude and phase as

$$n / n_0 = A \exp(i\omega t - ik_x x - ik_z z) . \quad (5)$$

The set of equations (1–5) describes the ice-particle, dynamic transport process coupling with gravity waves. The numerical methods used to solve these equations are presented in the next section.

4.2 Model results

To address with our theoretical model to what extent gravity waves affect the tilting of dusty plasma layers, we first assume the ice-particle size and their initial number density distribution with height in this region, and then study the density variation of charged ice-particles relative to gravity-wave perturbations. To simplify the calculation procedure, we assume that the ice particles in the PMSE region have an initially fixed horizontal distribution, and are uniform in size, and that by imposing gravity-wave perturbations on this region, any changes in the height distribution may be attributed to gravity waves. According to measurements of the temperature structure as observed by multiple sounding rockets, the initial vertical density distribution can be simply regarded as Gaussian,

$$n_d = n_{d0} \exp(-(h - h_0)^2 / 2\sigma^2) , \quad (6)$$

where the parameters assumed in this simulation are made as consistent with the experimental measurements as possible. Here, σ = 2.5 km is the half-width of the pre-existing layers, and the reference height h_0= 86 km. As a typical horizontal wavelength is around 100–1000 km, while the vertical wavelength is about 3–7 km in the mesopause region, for the reference case, values of the horizontal and vertical wavelengths are chosen to be 200 km and 4 km, respectively. The other gravity-wave parameters in the model are found by solving the relation for gravity-wave dispersion. Further model assumptions are a neutral atmosphere number density $n_0 = 1 \times 10^{20}$ m^3, a particle radius $r_d = 20$ nm, and the mass ratio of ice to neutral particles $m_d / m_n \approx 10^5$.

Equations (1) and (2) are solved by using the full-implicit-continuous-Eulerian (FICE) scheme with a difference grid technique as described in detail in Hu et al. (1984). In general, as the numerical solutions of the continuity equation (1) are dependent upon the boundary conditions, we used periodic boundary conditions in the horizontal direction, so that any material advected out of one side of the grid is advected into the opposite side. To avoid vertical boundary reflections at the upper and lower boundary conditions, the first-order spatial derivative is set to zero $\partial n_d / \partial z = 0$. The calculation domain in the horizontal direction is one wavelength, and the vertical domain extends from 78 km to 92 km.

Figure 3 illustrates the evolution of the ice-particle layer under the influence of gravity-wave perturbations according to the numerical results, with the layers displayed as a function of the horizontal distance and height. As evident from the simulation results, 2 h into the simulation (Figure 3b), the waves have already distorted the pre-existing layers (Figure 3a) by modulating the ice-particle concentration, which gradually transforms a single, thick ice layer into distinct, thin double layers. Most importantly, the reflection layers are not strictly horizontal, but have been tilted with respect to the horizontal by the gravity-wave perturbation. However, it should be noted that the ice-layer structures are transient, continuously varying with the cyclical activity of the gravity waves. In addition, because the diffusion of the ice particles is very slow, ice layers with a sharp gradient can be maintained for a long period after the disappearance of the gravity waves. These results are not only consistent with observations, but also confirm our contention that, on many occasions, the reflection layers are tilted.

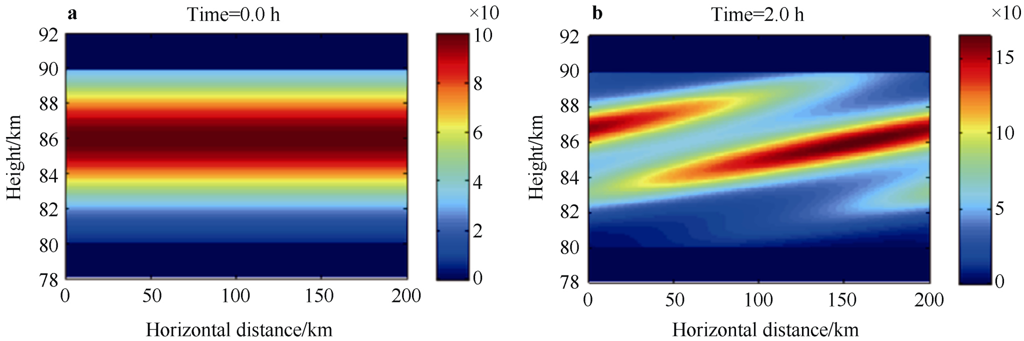

Figure 3 Ice-particle-layer evolution resulting from gravity-wave perturbations as functions of the horizontal distance and height.

5 Conclusions

We have presented data from the EISCAT VHF radar to investigate the aspect sensitivity of PMSE during the period 13–15 July 2010 by traversing the antenna beam in the zenith direction, and comparing the corresponding received power. Based on these data, we find a complex angular dependence of the PMSE, which cannot be explained by the pure isotropic structure of turbulence. Instead, these experimental results are consistent with, at least qualitatively, with the idea that partial reflections from the gradients of the refractive index of dusty plasma layers at the altitudes of PMSE contribute significantly to the received echo power of the VHF band. Additionally, the experimental results demonstrate that the echo intensity received by the oblique beam is larger than the vertical beam, the cause of which we propose is the presence of tilted reflection layers. To confirm this idea and describe the physical process, we have developed a theoretical model to demonstrate the formation process of tilted reflection layers by using numerical simulations.

As mentioned above, because the individual rocket flights give us no information about the full two-dimensional scattering structure in the mesopause region, our model results not only attempt to make up for this shortcoming, but also explain why ice particles near the summer polar mesopause are frequently seen to be confined to multiple layers. Furthermore, for the reference case, the model contains a large number of assumed parameters, such as the ice size distribution, number density and other particle microphysics, which may affect the model results, but were not given a detailed consideration here, and thus need further investigation. The gravity wavelength is also a crucial parameter, since it determines the tilt angle of the layers, which depends on the ratio of the horizontal to the vertical gravity wavelength in our model. This dependence may be used to explain why the maximum echo power can occur at different angles in our experimental data.

It should be noted that while we have primarily considered a possible theory to explain the aspect sensitivity of PMSE, the quantitative relationship between the dusty plasma layers and the strong radar echoes has not been addressed. We have only shown that the presence of dusty plasma layers with sharp gradients may contribute significantly to the received echo power, which should be further confirmed with the help of more *in situ* and ground-based observations. Further studies of the characteristics of the radar signals are also needed for a better quantitative understanding of the overall reflection and scattering processes, using, for example, multi-frequency observations, the frequency dependence of the echo power on the turbulence scattering, the degree of partial reflection, as well as techniques, such as the variation in the pulse length and the examination of the power spectrum of the received signal. These methods are proposed to be implemented simultaneously in future investigations.

Acknowledgments The authors thank the staff of the EISCAT for their collaboration in running the experiments and giving useful advice. The EISCAT Scientific Association is supported by CRIRP (China), NIPR (Japan), NFR (Sweden), PPARC (UK), RCN (Norway) and SA (Finland). The authors would like to thank Dr. Xu Bin for his help during the experimentation.

References

ALCALA C M, KELLEY M C, ULWICK J C. 2001. Nonturbulent layers in polar summer mesosphere: 1. Detection of sharp gradients using wavelet analysis. Radio Sci, 36(5): 875-890.

ALCALA C M, KELLEY M C. 2001. Nonturbulent layers in polar summer mesosphere 2. Application of wavelet analysis to VHF scattering. Radio Sci, 36(5): 891-903.

BELOVA E, DALIN P, KIRWOOD S. 2008. Polar mesosphere summer echoes: a comparison of simultaneous observations at three wavelengths. Ann Geophys, 25: 2487-2496.

BLIX A T, THRANE E B, KIRKWOOD S, et al. 1996. Experimental evidence for unstable wave in the lower E/upper D-region excited near the bisector between the electric field and the drift velocity. Geophys Res Lett, 23(16): 2137-2140.

CHEN J S, HOFFMANN P, ZECHA M, et al. 2004. On the relationship between aspect sensitivity, wave activity and multiple scattering centers of mesosphere summer echoes: A case study using coherent radar imaging. Ann Geophys, 22: 807-817.

CHILSON P B, YU T Y, PALMER R D, et al. 2002. Aspect sensitivity measurements of polar mesosphere summer echoes using coherent radar imaging. Ann Geophys, 20: 213-223.

CHO J Y N, RÖTTGER J. 1997. An updataed review of polar mesosphere summer ehcoes: observation, theory, and their relationship to noctilucent clouds and subvisible aerosols. J Geophys Res, 102: 2001-2020.

CZECHOWSKY P, RUSTER R. 1997. VHF radar observations of turbulent structures in the polar mesopause region. Ann Geophys, 15: 1028-1036.

CZECHOWSKY P, REID I M, RÜSTER R. 1988. VHF radar measurements of the aspect sensitivity of the summer polar mesopause echoes over Andenes, Norway. Geophys Res Lett, 15(11): 1259-1262.

DOVIAK R J, ZRNIC D S. 1984. Reflection and scatter formula for anisotropically turbulent air. Radio Sci, 19(1): 325-336.

ECKLUND W L, BALSLEY B B. 1981. Long-term observations of the arctic mesosphere with the MST radar at Poker Flat, Alaska. J Geophys Res, 86: 7775-7780.

HAVENS O, TRØIM J, BLIX T, et al. 1996. First detection of charged dusty particles in the earth's mesosphere. J Geophys Res, 101(A5): 10839-10847.

HAVNES O, BRATTLI A, ASLAKSEN T, et al. 2001. First common volume observations of layered plasma structures and polar mesospheric summer echoes by rocket and radar. Geophys Res Lett, 28(8): 1419-1422.

HINES C O. 1960. Internal atmospheric gravity waves at ionospheric heights. Can J Phys, 38: 1441.

HOPPE U P, FRITTS F, REID D C, et al. 1990. Multiple frequency studies of the high latitude summer mesosphere: implications for scattering process. J Atmos Terr Phys, 52: 907-926.

HOPPE U P, HALL C, RÖTTGER J. 1988. First observations of summer polar mesospheric backscatter with a 224 MHz radar. Geophys Res Lett, 15(1): 28-31.

HU Y Q, WU S T. 1984. A full-implicit-continous-Eulerian (FICE) scheme for multidimensional transient magneto dynamic flows. J Comput Phys, 55: 33-64.

KELLEY M, ULWICK J, ROTTGER J, et al. 1990. Intense turbulence in the polar mesosphere: Rocket and radar measurements. J Atmos Terr Phy, 52: 875-891.

LA HOZ C, HAVNES O, NAESHEIM L I, et al. 2006. Observations and theories of polar mesospheric summer echoes at a Bragg wavelength of 16 cm. J Geophys Res, 111(D4): D04203.

LI H, WU J, WU J, et al. 2010. Study on the layered dusty plasma structure in the polar summer mesospause. Ann Geophys, 28: 1679-1686.

LIE-SVENDSEN O, BLIX T A, HOPPE U, et al. 2003. Modelling the plasma response to small-scale particle perturbations in the mesopause region. J Geophys Res, 108: 8442, doi:10.1029/2002JD002753.

LÜBKEN F J, RAPP M, HOFFMANN P. 2002. Neutral air turbulence and temperatures in the vicinity of polar mesosphere summer echoes. J Geophys Res, 107(D15): ACL-9.

RAPP M, LÜBKEN F J. 2004. Polar mesosphere summer echoes (PMSE) review of observations and current understanding. Atmos Chem Phys, 4: 2601-2633.

RÖTTGER J, LA HOZ C, KELLEY M C, et al. 1988. The structure and dynamics of polar mesosphere summer echoes observed with the EISCAT 224 MHz radar. Geophys Res Lett, 15(12): 1353-1356.

RÖTTGER J, LA HOZ C. 1990. Characteristics of polar mesosphere summer echoes (PMSE) observed with the EISCAT 224 MHz radar and possible explanations of their origin. J Atmos Terr Phys, 52(10-11): 893-906.

SMIRNOVA M, BELOVA E, KIRKWOOD S. 2012. Aspect sensitivity of polar mesosphere summer echoes based on ESRAD MST radar measurement in Kirunna, Sweden in 1997–2010. Ann Geophys, 30: 457-465.

ULWICK J C, BAKER K D, KELLEY M C, et al. 1988. Comparison of simultaneous MST radar and electron density probe measurements during STATE. J Geophys Res, 93: 6989-7000.

ZECHA M, RÖTTGER J, SINGER W, et al. 2001. Scattering properties of PMSE irregularities and refinement of velocity estimates. J Atmos Sol Terr Phys, 63: 201-214.