

First observations of polar mesosphere summer echoes in Antarctica

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Abstract. A 25-kW peak power 50-MHz radar was installed at the Peruvian base on King George Island, Antarctica (62°S), in early 1993. A search for polar mesospheric summer echoes (PMSEs) was made during late January and early February of the first year of operation with negative results. These results have been reported in the literature [Balsley *et al.*, 1993; 1995]. We report here results obtained during the austral summer of the second year (1994) of operation. Observations during the second year were begun earlier, i.e., closer to the austral summer solstice. PMSEs were observed during this period, albeit the echoes were much weaker than what one would expect based on earlier Poker Flat radar results at a comparable latitude (65°N) in the Northern Hemisphere. A large and measurable asymmetry in PMSE strength in the two hemispheres therefore exists. We explain this asymmetry by postulating a difference in summer mesopause temperatures between the two hemispheres of ~ 7.5 K. This difference has been estimated using an empirical relationship between the variations of the Poker Flat PMSE power as a function of temperature given by the mass spectrometer incoherent scatter extended (MSISE-90) model.

1. Introduction

A relatively recent geophysical discovery [Ecklund and Balsley, 1981] has come to be known as polar mesospheric summer echoes or PMSEs. These are manifested as very strong VHF (30–300 MHz) radar echoes near the mesopause at high latitudes during summer (see Cho and Kelley [1993], Röttger [1994], and Cho and Röttger [1997] for recent reviews).

There is currently no satisfactory theory to explain PMSE occurrence. A possibly related but weaker mesospheric echo is observed at lower latitudes at VHF during all seasons. These echoes, which are still significantly stronger than incoherent scatter returns, have been postulated to arise from small-scale turbulent fluctuations in the ionization density [Woodman and Guillen, 1974; Royrvick and Smith, 1984]. These lower-latitude echoes are only marginally explainable by tur-

bulent mixing processes, however, since the meter-scale turbulence responsible for the VHF echoes is difficult to support with the accepted energy dissipation rates expected at these altitudes. This difficulty arises because the “inner scale” of turbulence (i.e., the smallest fluctuation length-scale that turbulence can create as it works against the competition of molecular diffusion) is thought to be somewhat larger than the meter-scale wavelengths to which the radar is sensitive. In other words, echo-producing meter-scale turbulence may be very difficult to sustain, since viscosity and diffusivity will heavily damp such small-scale irregularities.

The stronger PMSEs observed at higher latitudes are even harder to explain on the basis of the same standard turbulent mixing theories. PMSE observations at even higher frequencies (UHF = 300–3000 MHz) [Röttger *et al.*, 1990a] make their existence even more puzzling.

The reader is referred to the work of Cho and Kelley [1993] and Cho and Röttger [1997] for a review of the physical processes that have been put forward to explain PMSE occurrence. One current speculation on VHF PMSE generation is that while turbulence must still play an important role in the generation of PMSE, it is also necessary to include the existence of large, heavy ions with slower diffusivity, i.e., large Schmidt numbers [Kelley and Ulwick, 1988; Kelley *et al.*, 1987; Ulwick *et al.*, 1988]. Recent experimental evidence for the existence of charged aerosols and large Schmidt numbers during PMSE conditions is given by Havnes *et al.* [1996] and Lübken *et al.* [1998], respectively. This requirement is satisfied by the existence of charged

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ice particles [Cho *et al.*, 1992], which also explains the close altitudinal, latitudinal, and seasonal relationship of PMSE with both noctilucent clouds (NLCs) and a related phenomenon, polar mesospheric clouds (PMCs) [Thomas, 1991]. It also explains PMSE occurrence under only the coldest mesospheric conditions (i.e., during summer at high latitudes). Additional experimental support for the existence of charged ice particles during PMSE conditions is given by Zadorozhny *et al.* [1997].

Although the correlation between PMSE occurrence and that of NLC has not been well established, close coincidences have been reported, indicating common physical processes. More recently, Inhester *et al.* [1994] have found agreement between ice cloud model calculations and PMSE occurrence. Their model calculations use simultaneous falling sphere mesospheric temperature measurements and 50-MHz radar PMSE observations. This study gives strong support to a direct relationship between the two phenomena. In addition, Inhester *et al.* [1994] directly establish an upper limit of 140 ± 5 K as a temperature threshold for the existence of PMSE.

Even more recently, Nussbaumer *et al.* [1996] found very close agreement between NLC, as observed by a lidar, and the presence of PMSE. In two of the four cases presented, the NLC cloud delineates almost exactly the bottom edge of the PMSE region. The close connection between the two phenomena is a consequence of using the lidar to observe NLC in the same scattering volume as that of the radar.

Thus the possibility that VHF PMSEs are generated at temperatures low enough to freeze water vapor is definitely a valid working hypothesis. It is, moreover, one that we shall use in discussing our results.

The purpose of this paper is to report the results of Antarctic PMSE observations made during the austral summer of 1993-1994. During the previous summer (1992-1993), our team of Peruvian and North American scientists and technicians had installed a VHF radar at Peru's Machu Picchu station ($62^{\circ}06'S$, $58^{\circ}28'W$) on King George Island, Antarctica. The most interesting result of the first campaign was the discovery that essentially no PMSE was observed, although the latitude and season were consistent with observations of very strong PMSE returns in the Northern Hemisphere [Balsley *et al.*, 1993]. A more extensive summary of the first year's observations [Balsley *et al.*, 1995] compared our surprising (negative) Southern Hemisphere results with Northern Hemispheric, high-latitude observations. We concluded that Antarctic PMSEs, if they existed at all, had to be at least 34 to 44 dB weaker than their Northern Hemispheric counterparts. We also reported, as the note added in proof in our previous study [Balsley *et al.*, 1995], that a more thorough analysis of the first year's using refined noise reduction techniques yielded one very weak PMSE return that lasted for a few hours. While this result did not alter our fundamental conclusions regarding the disparity between PMSE intensities

in the two hemispheres, it did change the estimated magnitude of the difference by ~ 8 dB to 26-36 dB.

In the present paper we will discuss the significance of our second year's results in the context of our previous (largely negative) results. In addition, we will compare our results with more quantitative statistics derived from the Poker Flat VHF radar ($65^{\circ}08'N$, $147^{\circ}27'W$). After considering the influence of other mesospheric state parameters as possible sources of the north-south PMSE asymmetry, we will conclude that temperature is possibly the most critical parameter determining the difference. Assuming that this conclusion is correct, we will use the temporal behavior of PMSE strength and measured mesopause temperature at near Poker Flat latitudes to "calibrate" an empirical echo power versus temperature relationship. We will then show that an interhemispheric temperature difference of 7.5 K, comparable with expected values derived from existing empirical models, could explain the observed asymmetry in PMSE strength.

2. Experimental Description

2.1. Radar System and Operations

Until January 15, 1994, the radar system employed at the Machu Picchu site during both the 1992-1993 and the 1993-1994 campaigns was the same system reported by Balsley *et al.* [1995]. This early system used a single system that was switched manually between three antennas fixed to point to the vertical and to 15° off vertical toward the north and east [Sarango *et al.*, 1994]. An improved system was put into operation after January 29, 1994. This new system was capable of controlling and parallel processing three independent radars with antenna beams pointing in three different directions. Furthermore, each of these radars could process data on line simultaneously from both the mesosphere and the troposphere [Sarango *et al.*, 1995]. For the present purposes we used only the beam positions that were directed to the vertical and 15° off vertical to the north. The pertinent parameters that determined the sensitivity of these systems are shown in Table 1.

Table 1. Machu Picchu Radar Parameters

| Parameter | Value |
|---------------------------------------------|--------------------|
| Antenna area, vertical, m^2 | 2500 |
| Antenna area, 15° westward, m^2 | 5000 |
| Antenna area, 15° northward, m^2 | 2500 |
| Peak transmitter power, kW | 25 |
| Pulse width, μs | 8, 16 |
| Interpulse period, ms | 1 |
| Coherent integration time, ms | 128 |
| Receiver bandwidth, μs | 8, 16 ^a |
| Receiver noise figure | ~ 3 dB |

^aWhen a $16\mu s$ pulse width is used

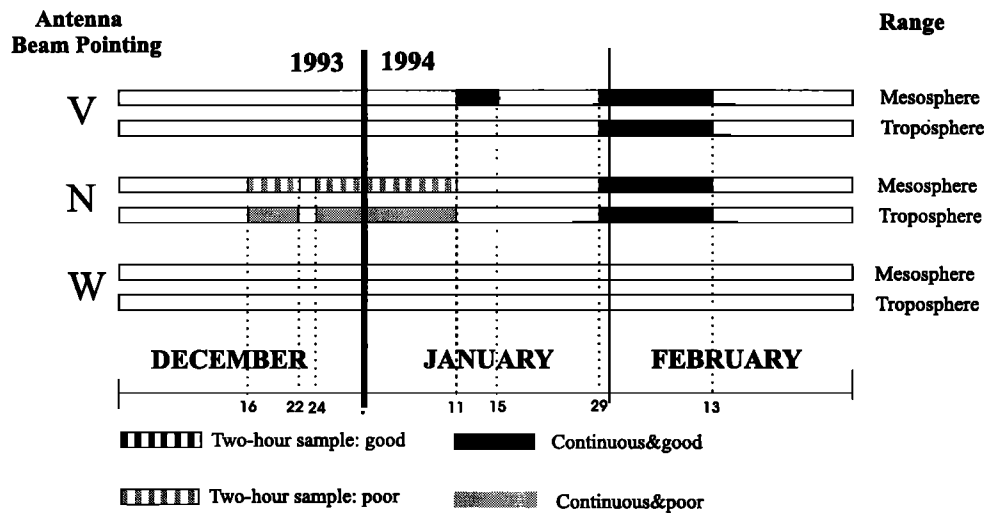


Figure 1. Summary of the observational modes used during the austral 1993-1994 summer campaign. The graph also shows the quality of the observations.

Although we arrived for the summer campaign (1993-1994) in mid-December, much earlier than that of the previous summer, we did not get a fully working system until mid-January. Unfortunately, the antennas had suffered some damage from the harsh winter conditions and repair was not possible until the ice covering the ground structure and foundation had melted. Because of this problem, only a partially working north pointing antenna was placed into operation on December 16, 1993. We suspect that this system did not achieve full design sensitivity until 2100 LT (60°W) on January 11, 1994. In spite of this limitation, during this period, except for a period between December 22 and 24, a 2 hour time window beginning at local noon was dedicated to mesospheric observations. A summary of the observing times for the second summer campaign, including “down” times and times with questionable system sensitivity, is shown in Figure 1.

As shown in Figure 1, the system operated using only the north directed beam until 1400 LT on January 11. After 2100 LT on January 11, the system was switched to the repaired vertical beam and an improved receiver system and the operating mode was changed to continuously sample the mesospheric altitudes.

Following a system failure on January 15, no observations were made until January 29. At this point a newly developed, multibeam and multirange system was put in operation. This new system used both the north and vertical antennas and sampled tropospheric and mesospheric heights simultaneously. This operating mode continued until the end of the campaign on February 13.

2.2. Processing Techniques: Overview

In the following sections we will discuss PMSE characteristics obtained during the entire 1993-1994 campaign. Note that we will mainly discuss just PMSE am-

plitude characteristics. The amplitudes are presented and discussed in terms of signal-to-noise ratios (SNRs) expressed in decibels. At 50 MHz the noise level is determined primarily by the (known) sky radio temperature (cosmic noise). SNR therefore can be used to compare signal strengths at Machu Picchu with those obtained by other systems at other geographical locations. We have normalized all signal powers relative to a single value of noise that was obtained from the noise level of a particular time period around 2100 LT on January 14, when the noise was low and the signal was free from interference.

The “signal” used in the SNR is that obtained after subtracting the noise and interference contributions from the total signal received at a given time and from a given altitude. It is important to point out that we occasionally experienced interference problems with interference power levels comparable to the noise level. This interference, which originated primarily in the processing and control electronics, was, for the most part, independent of altitude. Both the cosmic noise and the altitude-independent interference for a given integration time were estimated from the lowest 10 mesospheric altitude samples. This procedure took advantage of the fact that PMSEs are never observed at these altitudes.

3. Data Presentation

3.1. The Antarctic Results

Except for a series of weak echoes that were observed on January 9, the entire data set containing detectable echoes is presented in Figure 2. In Figure 2 the echo intensities have been plotted using a gray scale according to the logarithmic scale shown at the bottom of the figure. Note that the detectable signal level is around 14 dB below the noise level. Antenna pointing directions appear in Figure 2, top, in the black (system down)

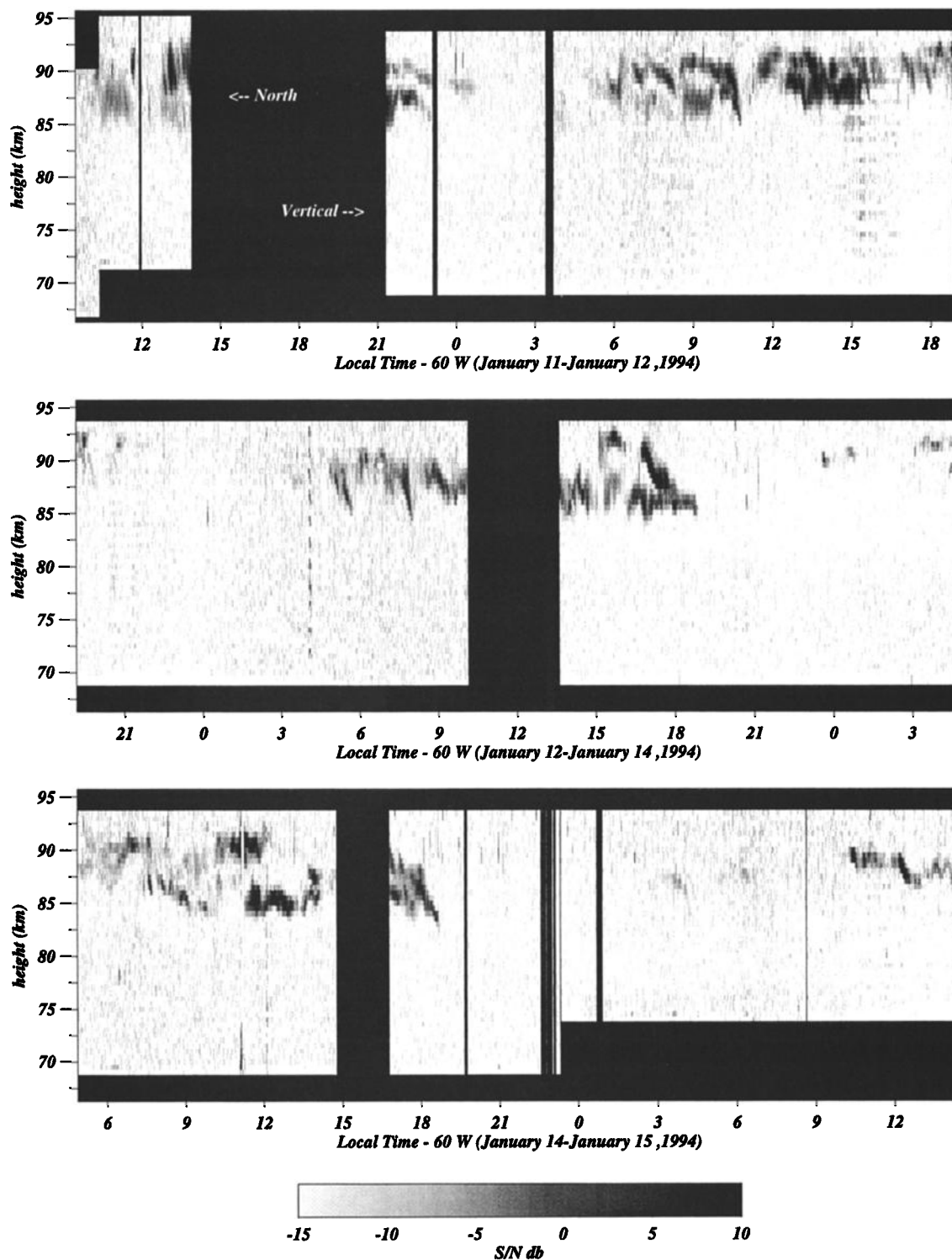


Figure 2. Range-time-intensity plot covering the period between late January 11 to midday January 15, 1994, when continuous observations at mesospheric heights were made and polar mesospheric summer echoes (PMSEs) were observed.

area. The weak January 9 echoes (not shown in Figure 2) were observed using the marginal system on the north directed antenna and lasted during the entire 2 hours of the (mesospheric) observing period during that day. These echoes occupied a single height range at 82 km

of altitude. Their intensity, even at maximum levels, never exceeded 3 dB above noise level.

The January 11 echo event that was obtained using the north directed beam between 1000 and 1400 LT appears in Figure 2, top left. The remaining data in

Figure 2 correspond to the period between January 11 and 15 when the antenna was directed vertically. This was the only period when we observed the mesosphere almost continuously and when PMSEs were present.

Although we have no data for the period January 16 to 29, we do have continuous data using the updated system for the subsequent period between January 29 and February 13. These data are not shown since no echoes were detected. The lack of detectable echoes implies that if weak echoes were present, they were at least 14 dB below the noise level.

The two-hour-per-day mesospheric midday observations made prior to January 11 require a separate discussion. Although the radar was not operating up to its full specifications during this period, the data are not completely devoid of useful information. Data during this period are very important for our discussion because, based on Poker Flat PMSE analysis, this is the season of strongest echoes. Therefore any information, albeit qualitative, available from the Machu Picchu data during this period is important in assessing relative differences of echo strengths between the two hemispheres. Specifically, the radar used until January 11 was sufficiently sensitive to detect reasonably strong PMSEs. We know this because that system typically recorded tropospheric echoes up to ~ 5 -km altitude on the north directed beam. In fact, on one occasion, we were able to obtain tropospheric echoes up to 10 km,

and we did detect PMSE on the north-directed beam on January 9 and 11. However, we were unable to detect mesospheric echoes prior to 9 January. On the basis of the strengths of the typical tropospheric returns, we can establish that the loss of sensitivity was less than ~ 10 -20 dB.

On the basis of these arguments and the ≤ 10 dB SNR levels in Figure 2, we deduce that PMSE intensities prior to 9 January could not have been much stronger than the strongest PMSE illustrated in Figure 2. It follows that PMSE intensities prior to January 9 were either comparable or weaker than the echoes observed later or were nonexistent.

It is clear from Figure 2 that the observed Southern Hemispheric echo returns are similar to Northern Hemispheric PMSEs. They have the same morphology (regions of echo intensity that move downward with time) as similar plots taken at other Northern latitude stations. Furthermore, the altitude range of our observations lies within the same range as the strongest echoes obtained at Poker Flat [Ecklund and Balsley, 1981] and other Northern Hemispheric observations [e.g., Röttger, 1994]. In addition, both the velocity and spectral width of the returns correspond to those expected for PMSE values. These statements are supported by Figure 3, which shows both instantaneous SNR profiles (Figure 3, left) and a typical Doppler spectrum profile (Figure 3, right). The mean velocities are consistent with

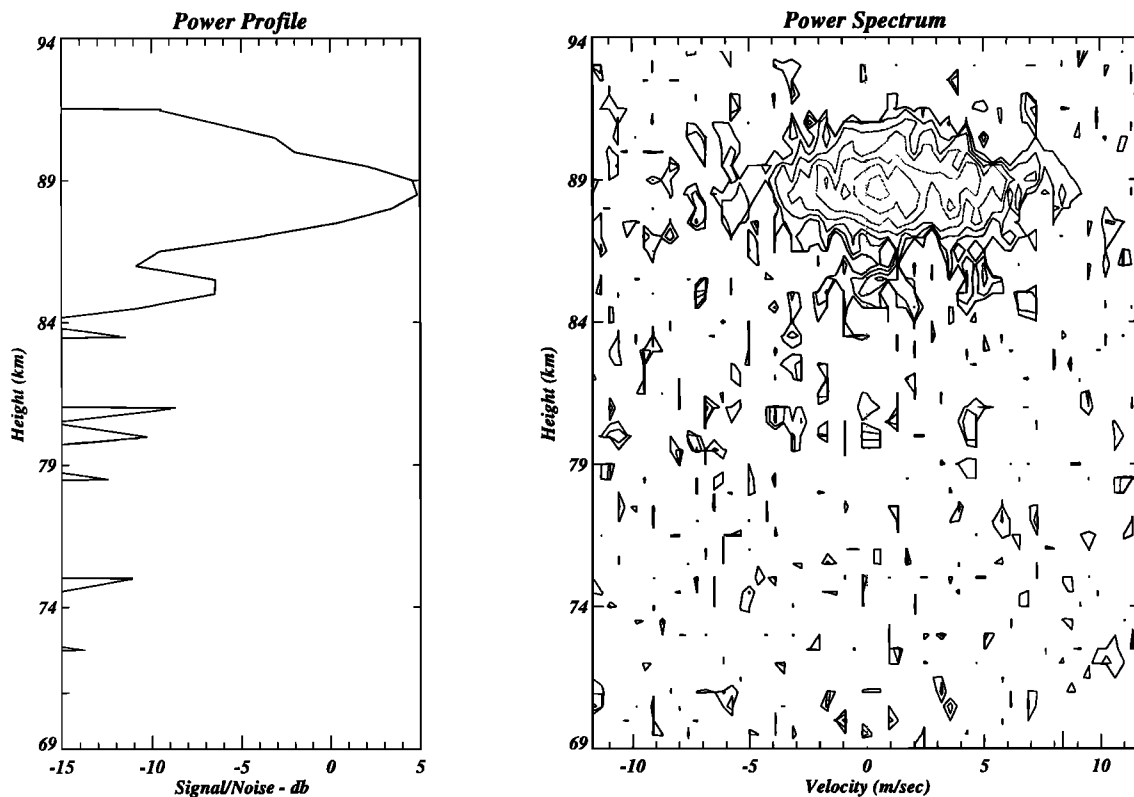


Figure 3. Typical (left) power profile and (right) spectral contour plot of mesospheric echoes obtained by the vertical beam radar at Machu Picchu station, Antarctica, January 12, 1994, 1650 LT. Contours are shown every 3 dB. The lowest contour is at the detectable level.

the expected velocity of vertical PMSE returns (typical short-period gravity wave vertical velocities), while the spectral width is that which would be expected for beam-broadened spectra, i.e., a width determined by Doppler shifts due to the projection of the horizontal mesospheric velocities to all the lines of sight included within the beam width of the antenna.

One conspicuous feature apparent in Figure 2 is the quasi-periodic (30-60 min) occurrence of downward propagating structures mentioned above. Note, for example, the almost identical features between 1640 to 1740 LT on January 12. The form of these features is very similar to other isolated features, which can be seen at 1030 and 1500 LT on the same day, at 0500, 0730 and 0900 LT on January 13, and again at 1800 LT on January 14. All of these structures appear to progress downward, slowly at the beginning and more precipitously at the end. This downward phase progression and its quasi-periodicity suggest a close relationship with gravity waves. Such a relationship has also been observed at northern high latitudes [Balsley *et al.*, 1983; Fritts *et al.*, 1988; Röttger *et al.*, 1990b].

The 5 days displayed in Figure 2 show minimum activity somewhere around 2100 and 0300+ LT, with a maximum activity occurring somewhere between 0600 and 1900 LT. This feature suggests strong solar and/or diurnal tidal control. Unfortunately, the time series is not long enough to derive a climatology. This behavior in time is somewhat similar to the northern latitude PMSE counterpart. At northern latitudes a minimum in activity has been reported between 2100 and 2400 LT [Balsley *et al.*, 1983], although the minimum shows a larger day-to-day variability. The broad maximum also agrees well with the maximum activity reported by Bremer *et al.* [1996] using the ALOMAR-SOUSY radar at Andenes (69.28°N, 16.02°E), although our minimum is shifted towards later times including times where Andenes shows a secondary maximum around midnight. Note that the measured echo strengths over the Machu Picchu radar rarely exceed ~10 dB (or 6 or 7 dB, if we use hourly averages as in Poker Flat) over the noise level. The maximum values, moreover, never last longer than an hour during the entire period. Most of the time, when echoes are visible, the power levels lie near 0 dB or weaker.

3.2. Interhemispheric Differences

At this point, the two most important inter hemispheric differences in PMSE behavior lie with the echo strength and the seasonal duration of the echoes. In order to discuss our results quantitatively in relationship to the extensive observations carried out at Poker Flat in the Northern Hemisphere, we have evaluated Northern Hemisphere PMSE statistics using the so-called "clean" reduced (hourly averaged) parameter data files obtained from the Aeronomy Laboratory of the National Oceanic and Atmospheric Administration

(NOAA). Weekly power level statistics obtained from these data are shown in Figure 4. The results include data from both off-vertical (north and east) beams, since both data sets were obtained with the same sensitivity. The statistical curves are shown in terms of percentile contour levels. Here the signal-to-noise ratio of a point in a given percentile curve should be interpreted as the level that the signal has exceeded the percentage of time given by the subscript. The 50% percentile curve P_{50} can be interpreted as the weekly median SNR as a function of season. The 10% and the 90% percentile curves convey information on the variance of the power level for a given period. Also plotted in Figure 4 are the maximum (1-hour average) power levels P_{\max} observed for the corresponding weekly periods.

In Table 2 we have tabulated the critical system parameters of the vertical antenna system of the Machu Picchu radar for the second campaign as well as that of the east and west Poker Flat systems. These specific values were used to obtain the data shown in Figures 2 and 4. The comparative values (Machu Picchu/Poker Flat) are expressed in dB. Examination of Table 2 shows that the overall sensitivity difference between the two systems is 21 dB. Note that we have assumed a 5-dB enhancement for the height-averaged aspect sensitivity, i.e., a correction to take into account the higher power levels at vertical incidence relative to those made at oblique angles. This value has been adopted using the recent results of Huaman and Balsley [1998] for the altitudes of interest (84-88 km) using the same Poker Flat CEDAR database. The "processed bandwidth" indicates a gain in sensitivity obtained by the digital processing of the data, mainly due to differences in the coherent integration times (digital filter bandwidth) used.

In addition to the Poker Flat statistics, we have plotted in Figure 4 the results of both seasonal campaigns in Antarctica. The sensitivity difference in the two systems has been addressed by the use of two SNR power scales that differ by 21 dB. The left-hand scale refers to Poker Flat results, while the right-hand scale of Figure 4 refers to results from Machu Picchu. Plotted in this way, the relative difference in power obtained at the two sites is valid if read from either the left or the right scale. These differences should be attributed to differences in the nominal echo cross section in the two hemispheres. We should also note that we have added an additional 2 dB to the first-campaign Machu Picchu observations to account for the fact that they were made using an off-vertical antenna (-5 dB) but with twice (+3 dB) the area used on the second campaign.

A comment is in order regarding the temporal scale of Figure 4. Note that we have shifted the Machu Picchu results by 6 months to correspond to the comparable season in the Northern Hemisphere. Accordingly, December, January and February in Antarctica correspond to June, July, and August in the Arctic, respectively.

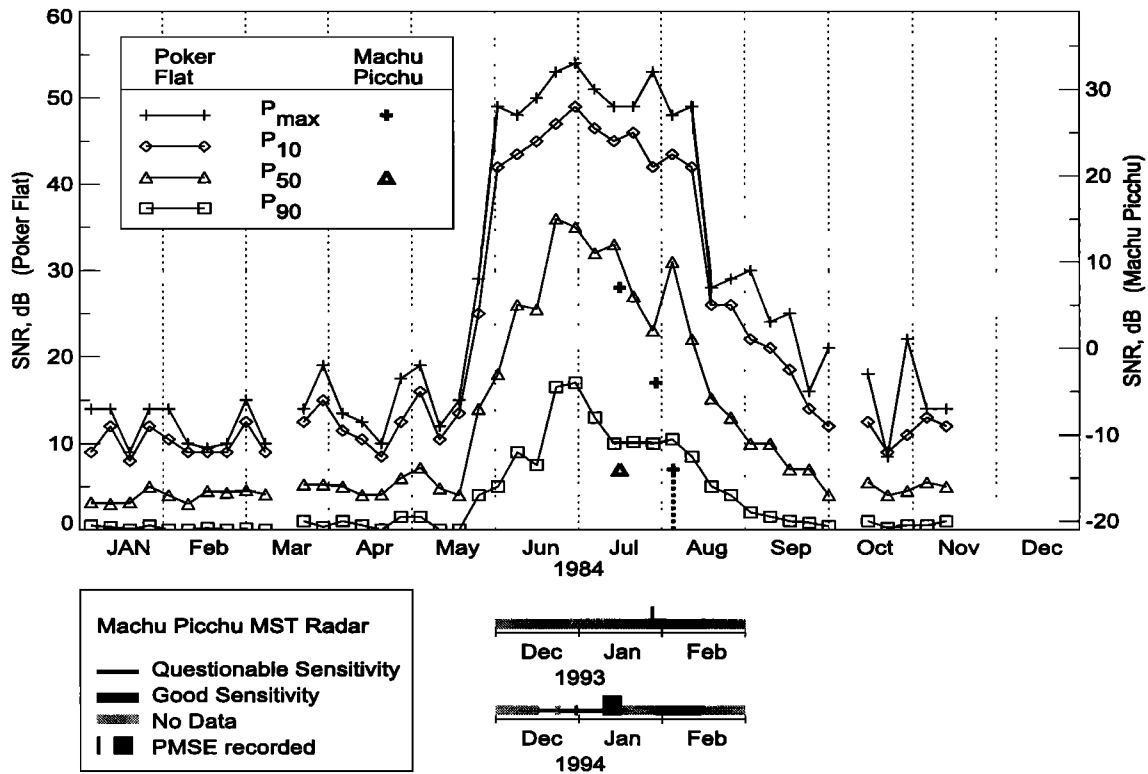


Figure 4. Statistical distribution of the echo power levels observed at Poker Flat between 84 and 90 km with the east and north beam during 1984. One-hour-averaged maximum powers, in 1-week period, are shown as joined crosses. Power levels exceeded for 10, 50, and 90% of the time are shown as joined diamonds, triangles, and squares, respectively. The isolated crosses and the isolated triangle correspond to the same definitions but for the Antarctic observations. The isolated cross for the first week of February (August) shows an upper limit. The labels on the left axis correspond to power levels using the sensitivity of a Poker-Flat-like system, and the ones on the right axis correspond to one with the sensitivity of a Machu-Picchu-like system. The additional temporal scales on the bottom have been shifted 6 months and show the times when observations were made, with either good or questionable sensitivity, and the times when echoes were received in Machu Picchu.

The 1-hour-averaged received SNR values at Machu Picchu are shown in Figure 4 by the two isolated bold crosses at +7 and -4 dB. One cross (7 dB) corresponds to the hourly averaged maximum signal observed during mid-January (January 13) 1994 and shown in Figure 2; the other (-4 dB) value corresponds to observations

made toward the end of January 1993. Observations of the absence of PMSE activity during the first week of February for both campaigns are indicated by a third isolated cross at the -14 dB minimal detectable level. In this instance, the cross is shown above a sequence of dots to indicate that the cross is an upper limit of PMSE SNR values and that values below this are possible. To compare hourly averaged maximum SNR levels between the two stations, the bold Machu Picchu crosses should be compared with the joined crosses corresponding to Poker Flat values.

Table 2. Machu Picchu (MP)/Poker Flat(PF) Sensitivity Comparison

| Parameter | MP | PF | MP/PF ^a |
|---------------------------------|-------|--------|--------------------|
| Antenna area, m ² | 2,500 | 30,000 | -11 |
| Average power, Watts | 250 | 10,000 | -16 |
| 1/bandwidth, μs | 8 | 10 | -3 |
| 1/(process bandwidth), ms | 128 | 49.3 | +4 |
| Aspect sensitivity ^b | 128 | 49.3 | +5 |
| Overall sensitivity difference | | | -21 |

^aAll values in dB
^bHeight-averaged

We also show a single statistical point (the bold isolated triangle) in Figure 4 for the Machu Picchu radar (P_{50}). This point shows the SNR level that was exceeded 50% of the time during the entire vertical beam mid-January 1994 observations. During this period (see Figure 2), the -14-dB minimal detectable level was exceeded (that is, echoes were observed) 50% of the time. It is possible to establish the value of this point, despite the fact that for the other 50% of the time the signal was below the sensitivity of the system. Note that

this point is much more statistically significant than the maximum power estimates derived from a single point and corresponds to the median PMSE. It should be directly compared to the series of weekly medians, P_{50} (joined triangles), for July in the Poker Flat results.

Note that the maximum power level and the 10% percentile curve for the Poker Flat radar remain relatively flat during the nonsummer months between mid-September and mid-May. The median SNR value during this period is ~ 10 dB SNR, with peaks reaching the 20-dB level. Typically, these echoes are of relatively short duration and occur usually at times of energetic particle precipitation. As one would expect, the correlation is highest when the D region solar ionization is at minimum and the ionization is mainly produced by the energetic particle precipitation. During summer, *Ecklund and Balsley* [1981] and *Czechowsky et al.* [1989] found a minimal correlation between precipitation events and PMSE intensity at high magnetic latitudes. Apparently, given sufficient ionization by solar radiation, enhancements in echo power produced by PMSE-related mechanisms mask the enhancements created by energetic particle ionization. It is worth noting that because of the lower geomagnetic latitude of Machu Picchu (-55° dip), one would expect precipitation events only during extreme magnetically disturbed days.

4. Discussion

4.1. Observational Summary

The observations made during our second Antarctic (1993-1994) campaign complement our observations of the previous year campaign, insofar as they provide observations closer to the austral summer equinox. Although the second-campaign observations reported here were not made as early in the season as we had hoped, they do cover the important transition period between the time when (based on earlier Northern Hemisphere results) (1) PMSE should achieve maximum SNR values and (2) they disappear at the end of summer (at least for radars with sensitivities comparable to ours).

Inspection of Figure 4 shows that the strongest (P_{max}) echoes received in mid-January at Machu Picchu (~ 7 dB SNR, on the right-hand scale) correspond to about a 28-dB SNR (left-hand scale) echo at Poker Flat. This level is clearly 22 to 26 dB weaker than the actual Poker Flat SNR values, depending on whether we use a 50- or 54-dB value for the maximum SNR ratio plotted for the equivalent period at Poker Flat. Similarly, the median (P_{50}) values at Machu Picchu are ~ 25 dB weaker than the Poker Flat values for the same period. Machu Picchu PMSEs, toward the end of January (July in the Northern Hemisphere), as depicted by the P_{max} values, are even weaker, although the Poker Flat echoes remain relatively constant. Thus, during the end of January (July), the maximum strengths of the Machu Picchu PMSEs are some 32-35 dB weaker than the maximum strengths seen at northern latitudes. These dif-

ferences become even larger as the end of the season approaches. Indeed, the negative results obtained during the first week of February in the Antarctic suggest that the echoes could be at least 40 dB weaker than their northern counterparts for the same season.

Finally, despite the lack of sensitivity during the last half of December and the first of January, we can claim that the echo strengths could not have been much higher than 20 dB above the detectable level: that is, they must be comparable to, or weaker than, the maximum strengths reported for the middle of January when the system was working properly.

Clearly, these new observations reinforce our previous conclusions [*Balsley et al.*, 1995] that there are large differences between the powers of the PMSE observed in the two hemispheres during comparable periods. How can we account for such large hemispheric differences in behavior at these two high-latitude locations that differ only 3° in latitude? It continues to be reasonable to postulate that inter-hemispheric difference in temperatures postulated by *Balsley et al.* [1993] is a primary cause. In the following paragraphs we will extend these early discussions and consider other mesospheric state parameters and conditions that could influence PMSE intensities. The points outlined below will confirm that, indeed, temperature is the most critical parameter. Following that, we will use the Poker Flat results in conjunction with empirical temperature models to obtain a more quantitative evaluation of how large this temperature difference could be.

4.2. The Role of Temperature and Other Mesospheric State Parameters of Importance

We assume the presence of ionized ice aerosols discussed in the introduction, as a reasonable working hypothesis for the occurrence of VHF PMSE. However, regardless of the anticipated importance of temperature in PMSE production, the other state parameters and conditions of the mesosphere could have a bearing on the strength of PMSE and cannot be ignored. Specifically, we need to consider the possible importance of water vapor, partial pressure (or mixing ratio), phase state of water, turbulence and gravity waves, ionized particles, electron density (index of refraction), and condensation nuclei. The intensity of gravity waves also comes into the picture since it affects the instantaneous temperature [*Reid*, 1975]. Furthermore, considering that the two radars, besides being at different hemispheres, have different longitude and latitude, we first need to examine possible latitudinal and longitudinal dependencies of the same quantities in either hemisphere. This is done in the following section.

4.3. Possible Longitudinal and Latitudinal Effects on PMSE Intensity in the Same Hemisphere

Regarding longitudinal dependencies, the most sensitive state parameter at high latitudes out of the ones

mentioned above is the mesospheric ionization level. The two primary sources of ionization are solar radiation and particle precipitation. Clearly, solar radiation has no longitudinal dependence. Particle precipitation, on the other hand, depends strongly on geomagnetic latitude. Geomagnetic latitude, in turn, depends heavily on geographic longitude. Although the geographical latitude of the Poker Flat and Machu Picchu sites differs by only 3° , the geomagnetic latitude of the two stations is very different. Poker Flat has a dip angle of 77° and is often subjected to particle precipitation; Machu Picchu has a dip angle of -55° and is only subjected to particle precipitation events during very disturbed conditions. Two studies of the effects of particle precipitation on PMSE activity [Ecklund and Balsley, 1981; Czechowsky et al., 1989], however, have shown that during the summer months there is little correlation between particle precipitation and echo strength. On the base of these results, it appears that the Sun by itself provides sufficient ionization to produce very strong PMSE. PMSEs are strong in the absence of precipitation events. We need to qualify this last statement slightly to account for a weak variation in PMSE intensity that depends on D region ionization as observed by an absorption instrument [Czechowsky et al., 1989]. This small effect definitely cannot explain the large observed power differences between the two hemispheres. We could exclude from our comparisons the times when there was a precipitation event and still be left essentially the same large differences in power levels.

There is no reason to expect a significant longitudinal dependence, at mesospheric altitudes, in any of the average properties of any of the other parameters mentioned above, e.g., turbulence, condensation nuclei (meteoric activity), or gravity waves. We are not aware of any observations showing the contrary. In any case, we are assuming such independence. It is reassuring to note, in passing, that the the mass spectrometer incoherent scatter extended (MSISE-90) model [Hedin, 1991], which does show a measurable temperature difference between hemispheres, shows negligible longitudinal temperature differences at mesopause altitudes during summer. Thus, at least to first order, both stations can be considered representative of their corresponding latitude, except that a slightly higher average power at the Poker Flat radar might be observable during periods of high energetic particle precipitation.

Concerning a possible latitudinal dependence, we should recall that the latitude difference between Poker Flat and Machu Picchu is only $\sim 3^\circ$. Except for a mesospheric temperature effect, the expected differences in any other relevant state parameters for such a small change in latitude are insignificant. Differences in solar ionization levels could be consequential but only during local sunset and sunrise times. At any other time, the difference in solar incidence angle and thus in ionization and PMSE strength would be comparable to that produced by less than 1 hour in local time. Temperature changes, on the other hand, need to be considered

carefully, since small temperature changes can strongly affect the water vapor saturation temperature. Thus a few degrees in temperature can make the difference between water being in the ice phase or not. According to the MSISE-90 model [Hedin, 1991], the summertime mesopause temperature at a latitude 3° south of Poker Flat is 1.5 K warmer than the mesopause temperature at Poker Flat. We will consider this difference when we quantitatively discuss possible interhemispheric temperature differences.

4.4. Possible Interhemispheric Asymmetries

In contrast with the expected latitudinal and longitudinal insensitivity (within the same hemisphere) discussed above, there are reasons to expect differences in mesospheric summertime temperature and water vapor at comparable latitudes in the two high-latitude hemispheres. Specifically, mesopause temperatures in both hemispheres are strongly influenced by the atmospheric general circulation. The cold summer mesopause temperature is a consequence of adiabatic cooling produced by the vertical component of the summer-to-winter circulation cell [e.g., Garcia, 1989, and references therein]. This same circulation influences the water vapor mixing ratio equilibrium profile in summer. In addition, there is a steep vertical gradient in the water vapor mixing ratio that arises from photodissociation at higher altitudes. This gradient is maintained by the upwelling of the water vapor that is driven by the same circulation [Thomas, 1996b]. This meridional circulation cell is driven, in turn, by the momentum deposition of gravity waves propagating from below and breaking at these altitudes [e.g., Garcia, 1989]. Thus orographic differences and differences in troposphere circulation and convective activity in the two hemispheres can reasonably produce differences in gravity wave activity that could lead to differences in circulation, temperature and water vapor mixing ratio.

As discussed by Balsley et al. [1995], a difference in both upper level gravity wave activity and mesosphere circulation has been noted by Vincent [1994]. In his preliminary study, Vincent found that the mesospheric meridional winds and the gravity wave variance at Mawson (67°S , 63°E) were approximately one half as large as corresponding quantities at Poker Flat. More recently, Huaman and Balsley [1998] compared summer mesospheric wind velocities obtained using the Poker Flat (65°N) mesosphere-stratosphere-troposphere (MST) radar and the Mawson (67°S) and McMurdo (78°S) HF radars. They find that the Northern Hemisphere meridional winds are $\sim 0\text{--}15$ m/sec stronger than the southern ones. In relative terms the difference also corresponds to a ratio of the order of 2 to 1. Moreover, the MSISE-90 model, which incorporates rocket and satellite measurements of temperature, shows an interhemispheric mesopause temperature difference of 5.4 K at 62° near the time of expected temperature minimum. Taking into account the latitudes of

the two stations, this difference increases to ~ 7 K. Although one could question the accuracy of the MSISE-90 model in representing the southern mesospheric temperatures, because of the scarcity of measurements, in the following sections, we will argue, using only Poker Flat and Machu Picchu PMSE observations, that temperature differences of this order could indeed be sufficient for explaining the observed differences in PMSE strength.

There is, as yet, no analytical empirical model for water vapor. In fact, most quoted values are derived from theoretical considerations based on modifications of the Garcia-Solomon model [Garcia, 1989; Thomas, 1996b]. The models do not discuss possible effects due to differences in circulation between both hemispheres, but one can notice that at any given time and altitude, they show relatively constant values of water vapor mixing ratio for a wide range of latitudes. One can then infer that water vapor mixing ratio is relatively constant over a wide range of values of vertical circulation velocities. Thus, in spite of the differences in circulation, it is reasonable to assume that there will be little asymmetry in water vapor between the two hemispheres. This assumption is corroborated by recent Microwave Limb Sounder (MLS) water vapor far-infrared brightness [Pumphrey and Harwood, 1997] global measurements. Even more recently, Huaman [1998] has compared water vapor mixing ratios in the two hemispheres using Halogen Occultation Experiment (HALOE) and MLS satellite data and found differences of only ~ 1 ppmv at PMSE altitudes. This difference is of the order of 20% of the measured levels of ~ 5 ppmv (with the Northern Hemisphere being drier).

The importance of water vapor in explaining the interhemispheric asymmetry of PMSE can be reduced even more if we consider its relatively weak effect on condensation in contrast to possible differences in mesosphere temperature. According to the ionized ice aerosol hypothesis we have assumed, the existence of PMSE depends primarily on proper temperature and water vapor conditions. Specifically, the water vapor partial pressure must exceed the saturation pressure (supersaturation) by some reasonable threshold. Temperature is the more crucial of these two parameters, since the supersaturation ratio depends only linearly on partial pressure but depends exponentially on temperature [Reid, 1975; Gadsden, 1981]. To illustrate this point, for a supersaturation ratio of 1 and a mixing ratio of 1 ppmv, one can show that the freezing point temperature is decreased by only 2.7% for a 200% increase in mixing ratio (1 to 3 ppmv). Thus we conclude that temperature is the most likely major contributor to the north-south asymmetry in PMSE intensities.

One could argue, based on the findings of Hansen and von Zahn [1994], that there is a direct effect of the interhemispheric asymmetry in the meridional winds in the asymmetry of the PMSE intensity. The referred authors find a lack of correlation between the local

mesopause temperature and the occurrence of NLCs. They postulate that, given the large equatorward summertime mesospheric winds and the relatively long time it takes the ice particles to grow and sediment to NLC altitudes, what matters is the temperature at the nucleation altitudes (~ 88 km) several hundred kilometers north of where the NLCs are observed. A difference in the meridional winds therefore would advect NLCs to lower latitudes in the Northern Hemisphere than in the Southern Hemisphere. Although this is a plausible mechanism for NLC, we do not believe it plays a similar direct role in the generation (advection) of PMSE, the main difference being the ice particle sizes and growth times involved in both phenomena. We should recall that the maximum occurrence and maximum power of PMSE occur very close to the mesopause (~ 87 km), i.e., the coldest altitude, the reason being that very soon after the ice particles are nucleated, they already would have a large enough size to alter their diffusivity and hence their corresponding Schmidt number [Ulwick *et al.*, 1988]. PMSEs, then, are more sensitive to the local temperature conditions. NLC ice particles, on the other hand, need to obtain larger sizes to become visible and are advected farther away from their nucleation region.

Nevertheless, the north-south asymmetry in meridional winds does exist. We have taken care of its indirect effects through its consequences in the mesopause temperature. The asymmetry in the meridional winds is one of the reasons, besides the different adiabatic cooling produced by different vertical velocities, for the asymmetry in mesopause temperatures, which we claim is responsible for the difference in PMSE occurrence and strength. The temperature of the mesopause can be taken, then, in addition to its own significance, as a proxy of the asymmetric meridional circulation. Moreover, it can be taken as a proxy of the gravity wave activity, including the breaking of the waves into turbulence, all of which are necessary for the temperature to be lower than the value it would have under radiative equilibrium conditions. The turbulent breakdown is necessary for the gravity wave momentum to be deposited and drive the circulation.

4.5. A Quantitative Estimation of the Interhemispheric Temperature Asymmetry

Is it possible that the temperature difference of ~ 7 K obtained from the empirical MSISE-90 model can explain the large PMSE intensity differences in the two hemispheres? We believe that the answer is affirmative. In fact, we can independently estimate what the temperature difference should be, based on the power levels of the Machu Picchu station. To accomplish this, we will use Poker Flat PMSE power levels to empirically "calibrate" radar power as a function of mesospheric temperature based on the seasonal temperature variations at this location derived from the MSISE-90 model [Hedin, 1991]. Note that this approach is similar

to that taken by *Hall* [1995] to estimate the regions in space and time where PMSEs should be observed. He uses the temperature for week 20 at 69°N as a calibration point, based on the onset of PMSE at the European Incoherent Scatter (EISCAT) VHF radar.

We are, in a way, assuming that the temporal variations in PMSE strength as a function of season at Poker Flat are due to the variations of mesopause temperature, both through its direct effect on the formation of the necessary ice nuclei and as a proxy of the intensity of the meridional circulation, gravity wave, and turbulence that made it vary. Moreover, of all possible points in this empirical relationship, we will use only one (actually, two redundant ones), in which we can have more confidence for the reasons explained below.

The maximum power as a function of time of the year at Poker Flat is depicted in Figure 4. The MSISE-90 model gives us a functional relationship between the mesopause temperature and the time of the year. Both functions parametrically define an empirical relationship between PMSE maximum power and the corresponding temperature using time as the common parameter. Here we are assuming that the same relationship for the two original functions repeat, within their typical standard deviation, every year. This is implicitly the case for the MSISE-90 model since it has been derived from many years' observations. The year-to-year consistency of the Poker Flat PMSE temporal behavior is discussed by *Balsley and Huaman* [1997].

Of all possible points in the derived power versus temperature function, we are interested in only one, that corresponding to the maximum power level (28 dB) observed at Machu Picchu on the week of January 13. From Figure 4, we note that there are two times during which Poker Flat shows powers comparable to the maximum observed at Machu Picchu, one at the beginning and the other at the end of the Poker Flat PMSE season. Fortunately, these two points fall at the lowest levels of the two very fast and drastic transitions in power level. The fast transition allows for a very accurate determination of the time of occurrence and hence of the corresponding (hopefully the same) temperature.

Note in passing that the transitions involve a very drastic drop in the derived power versus temperature function. The large change in magnitude, close to 3 orders of magnitude (~ 25 dB), can be taken as almost a yes/no transition for the occurrence of PMSEs. It is reasonable to assume that this drastic transition is due to a change in phase in the average state of water, from vapor to ice, and should correspond to a critical saturation temperature. This gives us additional confidence in the role of temperature as compared to other state parameters, at least during these critical times. It is difficult to find any other state parameter that would produce such a large jump in power in such a short time.

Examination of Figure 4 shows that the dates when Poker Flat goes through 28 dB, the maximum power level observed at Machu Picchu on the week of January

13, are approximately May 25 and August 17. According to the MSISE-90 empirical model, the Poker Flat mesospheric temperatures for these dates are 143 and 153 K, respectively. Here we have taken the lowest diurnal value given by the model, taking into account that there is a diurnal and semidiurnal tide with fluctuations of ± 2 K, according to the same model.

Note that we have already encountered a difficulty, since according to our assumptions, these two temperatures should be equal. They differ instead by 10 K. This is a large difference. We next consider two possibilities that could explain this discrepancy, namely, (1) year to year deviations of actual temperature values as compared with the model average behavior or (2) possible temporal variations in other mesospheric state parameters.

The discrepancy between the two temperatures at the transitions can be reduced considerably if we allow the phase of the annual temperature curve to vary from year to year by ~ 8 days. An 8-day shift, necessary to make both transitions occur at the same temperature, results in a transition temperature of 147.5 K. Note that it is not necessary to shift the model but, rather, the actual temperature behavior for 1984, when the statistics shown in Figure 4 were obtained. By way of justification, it is important to remember that the MSISE-90 model results from many years of observations. An 8-day shift in the actual values for any particular year is certainly within the residual values quoted for the model [*Hedin*, 1991]. We should compare 147.5 K, the estimated temperature at Machu Picchu from comparable power levels at Poker Flat, with the actual temperature at Poker Flat, 137 K, on July 13 (January 13 at Machu Picchu), i.e., the date of the actual observations being compared. The difference is 10.5 K.

The above relatively weak argument is supported by the very recent falling-sphere 10-year-averaged temperature statistics obtained by *Lübken* [1999] in the Arctic. These are in much better agreement with the expectation of equal temperature at the time of the PMSE power level transitions at Poker Flat. According to these measurements, the mesopause temperatures for May 25 and August 17 are 139 K and 141 K respectively, only 1 K different from a 140 K average. The temperature difference between this 140 K value and the temperature corresponding to July 13 (January 13 at Machu Picchu) is 10.7 K, in good agreement with the 10.5 K value obtained above using the MSISE-90. Although these rocket measurements were made around 70°N, we do not expect much difference between the above relative value and one taken a few degrees south.

For the second possibility mentioned above, we can relax our implicit assumptions regarding the constancy of the other state parameters during the 2 days used for this calibration and discuss their possible effects. Except for water vapor, a change in any of the other state parameters will have the effect of increasing or decreasing the echo power levels by some amount, but,

given the steepness of the transition lines at the edge of the PMSE season, changes in any of the other parameters would have very little effect on the dates used for the calibration and hence on the corresponding transition temperature. Water vapor mixing ratio, on the other hand, does indeed have a direct effect on the freezing temperature. In fact, *Balsley and Huaman* [1997] have postulated a possible difference in water vapor mixing ratio to explain a shift in PMSE occurrence statistics relative to seasonal mesospheric temperature data. However, as discussed above, an order of magnitude difference in mixing ratio is required to compensate for a 10 K temperature difference. Such differences are not supported by the theoretical models [e.g. *Garcia*, 1989; *Thomas*, 1996b], nor by the most recent satellite [*Pumphrey and Harwood*, 1997; *Huaman*, 1998] or ground based observations [*Kirkwood et al.*, 1998]. In fact, both theoretically and experimentally obtained water vapor values show comparable values at the times of the sharp PMSE season transition.

To summarize our discussion, the above reasoning leads us to a deduced temperature value of ~ 147.5 K for the mesopause temperature over the Machu Picchu radar in mid-January. This value should be compared with 137 K obtained from the MSISE-90 model for Poker Flat during mid-July. The difference is 10.5 K. Thus mesopause temperatures at roughly midseason over Poker Flat and Machu Picchu could differ by 10.5 K, with the Southern Hemisphere being warmer.

It should be stressed that the temperature difference of 10.5 K estimated above should be fairly independent of the absolute accuracy of the temperatures quoted, since they have been either measured with the same technique or obtained from the same model. Any bias in the absolute value would be eliminated when differences are evaluated.

There are two corrections to this estimate that need to be taken into account. The first correction arises from measured interhemispheric differences in gravity wave activity and considers differences in "instantaneous" temperatures [*Reid*, 1975]. The other relates to temperature differences due to the different latitudes of the two radar sites.

To account for the gravity wave differences, we shall use the 50% value in gravity wave velocity variance from *Vincent* [1994] to evaluate the temperature differences arising from gravity wave activity in the two hemispheres. For this variance ratio, the gravity wave amplitudes in the Southern Hemisphere would be only 70% of the equivalent amplitudes in the north. This difference would, in turn, produce temperature fluctuations of only 70% of those in the north. If we now attribute the (approximately) 5 K temperature fluctuations observed in typical rocket-measured temperature profiles to gravity waves [e.g., *Lübken et al.*, 1996], corresponding fluctuations in the Southern Hemisphere would yield only a 3.5 K fluctuations, i.e., 1.5 K less than in the north. Since water vapor freezing depends

on the minimum fluctuation temperature, the difference in the mean temperature between the two stations must be reduced from 10.5 K to 9 K.

The above correction assumes ice particle growth times comparable to half the period of the gravity wave. It could be overestimated (and the asymmetry underestimated) if a gravity wave hysteresis effect postulated by *Turco et al.* [1982] actually takes place. The hysteresis comes about because the evaporation of the ice particles in the positive temperature excursion is faster than its growth during its negative fluctuation. It is difficult to assess how important this mechanism is, since the authors model an unrealistically large wave amplitude of close to ± 25 K and do not consider the exponential increase of the fluctuating wave parameters with altitude. The latter would favor instead the negative over the positive temperature excursions. The effect should, in any case, be even smaller for the smaller ice particles (faster growth time) required for PMSEs than for the larger NLC particles considered by the authors.

Regarding the second correction, according to the MSISE-90 model, the temperature difference between 65°N and 62°N is 1.5 K, with the higher latitudes being colder. Taking both corrections into account, we deduce an average temperature difference between two comparable latitudes in both hemispheres to be close to 7.5 K.

5. Concluding Remarks

We have shown that the large interhemispheric asymmetry in PMSE power cannot be easily accounted for by either longitudinal or latitudinal differences of the two radars used in this comparison. We attribute the asymmetry to mesopause temperature differences between the two sites. We, furthermore, estimate this difference between sites to be ~ 9 K. Taking into account the 1.5 latitudinal difference of the two sites, this suggests a difference of ~ 7.5 K for radars at the same latitude (around 62°) in the two hemispheres.

Several assumptions had to be made to arrive at this figure as a consequence of our insufficient knowledge of the physical processes responsible for the large enhancement in the received signal power during PMSE conditions. The most important assumption is that VHF PMSEs require the presence of ionized ice aerosols as a necessary condition for the formation of the meter-scale fluctuations in electron density responsible for the scattering. The strong temperature sensitivity of ice formation allowed us to minimize (although not exclude) the importance of the possible differences that could be due to other mesosphere state parameters, including water vapor mixing ratio. This minimizing was further justified by the sharp and large transition in echo power actually observed at the beginning and end of the Poker Flat PMSE season.

Our deduced temperature difference is acceptable from both an experimental and a theoretical atmo-

spheric dynamics point of view. It agrees, within expected errors, with the MSISE-90 empirical temperature model and with recent (see below) satellite mesospheric temperature measurements. It is also consistent with theoretical expectations based on interhemispheric asymmetries in circulation due to differences in gravity wave activity.

We are now even more reassured of the plausibility of our temperature asymmetry estimate after the recent findings reported by *Huaman and Balsley* [1999]. After the initial submission of this paper, *Huaman and Balsley* [1999] examined and published mesospheric temperatures obtained by satellite remote sensing techniques. Using the High Resolution Doppler Imager (HRDI) data from the Upper Atmosphere Research Satellite, they find interhemispheric temperature differences as high as 15 ± 3 K at the times of the summer peak PMSE activities and about 10 ± 3 K at around the middle of July (January in the Southern Hemisphere), i.e., during the main period discussed here.

In spite of the above arguments, considering the speculative nature of many of them and the scarcity of direct temperature measurements in Antarctic latitudes, a direct temperature measurement at these latitudes, under the control of simultaneous PMSE observations, seems clearly necessary to resolve these issues. A series of summer temperature measurements taken with the falling-sphere rocket technique have recently been carried out (F.J. Lübken, personal communication, 1998) at Rothera, Antarctic ($67^{\circ}55'W$, $67^{\circ}30'S$). We are looking forward to the results of these measurements. We also hope that our findings and discussion will encourage temperature measurements using optical ground-based remote mesospheric sensing techniques, like lasers and OH emissions, to be deployed in summer at critical latitudes in the Antarctic.

Finally, in view of the large difference in PMSE strength for apparently small differences in mesopause temperature, it is reasonable to examine the following possibility: A fairly simple VHF radar operating at reasonably high latitudes during local summer periods could serve as a very sensitive tool for long-term monitoring of mesopause temperature changes. Such a radar would provide an excellent and inexpensive tool for monitoring mesopause temperatures changes over decadal timescales, regardless of whether these changes arise from anthropogenic or natural causes. If we include the idea that mesospheric temperatures are more sensitive to change than tropospheric temperatures [Thomas, 1996a], it becomes obvious that PMSE radars could provide us with a powerful tool for monitoring global change.

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