JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 96, NO. A1, PAGES 275–284, JANUARY 1, 1991

The Longitudinal Dependence of Whistler and Chorus Characteristics Observed on the Ground Near $L = 4$

A. J. SMITH,[1] D. L. CARPENTER,[2] Y. CORCUFF,[3]
J. P. S. RASH,[4] AND E. A. BERING[5]

Whistler activity at $L \simeq 4$ is known to be a function of longitude, peaking in the Weddell Sea sector of Antarctica; a combination of source and propagation factors, the latter possibly partly associated with the South Atlantic geomagnetic anomaly, is believed to be responsible. There is evidence, for example from satellite surveys, that chorus and hiss activity may also be longitude dependent. To investigate this further, we have compared VLF data from four $L \simeq 4$ Antarctic stations from a 2-day period in June 1982. Siple, Halley, and Sanae form a closely spaced ($\sim 20°$–$0°$ geomagnetic longitude) triplet, while Kerguelen is $\sim 120°$ (geomagnetic) to the east, on the opposite side of the anomaly. To a large extent there was a repeatable diurnal variation in activity at all stations on the two days. Events observed at Siple tended to be similar to those observed ~ 9 hours earlier (the same MLT) at Kerguelen on the same day. There was a very marked drop-off in both whistler and VLF emission activity between Siple and Halley on the one hand and Sanae on the other. The reason for this is not clear; it may be either a source effect such as the lower occurrence of lightning over eastern North America compared to the adjacent Atlantic Ocean, or else a wave-particle interaction effect whereby the conditions for wave growth or amplification are more favorable, or substorm particle injections penetrate the magnetosphere more deeply, at the longitude of Siple than further east. Comparison of the spectral forms of whistler mode activity at neighboring stations suggests that wave generation occurs simultaneously over relatively wide longitude (or local time) sectors ($\gtrsim 30°$ or 2 hours). Individual interaction regions are smaller than this, $\lesssim 5°$ in longitude, comparable with the previously inferred sizes of whistler ducts. Data sets with longer time coverage and better spatial resolution are required to answer some of the problems raised by this limited study.

1. INTRODUCTION

Wave-particle interactions between whistler mode waves and energetic electrons are well established as playing a significant role in the distribution of particle and wave energy in the magnetosphere. In particular, the cyclotron resonance interaction is believed to be responsible for the generation of ELF and VLF radio waves such as chorus and hiss, and for the amplification of others such as lightning-generated whistlers. Accompanying changes in the particle distribution function, for example through pitch angle diffusion, may result in the precipitation of energetic particles into the upper atmosphere. The morphology of VLF wave activity in the magnetosphere can be largely understood in terms of the availability of resonant particle fluxes, which depends primarily on local time, L shell, and geomagnetic disturbance level; dependence on longitude might be expected to be of secondary importance. Nevertheless, satellite surveys have shown that there is a longitudinal dependence, and the purpose of this paper is to investigate this further experimentally, using data from ground stations in the Antarctic near $L = 4$.

There has been considerable treatment in the literature of longitudinal variations in particle precipitation due to the South Atlantic geomagnetic anomaly [*Torr et al.*, 1975; *Vampola and Gorney*, 1983] and due to the influence of high-power VLF transmitters [*Vampola and Kuck*, 1978]. More recently, *Rosenberg and Dudeney* [1986] and *Bering et al.* [1988] have reported longitudinal asymmetries at $L \simeq 4$ in average cosmic noise absorption and the occurrence of X ray microbursts, respectively.

Less attention has been paid to any longitudinal dependence in VLF wave activity. *Bullough and Kaiser* [1979] found that VLF emissions at 3.2 kHz, received at about 500 km altitude by the polar-orbiting satellite Ariel 4, were more common over North America and its conjugate region than over other regions at the same latitude. This was ascribed by the authors to the catalytic effect on wave generation of power line harmonic radiation from the industrialized United States. Similar results were obtained by *Luette et al.* [1977] using the OGO 3 satellite.

In this paper we discuss the similarities and differences in ELF and VLF whistler mode waves — chorus, hiss, and whistlers — received at a chain of Antarctic ground stations which are at almost the same geomagnetic latitude ($L \simeq 4$) but at different longitudes. This approach is complementary to the satellite surveys in that there is no convolution of longitude with UT and LT inherent in a satellite orbit, and furthermore ground data are usually available for long periods in high-speed (broadband) form, which aids classification of the waves received. It is of interest to investigate the extent to which longitudinal asymmetries in wave sources (e.g., lightning) and in wave amplification efficien-

[1]British Antarctic Survey, Natural Environment Research Council, Cambridge, United Kingdom.
[2]Space, Telecommunications and Radioscience Laboratory, Stanford University, Stanford, California.
[3]Laboratoire de Physique de la Haute Atmosphère, Université de Poitiers, Saint Julien l'Ars, France.
[4]Department of Physics, University of Natal, Durban, South Africa.
[5]Physics Department, University of Houston, Houston, Texas.

Paper number 90JA01077.
0148-0227/91/90JA-01077$05.00

cies (due, for example, to the South Atlantic anomaly) give rise to an asymmetrical wave distribution.

To date, there has been no systematic attempt to study the dependence of ground-observed VLF activity on longitude. This is largely due to the sparseness of suitable observing stations, and the difficulty of making data comparisons which is associated with the diverse receiving, recording, and analysis equipments in use at different sites. Early work from International Geophysical Year (IGY) whistler networks [*Helliwell*, 1965; *Laaspere et al.*, 1964] concentrated on latitudinal, diurnal, seasonal, and disturbance-related dependences. (Even these studies were heavily biased toward observations in the American longitude sector.) However, *Woods et al.* [1979] have reported a systematically lower occurrence of knee whistlers (whistlers propagating near the knee in electron density, i.e., the plasmapause [*Carpenter*, 1963]) at Sanae compared to Siple, Antarctica. Furthermore, subjective comparisons of the chorus and hiss data from these two stations have suggested that VLF wave activity in general is significantly greater at the more westerly of the two (Siple). This is one of the topics discussed in the present paper.

The work reported here arose out of a Scientific Committee on Antarctic Research (SCAR) data analysis workshop (see acknowledgments), in which many geophysical data were assembled, from a variety of sensors and from many participating Antarctic ground observatories and orbiting spacecraft, for 7 days of special interest (June 10–13 and 27–29) in 1982. The scientific aims of the workshop were defined in terms of six topics to be addressed using the available data set, one of which was the subject of the present work. Originally it was planned to carry out a comprehensive analysis involving quantitative measurements on whistler and noise intensities for all the available VLF ground data. However, in interests of timely publication, coincident with the other papers from the workshop, we here offer a more preliminary study restricted to a selection of data from just two days and four stations, but which nevertheless illustrates some important features and raises questions which it is hoped will be addressed more fully in a later paper.

2. Data Description

In this paper we have used broadband VLF data, recorded on analogue magnetic tape, from four Antarctic ground stations near $L = 4$: Siple, Halley, Sanae, and Kerguelen. The locations of these stations are shown in Figure 1 and their coordinates in Table 1. Although small in number, the stations are well situated for the purposes at hand; the first three — Siple, Halley, and Sanae — form a triplet spaced 1–2 hours apart in magnetic local time (15°–30° apart in magnetic longitude), comparable with the longitudinal extent of the typical "viewing window" of a ground VLF receiver. They are thus well placed for studying relatively small scale longitudinal/local time variations. The fourth station, Kerguelen, being ~ 140° (magnetic) east of Siple provides a more global perspective.

While no two of the four receivers were identical (for example, the Halley receiver alone was of the goniometer type), they were sufficiently similar that their outputs could be used satisfactorily in the qualitative study presented here. In the proposed more quantitative comparison of received wave intensities, it will be necessary to compensate carefully for the different receiver characteristics.

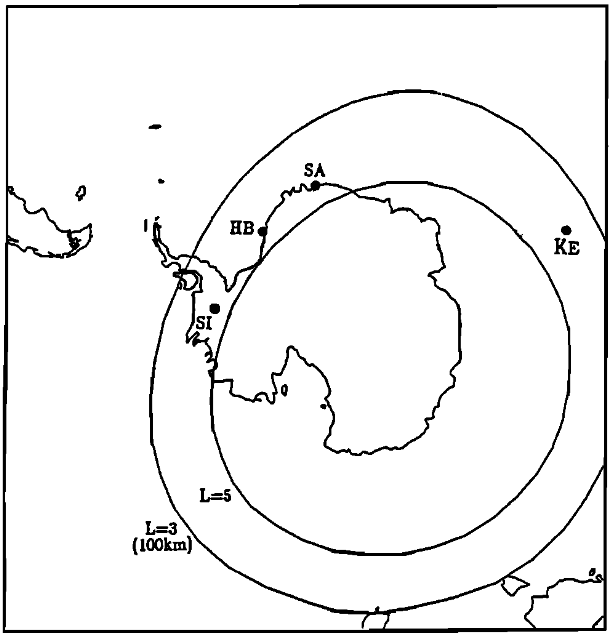

Fig. 1. Map showing the locations in Antarctica of the $L \simeq 4$ ELF/VLF ground receivers used in the study: Siple (SI), Halley (HB), Sanae (SA), and Kerguelen (KE). The $L = 3$ and $L = 5$ contours at 100 km altitude are shown.

Out of the seven days selected for the SCAR data analysis workshop, two, namely June 28–29, 1982, were selected for the wave activity study. Compared to the other five days, there was better data coverage from the four participating stations, and more intense and varied VLF activity observed on these two days. Geomagnetic conditions were moderately disturbed ($Kp \sim 3 - 5$) throughout.

Most of the data were recorded on a synoptic one minute in five sampling basis. All the available data were examined in spectrographic form. Illustrative examples are given in the next section.

3. Observations

Overall Features

In a study such as this, one might expect the predominant effect to be the ordering of particular VLF phenomena by local time. In fact this is confirmed, but the compared data also show some pronounced longitude effects and provide details about the spatial extent of wave activity that may have geophysical importance. In the paper, emphasis is upon the longitude and spatial effects. We find similar

TABLE 1. Coordinates of the Four Antarctic Stations Providing VLF Data Used in This Paper

Station	Latitude	Longitude	L	MLT
Siple	75.9°S	84.3°W	4.3	~UT − 5
Halley	75.5°S	26.9°W	4.3	~UT − 3
Sanae	70.3°S	2.4°W	4.1	~UT − 1.5
Kerguelen	49.4°S	70.2°E	3.7	~UT + 4

VLF activity at the same local time, such as quasi-periodic (QP) emissions, chorus, or banded hiss fed from echoing whistlers. Kerguelen is found to be spectrally independent of the more closely spaced trio of Siple, Halley, and Sanae. Spheric levels show clear evidence of attenuation over ice but also worldwide contributions.

The most striking longitude effect is the difference in observed levels of activity: high at Siple and Halley, low at Sanae, and intermediate at Kerguelen. The latter station shows substantial whistler activity on both sides of the plasmapause, but there may be a tendency to less triggering by whistlers and higher densities in the plasma trough. We now illustrate these features in more detail by reference to spectrograms of selected events of various types of VLF activity at the four stations.

Whistlers and Whistler-Triggered Emissions

In Figure 2*a* we show 0–10 kHz spectrograms of the VLF waves received simultaneously during a 9-s interval on June 28, 1982. Siple, Halley, and Sanae were in the morning sector; Kerguelen was in the afternoon sector.

A knee whistler was observed at ~ 1115:15.5 UT at Siple. The whistler triggered chorus-type noise in an upper band at ~5 kHz and also intensified a preexisting band at ~3 kHz. The triggered or intensified noise was stronger than the whistler trace itself, and this is typical of such events observed at Siple during the morning hours.

At Halley, a similar event was seen, although triggering only occurred here in the upper band near 4 kHz. In this case the whistler trace is barely discernable on the record.

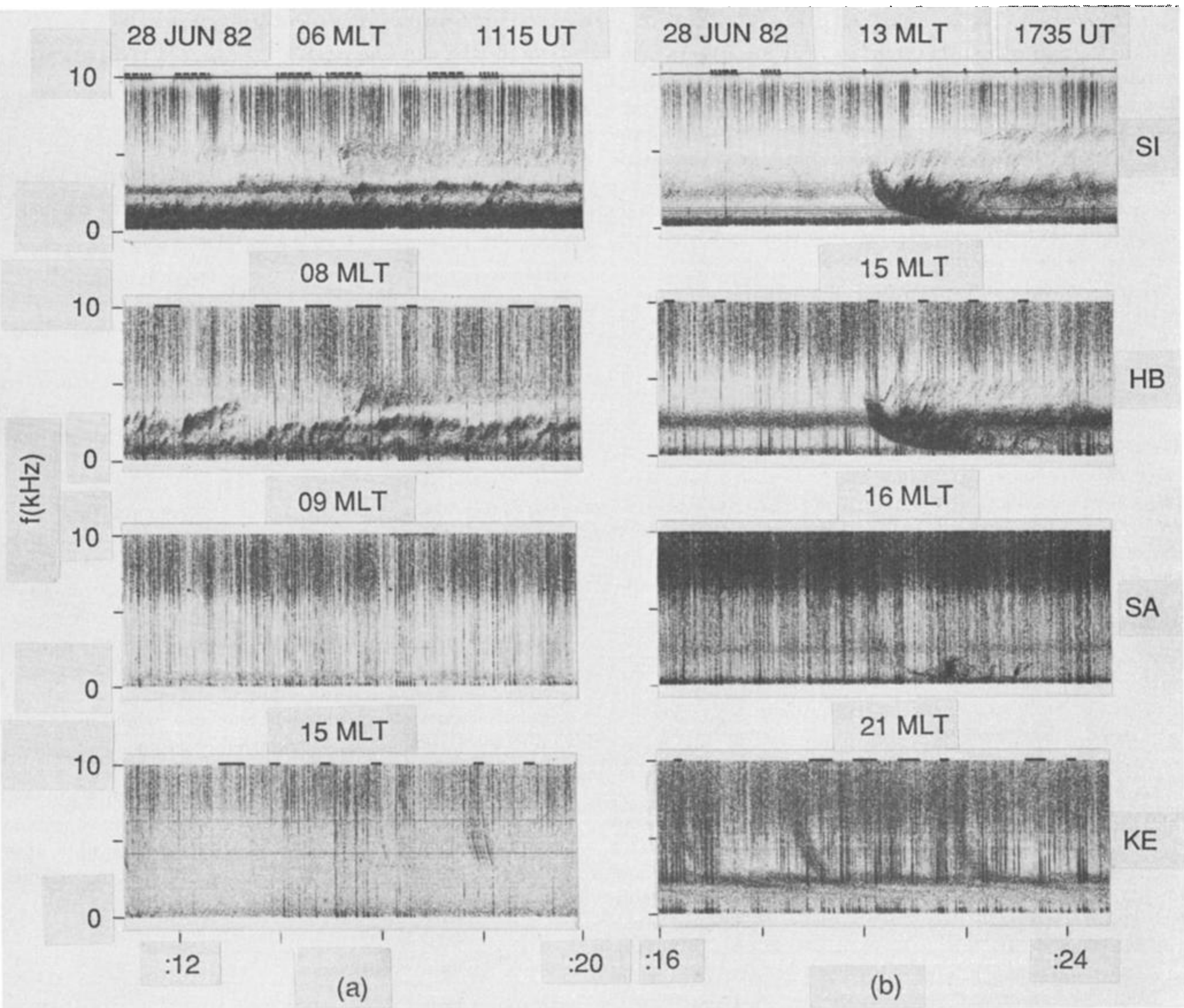

Fig. 2. (*a*) Stacked 0–10 kHz spectrograms for the four stations, in order of increasing east longitude, for a 9-s-long interval beginning 1115:11 UT on June 28, 1982. The approximate magnetic local time at each station is shown above the center of the spectrogram. A faint knee whistler, which triggered bursts of chorus, was recorded at about 1115:15 UT at both Siple and Halley. See the text for further discussion. (*b*) A similar plot to Figure 2*a* but beginning at 1735:16 UT on June 28, 1982. A knee whistler with triggering, though different in character from that of Figure 2*a*, was recorded near 1735:20 UT at Siple, Halley, and Sanae, while the whistlers seen at Kerguelen were predominantly plasmaspheric.

The coincidence of the Siple and Halley whistlers means that they originated from the same source, and the similar general appearance of the noise triggering implies that similar conditions, favorable for knee whistler propagation and triggering, existed near the meridians of the two stations. However, the fine structure of the triggered noise is different in the two cases, implying that two different and fairly localized whistler paths and wave-particle interaction regions were involved.

At Sanae, neither whistler nor triggered noise was observed. At Kerguelen the activity was of an entirely different character, as might be expected from the considerable separation between it and the other stations. Whistlers were observed there but they were plasmaspheric, i.e., propagating along field-aligned paths within the plasmasphere. Neither chorus nor hiss was observed at this time.

Figure 2*b* illustrates another knee whistler event some 6 hours later, when Siple, Halley, and Sanae had moved into the afternoon sector. In contrast to the morning event, the whistler itself is much more prominent (again typical of such events at this time of day), and both it and the triggered noise are similar in details of fine structure at Siple and Halley. This suggests that in this case there was a common whistler path and triggering region, probably located between the meridians of the two stations, or perhaps elongated in longitude. The event was associated with overhead burst precipitation at Siple, as indicated by correlated changes in the VLF, riometer, photometer, and wave magnetometer (pulsation indicator) data.

It is interesting to compare the Halley data in Figure 2*b* with those from Kerguelen in Figure 2*a* recorded on the same day at the same MLT. The activity is quite different: plasmaspheric whistlers at Kerguelen; knee whistlers and triggered chorus at Halley. This effect is quite commonly seen, but rarely the reverse. It might be possible to ascribe the effect to a change in magnetospheric conditions in the intervening 6 hours, or the fact that Kerguelen, lying 0.6 L further equatorward, is more likely than Halley to be inside the plasmasphere. However, it does seem that there is a real underlying difference between the Siple/Halley and the Kerguelen longitudes, which makes the former more favorable for the propagation of knee whistlers, and for the triggering of chorus bursts. In contrast, Figure 4*a* shows a case from the following day, June 29, 1982, in which similar knee whistlers that triggered choruslike bursts of noise were observed at Siple and Kerguelen at approximately the same local time.

As in the morning event, there was very little activity at Sanae relative to Halley and Siple. In this case, however, we do observe the lowest- frequency portion of the whistler and a short triggered riser, signals which appear to be weaker versions of the most intense part of the event as observed further west. This would be consistent with the source being located intermediate in longitude between Halley and Siple, and the signals traveling to Sanae from that meridian under the ionosphere — a path which at $L \sim 4.3$ is partly over the Antarctic ice sheet and therefore subject to strong attenuation [*Crary and Crombie*, 1972]. A faint hiss band near 2.5 kHz is similar to a much more intense band observed simultaneously at Halley.

The weakness or absence of both knee whistlers and chorus at Sanae relative to the other stations, particularly Halley and Siple just to the west, is a striking and persistent feature of the present 2-day data set, and will be discussed in more detail later. It is important to establish that it is a real effect and not an artefact of the Sanae receiver, for example due to poor signal-noise ratio compared to the other receivers. The arguments against this possibility are that (1) the response of the Sanae receiver to the spheric background is similar to that of the Halley receiver; (2) the weak signals at Sanae are usually, as in Figure 2*b*, weak versions of what is observed at Halley; however, there are rare exceptions to this, when strong waves which are different from those at Halley are received at Sanae (this would not occur if the receiver response was to blame); and (3) as regards knee whistlers, the effect has already been noted independently by *Woods et al.* [1979].

At Kerguelen, the principal whistler activity was again primarily plasmaspheric, with echoing present. A noise band at ~3 kHz appears to result from the merging of high-order hop whistler echoes. This is not an uncommon occurrence at this local time.

Banded Hiss and Chorus

In Figure 3*a* we illustrate the variety of banded VLF emissions observed simultaneously at the stations. At Siple and Halley there were two bands of chorus, centered near 1 kHz and 2 kHz. The bands are of similar general form at the two stations, although different in detail, as was the case for the triggered burst in Figure 2*a*. It is inferred that the longitudinal spread of the chorus from a given source region, by virtue either of the spatial extent of the source region or by propagation, is small relative to the longitudinal separation of the stations ($\sim 30^\circ$ magnetic), but that conditions favorable for the generation of bands at these frequencies exist over a longitude range at least of this order. The bands are not dissimilar to those present 3 hours earlier (Figure 2*a*) from which they have evolved. There does seem to be a tendency for noise at the lowest frequencies (< 1 kHz) to be more intense at Siple than at Halley.

Uniquely, Halley observed a higher-frequency noise band at about 6 kHz. This is of the type often observed to be triggered by knee whistlers with an associated sudden intensification and spectral broadening [*Carpenter*, 1978; *Smith et al.*, 1985].

At Sanae, no trace of any of the bands could be discerned, as was the case for the 1115 UT event. Again at Kerguelen, the activity was of a quite different nature: a mixture of echoing plasmaspheric whistlers and knee whistlers but no appreciable hiss, chorus, or triggered emissions.

Figure 3*b* shows data taken about 24 hours later and illustrates day to day variability. In contrast to Figure 3*a* there was a single VLF noise band at ~1.5 kHz, of a more unstructured (hiss) type. The band was seen at Siple, Halley, and, much more weakly, at Sanae. Again, the activity at Kerguelen was quite different.

Quasi-Periodic Emissions

During steady conditions it would be expected that, in many cases, stations at the same L shell and different longitudes would observe similar types of VLF activity at the same local time on the same day. In particular, Siple should observe similar phenomena about 9 hours after Kerguelen. Figure 4 shows two examples. In Figure 4*a*, similar knee whistlers with triggered noise were observed at the same

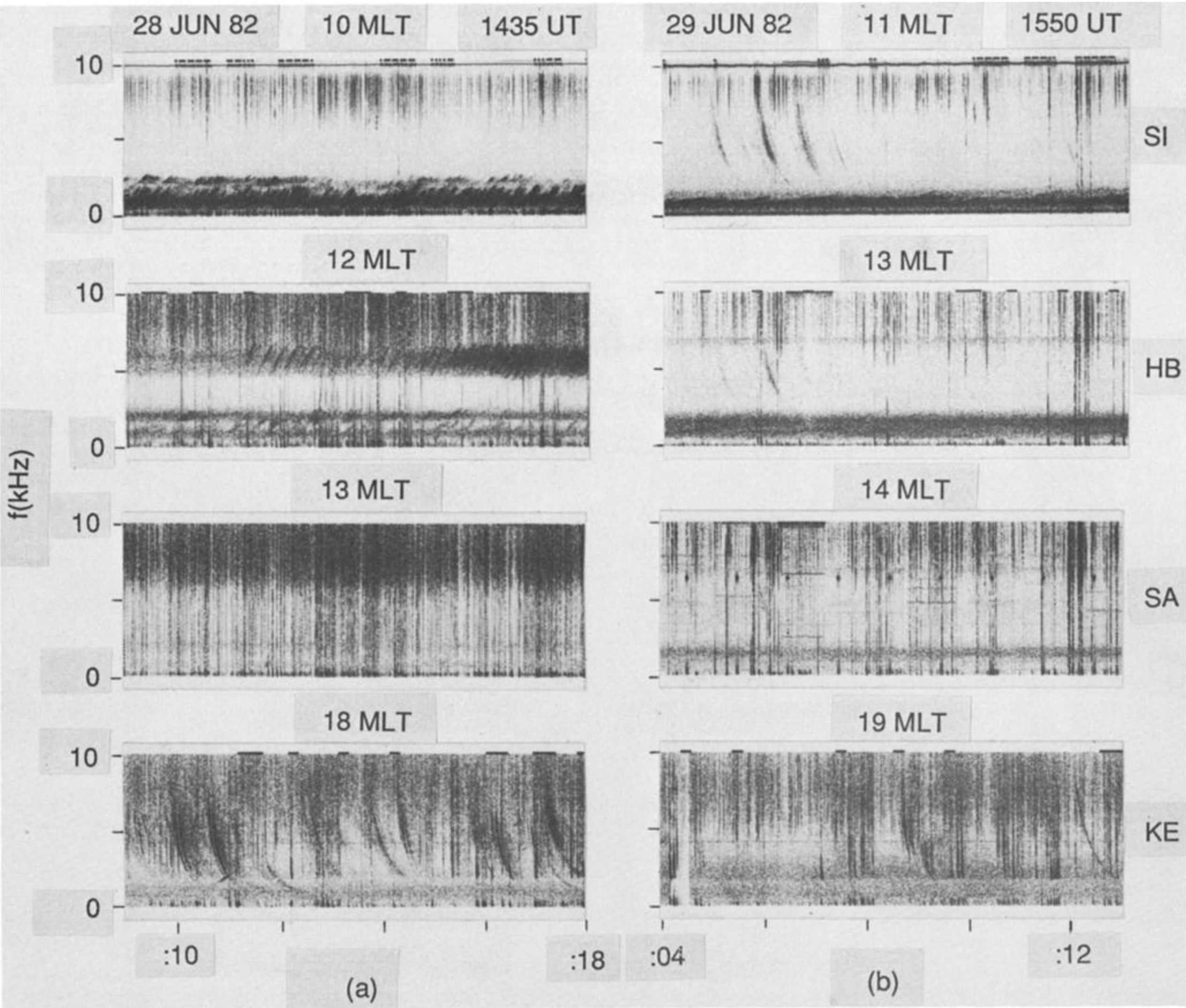

Fig. 3. Stacked spectrograms, in a similar format to Figure 2, for the intervals beginning 1435:09 UT on June 28, 1982, and 1550:04 UT on June 29, 1982. (*a*) The VLF activity was markedly different at the four stations. (*b*) The three closely spaced stations — Siple, Halley, and Sanae — observed similar hiss bands and whistlers.

MLT. The chorus and spheric backgrounds were, however, markedly different.

In Figure 4*b*, quasi-periodic emissions (QPs) were observed at Kerguelen and 9 hours later at Siple. QPs were observed several times during the June 1982 SCAR Special Interest period examined, and usually occurred in the prenoon sector, typically lasting for 2–3 hours.

Spherics

Although we are here principally concerned with VLF whistler mode waves, it is nevertheless of interest to discuss briefly the spheric noise received from distant thunderstorms (local thunderstorms are extremely rare in Antarctica), because it undergoes the same subionospheric propagation as do whistlers after they have emerged from the ionosphere. This propagation must be taken into account in properly interpreting the observations of whistler mode waves at spaced ground stations.

At Siple, Halley, and Sanae the spheric background is invariably similar, with an attenuation band below ~6 kHz [*Barr*, 1970]; at Kerguelen, e.g., in Figure 2*b*, a further deep attenuation band below ~1.7 kHz and the presence of "tweeks" [*Helliwell*, 1965] are a consequence of the nighttime conditions then prevailing at the more easterly station. Spheric noise may be somewhat less intense at Siple compared to the other, coastal stations, due to attenuation over the Antarctic ice sheet (see, for example, Figure 3*a*). At the same UT, essentially the same patterns of spherics are generally observed at Siple, Halley, Sanae [cf. *Smith and Carpenter*, 1982], and to a lesser extent Kerguelen (see, for example, the group of five closely and almost equally spaced elements at 1115:16.5 UT in Figure 2*a*), confirming the global nature of thunderstorm-generated VLF noise. Figure 3 shows a marked difference in spheric background at the same UT on two successive days, which is particularly marked at Sanae.

4. DISCUSSION

The four ground stations are all near $L = 4$ and may be considered mid-latitude. At this latitude (invariant geo-

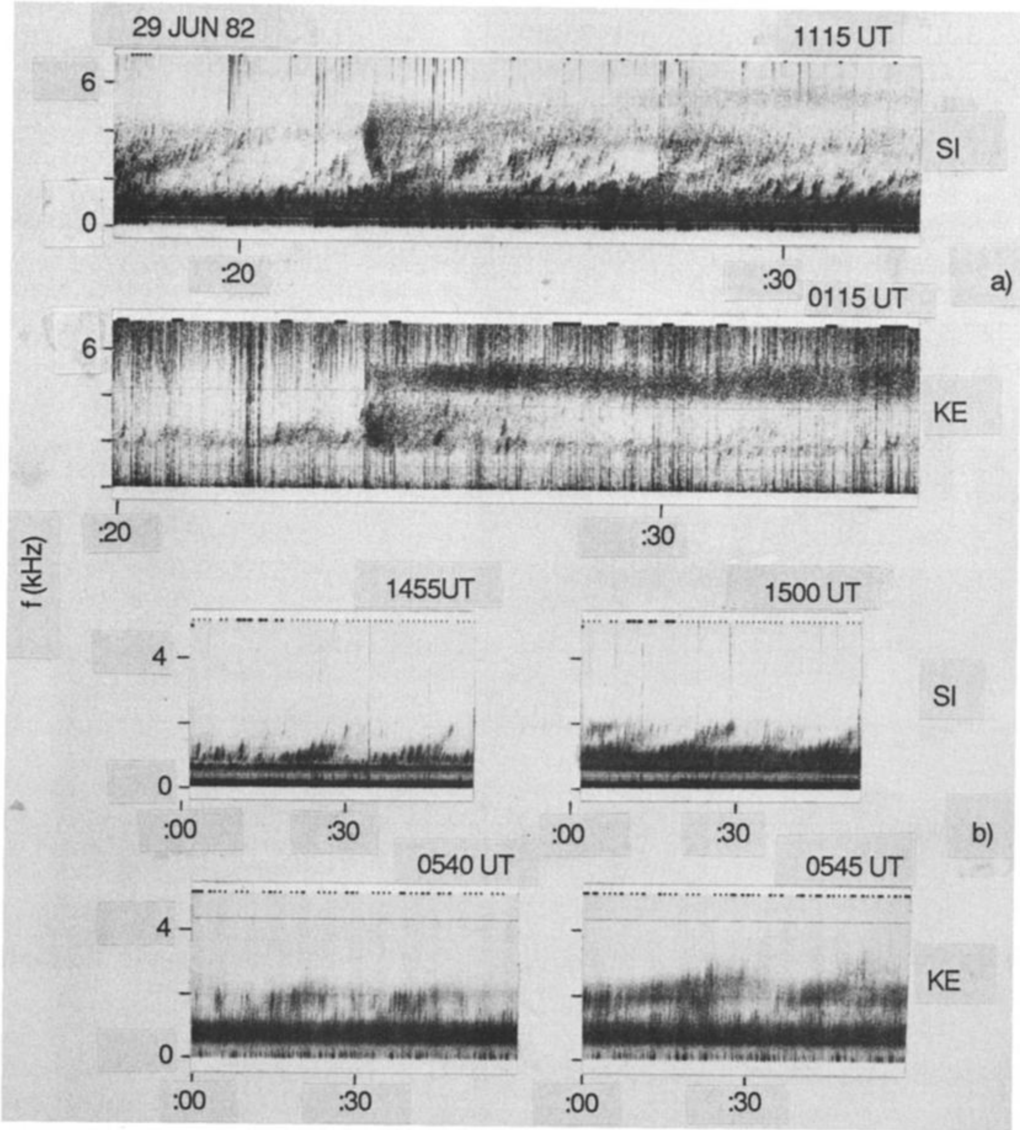

Fig. 4. (*a*) Siple and Kerguelen spectrograms for approximately the same local time ($\simeq$ 5–6 MLT) on the same day (June 29, 1982), showing knee whistlers and associated triggering of choruslike noise; the whistlers are weak relative to the triggered noise. The events are generally similar but different in detail. Background chorus is stronger at Siple. The spheric levels are markedly different, presumably due to different global and regional thunderstorm activity at the times shown. (*b*) Similar quasi-periodic (QP) emission events at Kerguelen and Siple, at approximately the same local time ($\simeq$ 09 MLT) on the same day (June 29, 1982). For each station, two successive synoptic minutes, 5 min apart, are illustrated. Again there are general similarities, e.g., the dominant 20–25 s periodicity, but differences in detail. At Siple, fine structure with a period of about 1.5 s is suggestive of modulation by echoing in the low-density region outside the plasmapause.

magnetic latitude $\Lambda \simeq 60$ deg) the stations are typically in the vicinity of the plasmapause projection, and most natural ELF/VLF waves received there from the magnetosphere are whistler mode waves such as hiss and chorus which have originated in or propagated through the region between the inner edge of the electron slot and the lower-latitude edge of the auroral zone.

To a first approximation, the wave activity observed in the present study was ordered in local time, i.e., stations tended to see similar activity at the same local times on the same day (see Figure 4) and from day to day (Figure 3). However, there were some striking longitudinal variations and these will be emphasized in the following discussion.

Two specific effects have been described: firstly the significantly lower intensities and occurrence rates of whistlers and banded chorus or hiss emissions at Sanae compared to Halley and Siple; secondly the different character of signals received at Kerguelen and Siple on the same day at the same local time, for example the predominance of echoing plasmaspheric whistlers at Kerguelen on the one hand and of knee whistlers with triggered emissions at Siple on the other (see, for example, Figures 2 and 3). Although the 2-day 4-station data set used here is severely limited in both temporal and spatial coverage, and may not represent in any sense a typical or average situation, at least the first of the above effects has confirmed an impression previously gained whenever Sanae VLF data have been compared with corresponding data from Siple or Halley.

The main purpose of this paper is to show that these longitudinal variations exist, at least at certain times and under certain conditions, and to suggest some possible explanations. With the limited data available we cannot hope to arrive at any firm conclusions; this must await a more detailed and quantitative study, ideally using a more closely spaced chain of receivers (though poor longitude coverage is inevitable owing to the lack of land near the southern $L = 4$ contour).

The observed longitudinal variations presented in section 3 may be related to the marked longitudinal asymmetry in electron precipitation [*Williams and Kohl*, 1965; *Imhof*, 1968; *Paulikas*, 1975; *Torr et al.*, 1975; *Voss and Smith*, 1980; *Varga et al.*, 1985]; generally higher precipitated fluxes are observed to the west of the South Atlantic geomagnetic anomaly (e.g., Siple and Halley) than to the east of it (e.g., Kerguelen). Although an association between electron precipitation and certain types of VLF waves has been shown to exist experimentally [*Oliven and Gurnett*, 1968; *Coroniti and Kennel*, 1970; *Rosenberg et al.*, 1971; *Hargreaves and Bullough*, 1972; *Holzer et al.*, 1974; *Inan and Carpenter*, 1987], it is not necessarily to be expected that the geomagnetic anomaly will be related to VLF wave activity in a simple way.

However, the self-consistent model of pitch angle diffusion due to *Etcheto et al.* [1973], in which the wave field that drives pitch angle diffusion is produced by instabilities of the same particle population that is being precipitated, suggests that the relationship between precipitated fluxes and wave intensity may be nonlinear. Thus to the east of the anomaly, where the particle fluxes are reduced, both the wave intensity and the pitch angle diffusion coefficient may exhibit minima. Recently *Bering et al.* [1988], on the basis of data from rocket-borne bremsstrahlung X ray detectors launched from Siple and Kerguelen, reported systematic differences in electron precipitation above the two stations. Specifically they found that both the precipitation background and the occurrence of microbursts [*Foster and Rosenberg*, 1976] were very low at Kerguelen compared to Siple. They suggested that the lower background might be due to a longitudinal dependence of the electron pitch angle diffusion coefficient by as much as 2 orders of magnitude, consistent with the *Etcheto et al.* [1973] model. If this explanation is correct it would be consistent with our observations of different and generally lower wave activity at Kerguelen compared to Siple and Halley, as shown, for example, in Figure 2. The lower level of wave activity that we have found at Sanae is also consistent with *Bering et al.'s* [1988] inference that the pitch angle diffusion rate is usually very low between the longitudes of Sanae and Kerguelen. Finally, considering that chorus emissions are probably responsible for the production of microbursts [*Rosenberg et al.*, 1971; *Foster and Rosenberg*, 1976], the relative absence of microbursts at Kerguelen is consistent with the relative absence of knee whistlers and chorus found at Kerguelen in this study.

Another possibility is that substorm penetration into the magnetosphere near midnight may be deeper at the longitude of Siple than at others, perhaps due in some way to the geomagnetic field configuration. Freshly injected particles might then produce nearly overhead precipitation and correlated stimulated VLF emissions at Siple, as in the January 2, 1971, case of *Rosenberg et al.* [1971]. (An example from the data set of the present paper occurred at Siple at around 0150 UT on June 29, 1982, when an 8-min-long auroral hiss event with overhead aurora was terminated as overhead precipitation increased, indicating substorm expansion at that time.) If this speculation is correct, then, for a similar substorm occurring near Sanae, the chorus (and precipitation) would be produced somewhat poleward of the station, and thus appear weak, due to attenuation when propagating over ice. Such a longitude effect in the latitude of substorm-related chorus activity would continue to manifest itself at later local times, for example in the morning side banded chorus events discussed in section 3 (e.g., Figures 2*a* and 3*a*). In contrast, at the longitude of Kerguelen, chorus events centered poleward of the station would appear relatively strong, due to the low attenuation for VLF waves traveling over seawater.

Whistler mode waves observed on the ground have generally traveled in ducts, and it is possible that the occurrence of whistler ducts or the efficiency of the ducting process may be longitude dependent. *Tatnall et al.* [1983] have inferred from Ariel 4 satellite data that ducting at 3.2 kHz is stronger at American than at European longitudes, though there is little direct evidence to support this. If it is a real effect it may be related to the relatively active thunderstorm region in the eastern United States (see below), since thunderstorm electric fields have been proposed as a possible cause of duct creation [*Park and Helliwell*, 1971; *Lester and Smith*, 1980]; it could be a factor in explaining our observations, but more investigation is needed on this point.

In the case of whistlers, the role of thunderstorms in providing (in lightning discharges) the source of energy (before subsequent magnetospheric amplification) is probably more important than any effect they may have in influencing duct creation. The significantly lower occurrence of whistlers, particularly knee whistlers, at Sanae compared to Siple, reported by *Woods et al.* [1979] and more recently by *Ladwig and Hughes* [1989], has already been mentioned. This was confirmed in a previously unpublished study of five samples of simultaneous Siple, Halley, and Sanae whistler data from three different days in 1973. Table 2 lists these periods and the numbers of whistlers received at the three stations, derived by counting the whistler traces visible on spectrograms. The longitudinal gradient in whistler occurrence is consistent with the observation that the majority of whistlers received by the VLF goniometer at Sanae arrive

TABLE 2. Comparative Whistler Rates at Siple, Halley, and Sanae, for Five selected 1-min samples on Three Days in the Winter of 1973

Date, 1973	Time	Kp	Siple	Halley	Sanae
June 10	0415 UT	3–	67	94	4
June 10	0420 UT	3–	36	51	1
June 10	0425 UT	3–	36	77	12
June 27	1915 UT	1+	60	58	2
July 23	0035 UT	2+	20	20	3
Total			219	300	22

The table shows the number of whistlers observed in the first 53 s of the minute. Only those whistlers sufficiently well defined to be considered "scalable" for the purposes of whistler dispersion analysis have been counted.

from the northwestern quadrant [*Ladwig and Hughes*, 1989]. The low occurrence rate at Sanae will be accentuated by attenuation over the Antarctic ice sheet [*Crary and Crombie*, 1972] lying to the west of Sanae, and also by anisotropic propagation in the earth ionosphere waveguide. Signals in the attenuation band around 2 kHz are attenuated much more when traveling eastward than westward [*Barr*, 1971].

Imhof et al. [1986] have found that short-duration nighttime electron precipitation events maximize in the longitude range 250°–320°E in the northern hemisphere and associate these with lightning activity. *Orville and Henderson* [1986] have published the distribution of midnight lightning derived from DMSP satellite photographs. While restricted in local time, this data set is not subject to the bias in meteorologically derived thunderstorm occurrence statistics introduced by the denser network of observing stations on land than at sea. Outside the tropical and semitropical latitudes (40°S to 40°N), the lightning occurrence, particularly during the northern summer, is strongly concentrated in the region of the eastern United States and Canada, near the conjugates of Halley and Faraday. It drops off sharply over the North Atlantic Ocean (conjugate to Sanae) and increases slightly again over Europe (approaching the conjugate of Kerguelen). Thus the lightning source distribution has a strong gradient in the longitude range of our data. However, it is known that lightning whistlers [*Carpenter and Orville*, 1989] can propagate on field lines with footprints thousands of kilometers from the source. Thus it is difficult to understand why the observed sharp drop-off in whistler occurrence between Halley and Sanae could be entirely due to the source distribution.

Any explanation of the longitudinal variation in VLF emissions (hiss and chorus) in terms of lightning occurrence is likely to rely on wave-wave interactions between those emissions and whistlers. Although it is known that whistlers can trigger discrete emissions [*Helliwell*, 1965; *Reeve and Rycroft*, 1976], including intense chorus bursts up to 30 s long [*Carpenter*, 1978; *Smith et al.*, 1985], it seems unlikely that the geographical distribution of lightning can explain the longitudinal variations observed in the case of the typically long, relatively steady banded emissions of this study, which occur in the absence of whistlers or are unmodulated by whistlers which do occur.

The data described in section 3, besides providing evidence of the strong longitudinal variation in VLF activity discussed above, also confirm previously reported spatial characteristics of the generation and propagation of VLF phenomena, inferred through the similarities and differences in observed spectra at the four spaced stations. Except in the waveguide attenuation band (~ 2 kHz), the propagation of spherics is on a global scale, since essentially the same patterns are often seen at all four stations. On the other hand whistler spectra at Kerguelen are never similar to those at the other three stations. At Siple, Halley, and Sanae, whistlers generally show some similarities and some differences, indicating that the longitudinal extent of the typical viewing area for a ground-based whistler receiver is of the order of the Siple–Halley spacing, i.e., ~ 30° (geomagnetic). By contrast, the details of the spectral forms of chorus are rarely similar at adjacent stations, indicating an interaction region size small compared to the station spacing, say ~ 5° in longitude [cf. *Helliwell*, 1965, p. 291]. This corresponds to ~ 2500 km at the equator and ~ 250 km in the ionosphere and is consistent with the estimated size and shape of wave-induced precipitation regions inferred from studies of the Trimpi effect [*Carpenter and Labelle*, 1982; *Inan and Carpenter*, 1987] (although these studies related to lower L shells: $L \sim 2$). It is also roughly comparable with the size of whistler ducts reported by *Angerami* [1970], although *Strangeways* [1986], based on observations by *Ondoh* [1976], has argued that ducts as narrow as 25 km may be important, the minimum size being limited by the escape of whistler mode waves from a duct when its wavelength exceeds the duct dimensions.

Often the general form of banded chorus, for example, is similar at Halley and Siple, even though the spectral details may be different. This suggests that conditions which are generally favorable for wave generation frequently exist over at least ~ 30° in longitude or ~ 2 hours in local time.

We have not been able to reach any definite conclusions about the causes of the observed longitudinal variation in whistler mode wave activity, because of the limitations of the available data set, both temporally and spatially. A more detailed and quantitative study is needed, using a much longer interval, and preferably using identical receivers at the different stations, perhaps using synoptic radiometer type equipment [*Smith and Yearby*, 1987; *Fraser-Smith et al.*, 1988]. At $L \sim 4$ the longitudinal coverage is inevitably patchy, since the only possibilities for land-based stations are from ~ 100°W to ~ 10°E (the Weddell Sea sector of Antarctica from Thurston Island to Novolazarevskaya), near 70°E (Kerguelen and Heard Island), and near 160°E (the Auckland, Campbell, and Macquarie Island groups). In Antarctica, AGOs (automatic geophysical observatories) may provide the technology for a more closely spaced chain of receivers than is provided by the currently manned stations.

5. CONCLUSIONS

VLF data from four $L \simeq 4$ Antarctic stations from a 2-day period in June 1982 have been compared. Siple, Halley, and Sanae form a closely spaced (~ 20°–30° geomagnetic longitude) triplet, while Kerguelen is ~ 120° (geomagnetic) to the east, on the opposite side of the South Atlantic geomagnetic anomaly.

To a considerable extent there was a repeatable diurnal variation in activity at all stations on the two days; note, for example, the whistlers at Kerguelen and the chorus at Siple in Figure 3. Events observed at Siple tended to be similar to those observed ~ 9 hours earlier (the same MLT) at Kerguelen on the same day; for example, the knee whistlers and QP emissions of Figure 4. There seemed to be less tendency for knee whistlers to trigger emissions at Kerguelen than at Siple. Whistler activity at Kerguelen was mainly, but not entirely, plasmaspheric, at times when Siple was mainly seeing whistlers outside the plasmasphere (Figure 2); this may be due to the slightly lower L value of Kerguelen.

There was a very marked drop-off in both whistler and VLF emission activity between Siple and Halley on the one hand and Sanae on the other. The reason for this is not clear; it may be either (1) a source effect such as the lower occurrence of lightning in eastern North America compared to the adjacent Atlantic Ocean, or else (2) a wave-particle interaction effect whereby the conditions for wave growth or amplification are more favorable, or substorm injections of energetic electrons penetrate more deeply, at the longitude of Siple than further east (possibly related to the proximity of the South Atlantic geomagnetic anomaly). The latter is probably more likely since the effect is observed for cases in which there is no evidence of interaction with waves from near-ground sources, and in regions outside the plasmapause whither such waves have limited access.

Comparison of the spectral forms of whistler mode activity at neighboring stations suggests that wave generation occurs simultaneously over relatively wide longitude (or local time) sectors ($\gtrsim 30°$). Individual interaction regions are smaller than this, $\lesssim 5°$ in longitude, comparable with the previously inferred sizes of whistler ducts.

Data sets with longer time coverage and better spatial resolution are required to answer some of the problems raised by this preliminary study.

Acknowledgments. This work was initiated as a result of the coordinated Antarctic data analysis workshop convened by L.J. Lanzerotti in San Diego, June 1986, under the auspices of the Scientific Committee on Antarctic Research (SCAR) Upper Atmosphere Physics Working Group. We thank him for his encouragement. In connection with the 1973 whistler comparison, we are grateful to C.G. Park for providing the Siple data and for sharing the analysis, and to A.D.M. Walker for providing the Sanae data. The research was supported by the Natural Environment Research Council, and by the Division of Polar Programs of the National Science Foundation under grants DPP 86-13783 (at Stanford) and DPP 83-08128 and DPP 84-15203 (at Houston).

The Editor thanks R. D. Hunsucker for his assistance in evaluating this paper.

REFERENCES

Angerami, J.J., Whistler duct properties deduced from VLF observations made with the OGO-3 satellite near the magnetic equator, *J. Geophys. Res., 75*, 6115, 1970.

Barr, R., The ELF and VLF amplitude spectrum of atmospherics with particular reference to the attenuation band near 3 kHz, *J. Atmos. Terr. Phys., 32*, 977, 1970.

Barr, R., The propagation of ELF and VLF radio waves beneath an inhomogeneous anisotropic ionosphere, *J. Atmos. Terr. Phys., 33*, 343, 1971.

Bering, E.A., J.R. Benbrook, H. Leverenz, J.L. Roeder, E.G. Stansbery, and W.R. Sheldon, Longitudinal differences in electron precipitation near $L = 4$, *J. Geophys. Res., 93*, 11385, 1988.

Bullough, K., and T.R. Kaiser, Ariel 3 and 4 studies of power line harmonic radiation, in *Wave Instabilities in Space Plasmas*, edited by P.J. Palmadesso and K. Papadopoulos, p. 37, D. Reidel, Hingham, Mass., 1979.

Carpenter, D.L., Whistler evidence of a 'knee' in the magnetospheric ionization density profile, *J. Geophys. Res., 68*, 1675, 1963.

Carpenter, D.L., Whistlers and VLF noises propagating just outside the plasmapause, *J. Geophys. Res., 83*, 45, 1978.

Carpenter, D.L., and J.W. Labelle, A study of whistlers correlated with bursts of electron precipitation near $L = 2$, *J. Geophys. Res., 87*, 4427, 1982.

Carpenter, D.L., and R.E. Orville, The excitation of active whistler mode signal paths in the magnetosphere by lightning: Two case studies, *J. Geophys. Res., 94*, 8886, 1989.

Coroniti, F.V., and C.F. Kennel, Electron precipitation pulsations, *J. Geophys. Res., 75*, 1279, 1970.

Crary, J.H., and D.D. Crombie, Antarctic ice-cap attenuation rates of VLF signals determined from short and long great circle paths, *Radio Sci., 7*, 233, 1972.

Etcheto, J., R. Gendrin, J. Solomon, and A. Roux, A self-consistent theory of magnetospheric ELF hiss, *J. Geophys. Res., 78*, 8150, 1973.

Foster, J.C., and T.J. Rosenberg, Electron precipitation and VLF emissions associated with cyclotron resonance interactions near the plasmapause, *J. Geophys. Res., 81*, 2183, 1976.

Fraser-Smith, A.C., R.A. Helliwell, B.R. Fortnam, P.R. McGill, and C.C. Teague, A new global survey of ELF/VLF radio noise, in *Proceedings of NATO/AGARD Conference on Effects of Electromagnetic Noise and Interference on Performance of Military Radio Communication Systems, Lisbon, October 1987*, AGARD Conf. Proceedings No. 420, p. 4a-1, North Atlantic Treaty Organization, Brussels, 1988.

Hargreaves, J.K., and K. Bullough, Mid-latitude VLF emissions and the mechanism of dayside auroral particle precipitation, *Planet. Space Sci., 20*, 803, 1972.

Helliwell, R.A., *Whistlers and Related Ionospheric Phenomena*, Stanford University Press, Stanford, Calif., 1965.

Holzer, R.E., T.E. Farley, R.K. Burton, and M.C. Chapman, A correlated study of ELF waves and electron precipitation on OGO 6, *J. Geophys. Res., 79*, 1007, 1974.

Imhof, W.L., Electron precipitation in the radiation belts, *J. Geophys. Res., 73*, 4167, 1968.

Imhof, W.L., H.D. Voss, M. Walt, E.E. Gaines, J. Mobilia, D.W. Datlowe, and J.B. Reagan, Slot region electron precipitation by lightning, VLF chorus, and plasmaspheric hiss, *J. Geophys. Res., 91*, 8883, 1986.

Inan, U.S., and D.L. Carpenter, Lightning induced electron precipitation events observed at $L \sim 2.4$ as phase and amplitude perturbations on subionospheric VLF signals, *J. Geophys. Res., 92*, 3292, 1987.

Laaspere, T., M.G. Morgan, and W.C. Johnson, Chorus, hiss and other audio-frequency emissions at stations of the Whistlers-East network, *Proc. IEEE, 52*, 1331, 1964.

Ladwig, J.M., and A.R.W. Hughes, An asymmetry in the direction of arrival of whistlers at Sanae, Antarctica, *J. Atmos. Terr. Phys., 51*, 61, 1989.

Lester, M., and A.J. Smith, Whistler duct structure and formation, *Planet. Space Sci., 28*, 645, 1980.

Luette, J.P., C.G. Park, and R.A. Helliwell, Longitudinal variations of very-low-frequency chorus activity in the magnetosphere: Evidence of excitation by electrical power transmission lines, *Geophys. Res. Lett., 4*, 275, 1977.

Oliven, M.N., and D.A. Gurnett, Microburst phenomena, 3, An association between microbursts and VLF chorus, *J. Geophys. Res., 73*, 2355, 1968.

Ondoh, T., Field aligned irregularities in whistler ducts as observed by ISIS satellites, *Space Res., 16*, 555, 1976.

Orville, R.E., and R.W. Henderson, Global distribution of midnight lightning: September 1977 to August 1978, *Mon. Weather Rev., 114*, 2640, 1986.

Park, C.G., and R.A. Helliwell, The formation by electric fields of field-aligned irregularities in the magnetosphere, *Radio Sci., 6*, 299, 1971.

Paulikas, G.A., Precipitation of particles at low and middle latitudes, *Rev. Geophys., 13*, 709, 1975.

Reeve, C.D., and M.J. Rycroft, Unducted VLF energy from tropical thunderstorms as a possible source of midlatitude VLF emissions and electron precipitation, *J. Geophys. Res., 81*, 6201, 1976.

Rosenberg, T.J., and J.R. Dudeney, The local time, substorm and seasonal dependence of electron precipitation at $L = 4$ inferred from riometer measurements, *J. Geophys. Res., 91*, 12032, 1986.

Rosenberg, T.J., R.A. Helliwell, and J.P. Katsufrakis, Electron precipitation associated with discrete very low frequency emissions, *J. Geophys. Res., 76*, 8445, 1971.

Smith, A.J., and D.L. Carpenter, Echoing mixed-path whistlers near the dawn plasmapause, observed by direction-finding receivers at two Antarctic stations, *J. Atmos. Terr. Phys., 44*, 973, 1982.

Smith, A.J., and K.H. Yearby, A microprocessor based VLF signal acquisition, processing and spectral analysis facility for Antarctica, *Br. Antarct. Surv. Bull., 75*, 15, 1987.

Smith, A.J., D.L. Carpenter, and U.S. Inan, Whistler-triggered VLF noise bursts observed on the DE-1 satellite and simultaneously at Antarctic ground stations, *Ann. Geophys., 3*, 81, 1985.

Strangeways, H.J., Whistler leakage from narrow ducts, *J. Atmos. Terr. Phys., 48*, 455, 1986.

Tatnall, A.R.L., J.P. Matthews, K. Bullough, and T.R. Kaiser, Power line harmonic radiation and the electron slot, *Space Sci. Rev., 35*, 139, 1983.

Torr, D.G., M.R. Torr, J.C.G. Walker, and R.A. Hoffman, Particle precipitation in the south Atlantic geomagnetic anomaly, *Planet. Space Sci., 23,* 15, 1975.

Vampola, A.L., and D.J. Gorney, Energy deposition in the middle atmosphere, *J. Geophys. Res., 88,* 6267, 1983.

Vampola, A.L., and G.A. Kuck, Induced precipitation of inner zone electrons, 1, Observations, *J. Geophys. Res., 82,* 2543, 1978.

Varga, L., D. Venkatesan, and C.-I. Meng, Low altitude observations of the energetic electrons in the outer radiation belt during isolated substorms, *Planet. Space Sci., 33,* 1259, 1985.

Voss, H.D., and L.G. Smith, Global zones of energetic particle precipitation, *J. Atmos. Terr. Phys., 42,* 227, 1980.

Williams, D.J., and J.W. Kohl, Loss and replenishment of electrons at middle latitudes and high B values, *J. Geophys. Res., 70,* 4139, 1965.

Woods, A.C., M.W.J. Scourfield, D. Boynton, and M.A. Roach, Plasmasphere convection patterns observed simultaneously from two ground stations, *Planet. Space Sci., 27,* 643, 1979.

E. A. Bering, Physics Department, University of Houston, Houston, TX77004.

D. L. Carpenter, STAR Laboratory, Stanford University, Stanford, CA 94305.

Y. Corcuff, Université de Poitiers, Laboratoire de Physique de la Haute Atmosphère, Le Deffend, Mignaloux-Beauvoir, 86800 Saint Julien l'Ars, France.

J. P. S. Rash, Department of Physics, University of Natal, 4001 Durban, South Africa.

A. J. Smith, British Antarctic Survey (NERC), Madingley Road, Cambridge CB3 0ET, England.

(Received January 27, 1989;
revised February 19, 1990;
accepted April 10, 1990.)