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Characteristics of Pc5 activity at high latitudes stations in Antarctica

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A R T I C L E I N F O

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A B S T R A C T

We examined wave activities in the Pc5 frequency band (~2–7 mHz) using the magnetic field data from five Antarctic stations, which are AGO3 (72.5° S Altitude-Adjusted Corrected Geomagnetic latitude), South Pole (SPA, 74.6° S), McMurdo (MCM) and Jang Bogo Station (JBS, 80° S), and Dome C (DMC, 89.1° S), during 2017. Pc5 waves at AGO3 and SPA show characteristics associated with Kelvin-Helmohltz instability on the magnetopause and substorm activities, under closed field lines conditions. The local time and seasonal dependence of Pc5 wave activities at polar cap stations (MCM, JBS, and DMC) are significantly different from those at AGO3 and SPA. These indicate that the generation mechanism of Pc5 activities in the open field line region at polar cap is different from that in the closed field lines. We suggest that polar-cap Pc5 is generated by ionospheric current variations produced by solar dynamo between solar wind plasma and geomagnetic field.

1. Introduction

Ultralow frequency (ULF) waves in the Pc5 frequency range (~2–7 mHz) are commonly observed at high-latitude regions ($L > 6$) on the ground (Jacobs et al., 1964). The variation of Pc5 polarization and amplitude with latitude and local time (Samson et al., 1971) is associated with field line resonance (FLR) (Chen and Hasegawa, 1974; Southwood, 1974). The theory of FLR describes the coupling of an evanescent fast mode wave, which is generated on the magnetopause through Kelvin-Helmohltz instability (KHI), to internal transverse modes (standing Alfvén waves) on selected L shells. Since the solar wind velocity controls the KHI on the magnetopause, increase in Pc5 power is well correlated with increase in the solar wind velocity (e.g., Engebretson et al., 1998).

Many previous studies reported that the occurrence rate and intensity of Pc5 waves are higher in the dawn sector than in the dusk sector in space (e.g., Anderson et al., 1990; Nosé et al., 1995; Takahashi et al., 2015). Recently, Takahashi et al. (2016) reported that the dawn-dusk asymmetry of Pc5 waves does not originate from a dawn-dusk asymmetry of KHI on the magnetopause but from weaker FLR in the dusk sector than in the dawn sector. Thus, FLR is an important factor to understand the spatial variations of the intensity of Pc5 waves.

Geomagnetic pulsations in Pc5 band can be also be excited by changes in magnetopause current due to solar wind dynamic pressure variations (e.g., Kepko et al., 2002; Kim et al., 2002; Takahashi and Ukhorskiy, 2007). Therefore, wave amplitude depends on the change in solar wind dynamic pressures. Since the magnetospheric compression is due to magnetopause displacement caused by solar wind pressure variations and is strongest at the frontside magnetopause owing to strong magnetopause current variations in the subsolar region, the intensity of the compressional Pc5 waves has a peak near magnetic local noon (Takahashi and Ukhorskiy, 2007). These compressional waves driven by solar wind pressure variations can resonantly couple to standing Alfvén waves.

Magnetopause surface waves are one of possible mechanism to generate broadband irregular pulsations at cusp latitude. Pilipenko et al. (2018) compared long-period pulsations in Pc 5–6 band and optical measurements of open-closed field line boundary (OCB). They found that the ULF waves maximized at lower latitudes than optical OCB latitude.

Recently, De Lauretis et al. (2016) reported that Pc5 waves observed at a polar cap station in Antarctica around local magnetic noon are

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associated with ionospheric currents carried by Alfvén waves through the direct coupling (i.e., FLR) of the compressional waves generated by oscillations of solar wind dynamic pressure at lower latitudes. Francia et al. (2005, 2009) reported that Pc5 power observed at a polar cap station has a peak power near noon and suggested that such daytime Pc5 pulsations are related to FLRs occurring at lower latitudes. Although many previous studies showed the occurrence of several possible sources and types of ULF activity in the polar cap, mechanisms of their excitation have not been firmly established yet (Pilipenko and Engebretson, 2002; Engebretson et al., 2006; Pilipenko et al., 2015).

In this study, we statistically examine Pc5 activities observed at stations located in Antarctica. We observed that the local time dependence of Pc5 power at polar cap stations is different from that at the stations in the closed field lines, which is consistent with previous studies (e.g., Francia et al., 2005, 2009). We suggest that the generation mechanism of polar-cap Pc5 activities is not FLR, which is considered in the previous studies, and that polar-cap Pc5 activities are associated with the variation of solar wind velocity.

2. Data

We use magnetic field data from five stations in Antarctica acquired through the entire year 2017. The stations are Dome C (DMC) near the south magnetic pole, McMurdo (MCM) and Jang Bogo Station (JBS) at Altitude-Adjusted Corrected Geomagnetic (AACGM) latitude = ~80° S, South Pole (SPA) at AACGM latitude = 74.6° S, and one station (AGO3) of the Automatic Geophysical Observatories (AGO) at AACGM latitude = 72.5° S (Kwon et al., 2018). The geographic and AACGM coordinates (Shepherd, 2014) of these stations are listed in Table 1 with universal time (UT) of local magnetic noon. The sensor type of magnetometer (F: fluxgate, S: search-coil) installed at the stations and its sampling rate are shown in Table 1. The magnetic field data used in this study are resampled at 1 min by taking running averages, resulting in a Nyquist rate of 8.3 mHz. This Nyquist frequency is enough for capturing the Pc5 waves in the frequency band of ~1.7–6.7 mHz. The solar wind data acquired from the WIND satellite are used to examine external solar wind conditions for the interval of Pc5 activity observed at the Antarctic stations. The data have been time shifted to the bow shock nose and provided in 1 min time resolution.

Fig. 1 shows the southern hemispheric averaged monoenergetic auroral flux, which is calculated by Oval Variation, Assessment, Tracking, Intensity, and Online Nowcasting (OVATION) Prime (Newell et al., 2002), for four month (January–April 2017) interval to define the outermost closed geomagnetic field lines. The red lines indicates 80° S AACGM latitude, where the position of MCM and JBS. We confirmed that positions of stations could be classified into three categories; Polar Cap (DMC, MCM, and JBS), cusp latitude (SPA), auroral zone (AGO3).

According to the magnetic latitudes of ground stations, we expected that the magnetic field lines at AGO and SPA connected to closed line and those at JBS and DMC are in open field region. In order to confirm the magnetospheric region connected to ground stations, we investigated the trace of magnetic field lines using Tsyganenko model (Tsyganenko, 2002a, 2002b). Fig. 2 shows results of Tsyganenko model in the intervals of solstice and equinox. Solid lines with black, red, blue and magenta indicate the magnetic field lines at JBS, DMC, SPA, and AGO3. During spring equinox, the magnetic fields at AGO3 and SPA connect to northern hemisphere (closed filed lines) and those at JBS and DMC are characterized by open field lines. Such features are also revealed on summer solstice and fall equinox. On the winter solstice the trace of magnetic fields are somewhat difference, it connected to the reconnection region in dayside at SPA and JBS is positioned in the nightside lobe or mantle region. This is due to change of solar wind condition.

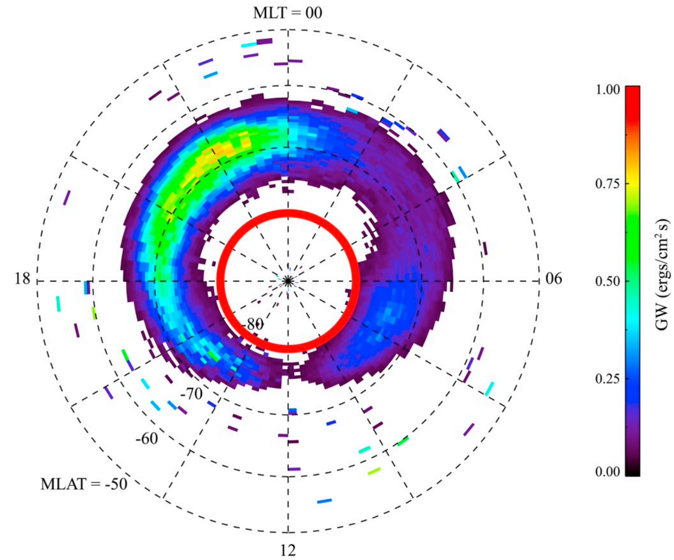

Fig. 1. The southern hemispheric averaged monoenergetic auroral flux for 4-month (January–April 2017) interval. The flux is calculated by OVATION Prime. The red circle indicates 80° S AACGM latitude. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

3. Observations

Fig. 3a–c shows the solar wind velocity (V_{sw}), density (N_{sw}), and dynamic pressure (P_{sw}) for the interval of 1 March (day 60) to 30 April (day 120), 2017. V_{sw} is characterized by high-speed streams with peak values larger than 600 km/s. N_{sw} and P_{sw} peaks, corresponding to a corotating interaction region, precede each V_{sw} peak by ~1 day.

Pc 5 powers observed at SPA, MCM, and DMC for the interval are plotted in Fig. 3d–f. The Pc5 power is given by the integral of power spectrum density over the 2–7 mHz band for 1-h segments of the time series in the north-south component. The red line in the plot of Pc5 power represents daily median values, calculated in 24 hourly bins (i.e., obtained from 24 Pc5 power samples).

The variability of the integral Pc5 power, measured by the separation between maximum and minimum powers, and the daily medians at SPA are larger than those at MCM and DMC. The integral power at DMC is smaller than that at SPA and MCM by a factor of ~10 for the entire interval. Although the Pc5 powers among the stations are significantly different, the level of the Pc5 power at the three stations strongly

Table 1
Coordinates of the Antarctic stations.

Station (code)	Geographic		Geomagnetic (AACGM)		UT of Noon MLT	Sampling rate/Sensor type
	Latitude	Longitude	Latitude	Longitude		
Dome C (DMC)	75.1° S	123.4° E	89.1° S	57.1° E	12:47	1m/F
McMurdo (MCM)	77.9° S	166.7° E	80.0° S	33.4° W	19:21	1s/F
Jang Bogo Station (JBS)	76.6° S	164.2° E	79.9° S	53.6° W	20:46	0.1s/S
South Pole (SPA)	90.0° S	0°	74.6° S	18.8° E	15:24	1s/F 0.1s/S
Automatic Geophysical Observatories 3 (AGO3)	82.8° S	28.6° E	72.5° S	41.3° E	13:48	1s/F

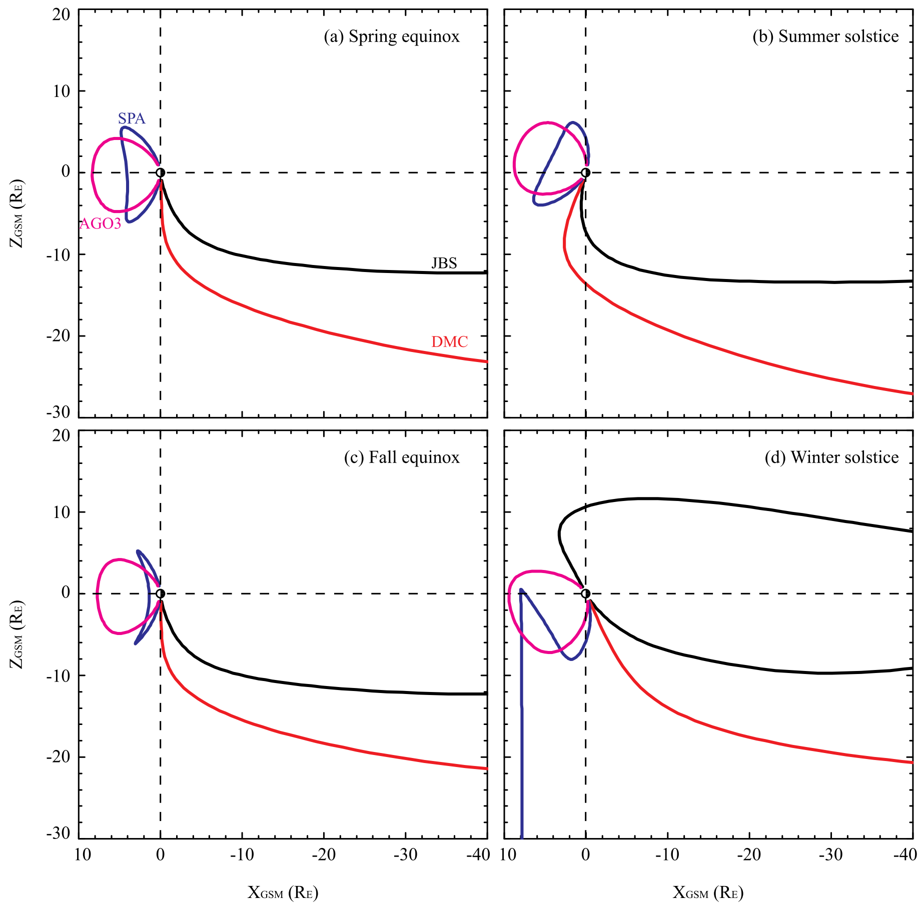

Fig. 2. The trace of magnetic field calculated by the T96 model at the high-latitude ground stations during the intervals of equinoxes and solstices in 2017. The curved solid lines indicate geomagnetic field lines connected to the stations,

depends on V_{sw}, as reported in previous studies (e.g., Engebretson et al., 1998; Francia et al., 2009), rather than N_{sw} and P_{sw}. That is, the Pc5 power increases rapidly and decreases monotonically with V_{sw}. This indicates that V_{sw} is a main source of Pc5 pulsations at auroral zone, cusp latitude, and polar cap region.

In order to examine the diurnal and seasonal variations of Pc5 activities, monthly median values of Pc5 power for each magnetic local time (MLT) bin and for each month bin at the Antarctic stations are plotted in Fig. 4. The monthly medians are derived using Pc5 power samples taken from 1-hr MLT bin. Note that the magnetic field data acquired by fluxgate and search coil magnetometer are marked by "FGM" and "SCM", respectively, on the Pc5 power plot in Fig. 3 and also note different power scale for FGM and SCM data. The midnight sun and polar night at the Antarctic stations are marked by the red and black bars, respectively, on each plot.

The diurnal variation of the Pc5 power at AGO3 in the auroral zone shows two dominant peaks; one between dawn and noon local times and the other in the premidnight sector. A similar MLT dependence of the Pc5 power is seen at SPA, which was located at cusp latitude (~2° north of AGO3 in AACGM latitude), but the peak power in the premidnight sector is not dominant as much as the peak in the prenoon sector. Comparison of FGM Pc5 power between AGO3 and SPA indicates that AGO3 is closer to the source of Pc5 activity than SPA. These auroral zone and cusp-latitude features are very similar to those reported by Engebretson et al. (1998) and Francia et al. (2005). Based on the analysis in the previous studies, we believe that Pc5 activities at the high latitudes resulted from field line resonances and that the enhanced power in the premidnight sector is likely related to substorms. It has been reported that the center of magnetic field variations associated with substorms is located in the premidnight sector (Nagai, 1982).

For the seasonal dependence of the prenoon peak of the Pc5 power at auroral zone and cusp latitude (Fig. 4a–c), there are two notable features. First, the peak occurs over a broad range of MLT in March and September. Second, the peak power shows a monthly variation. That is, it was enhanced from January to April and in September, and was reduced from May to June and from October to December.

The diurnal variations in the polar cap (JBS, MCM, and DMC) are different from those at lower latitudes. The FGM Pc5 power at MCM is much lower than that at AGO3 and SPA, and characterized by power maxima near the noon. There is no power enhancement in the premidnight sector, implying that substorm activities are absent in the polar cap region. The local time dependence of polar-cap Pc5 power at MCM is confirmed with search coil data at JBS, located nearly at the same AACGM latitude as MCM, and consistent with the result reported by Francia et al. (2005), who used search coil data at Terra Nova Bay (AACGM latitude = 80° S) in the polar cap. The FGM Pc5 power at DMC is very weak and shows no clear local time dependence even it slightly increases in the postmidnight sector. The different MLT dependence of the Pc5 peak powers observed at polar cap stations and at auroral zone and cusp latitude stations indicate that the generation mechanism of Pc5 pulsations in polar cap is different from that at auroral zone and cusp latitudes.

The peak power around noon seen at the polar cap stations, MCM and JBS (Fig. 4d–e), was enhanced in September, which is similar to that at auroral zone and cusp latitudes. The enhanced power is also seen at DMC in September, but the location of the enhanced power is in the premidnight and postmidnight sectors. The monthly variation of the polar cap peak power at MCM and JBS is significantly different from that at auroral zone and cusp latitude stations. It was enhanced from November to March with a broad peak and maximum power in January.

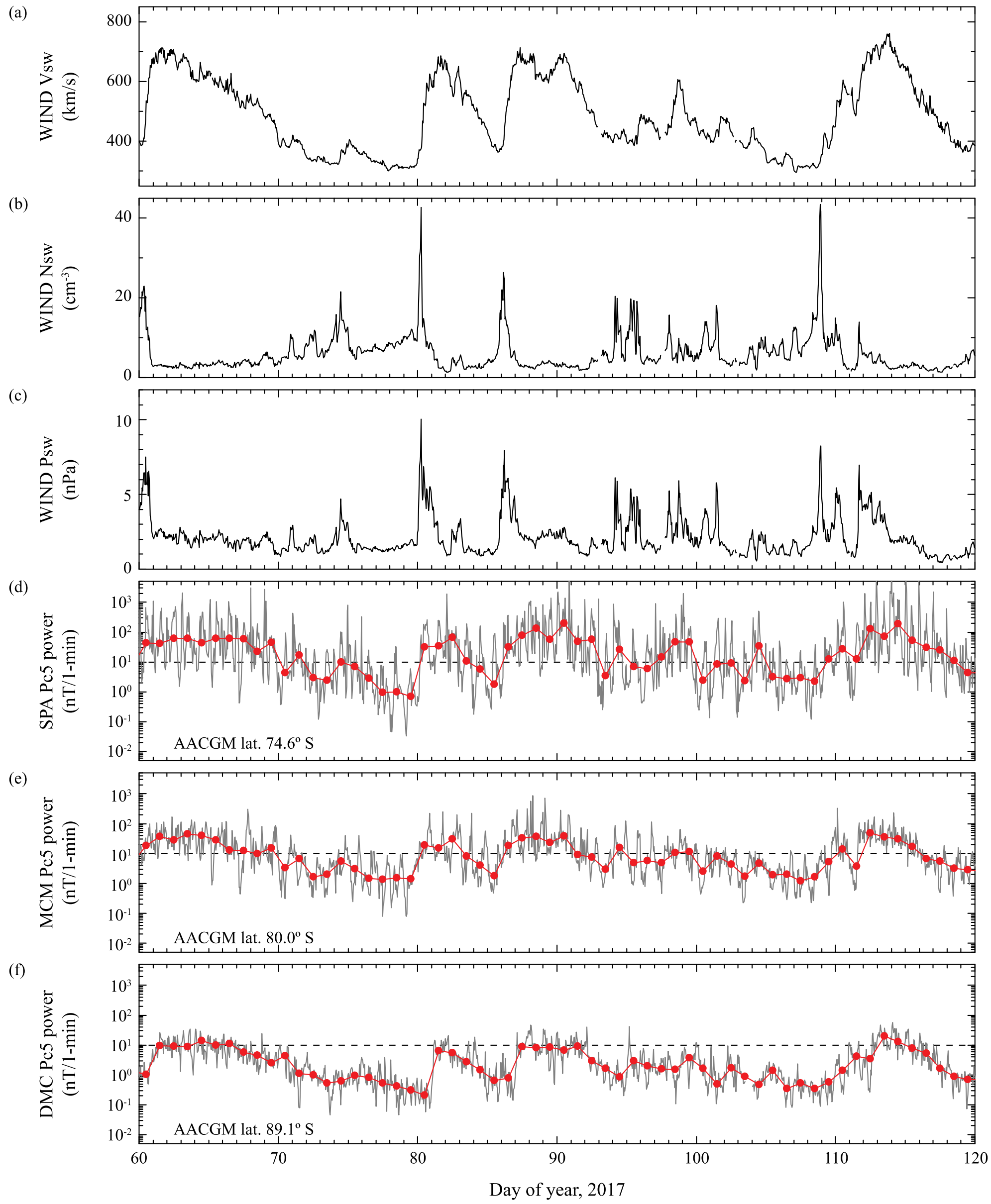

Fig. 3. Time series plots of (a) solar wind velocity, (b) density, (c) dynamic pressure measured by WIND from 60 to 120 day of year in 2017. The integral power in the Pc5 band at (d) SPA, (e) MCM, and (f) DMC during same the time interval same as solar wind data. The red line indicates 1-day medians of Pc5 power. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

These observations indicate that the generation mechanism of Pc5 magnetic variations under the open magnetospheric condition is not the same as that under the closed magnetospheric condition even though Pc5 power is largely controlled by solar wind velocity, as mentioned above.

The seasonal variations of Pc5 activity in the polar cap region are corresponding to the intervals of midnight sun and polar night. That is, power of Pc5 generally increased during midnight sun (red bar in Fig. 4) and decreased during polar night (black bar) while these relations are not clear seen at auroral and cusp latitudes in Fig. 4a–c.

Fig. 5a and b shows monthly median values of V_{sw} and V_{sw} standard deviations (σV_{sw}), respectively, made in hourly UT bins. The median of V_{sw} shows a clear transition from high to low between April and May and between September and October. A maximum peak of the median V_{sw} appears in September, and a secondary peak in March. The value of σV_{sw} is higher in the intervals of enhanced median V_{sw} from January to April and from July to September. This indicates that lager fluctuations of V_{sw} are embedded in high-speed solar wind streams. To confirm this argument, we examine the relationship between the solar wind fluctuation and solar wind speed and plot the results in Fig. 4c. The amplitude of the solar wind fluctuation (δV_{sw}) is defined to be the integral of the PSD of V_{sw} over the Pc5 frequency band. In order to calculate PSD of Vsw, we selected the time intervals when Vsw continuously recorded more than 1 h without data gap. As expected from Fig. 5a and b, there is a positive correlation (correlation coefficient = 0.53) between δV_{sw} and V_{sw}, implying that the large V_{sw} fluctuations appear in the high speed of V_{sw}.

4. Discussion

It is well known that Pc5 waves observed at high latitude ground stations, located at the closed magnetic field line region, are associated with azimuthally polarized toroidal Alfvén waves excited by FLR (i.e., the coupling of external compressional waves to internal toroidal waves on selected *L* shell) in the magnetosphere. The KHI on the magnetopause and magnetopause disturbances excited by a series of Psw changes have

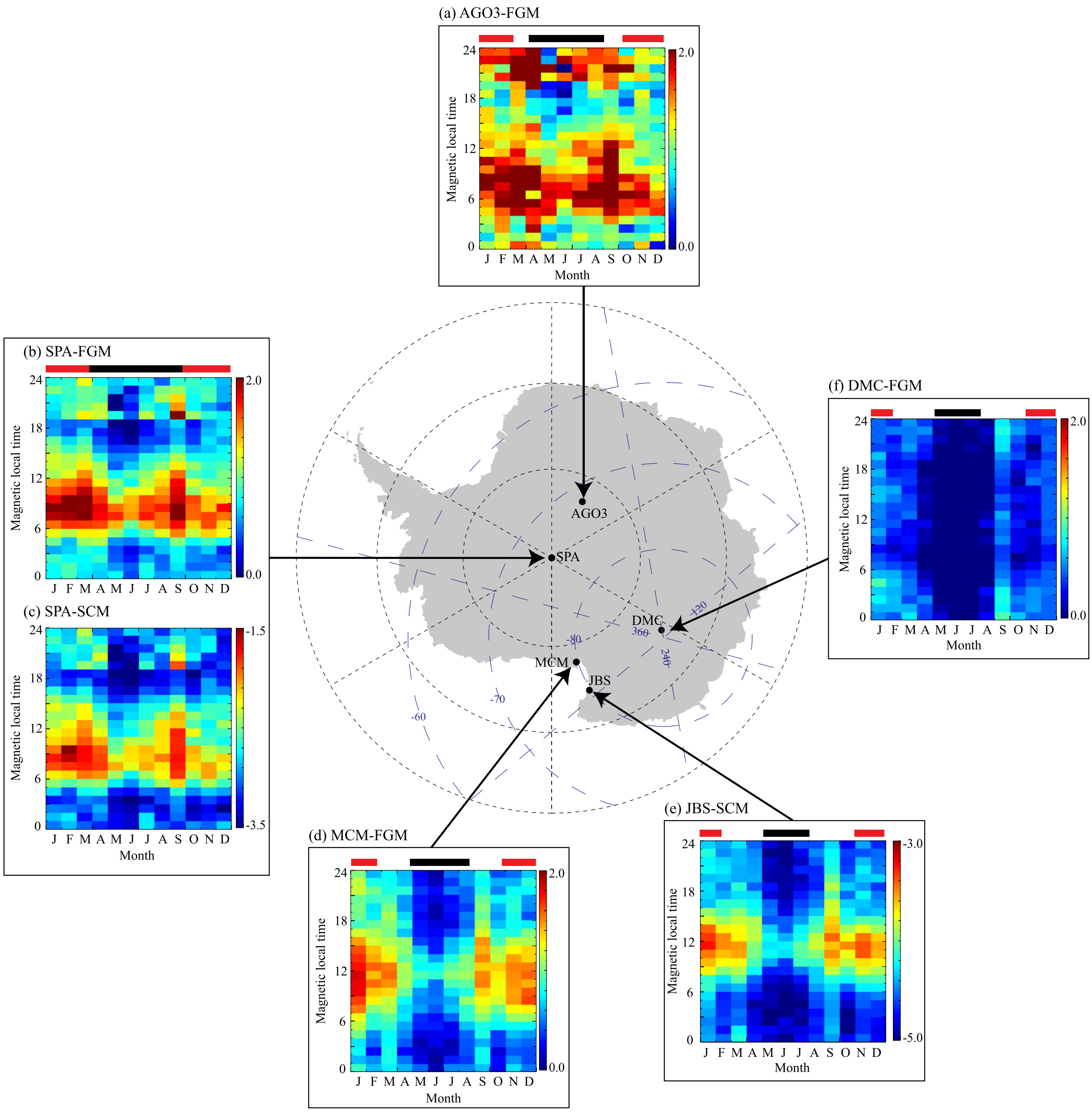

Fig. 4. The distributions of Pc5 power from Antarctic stations for monthly-MLT bins.

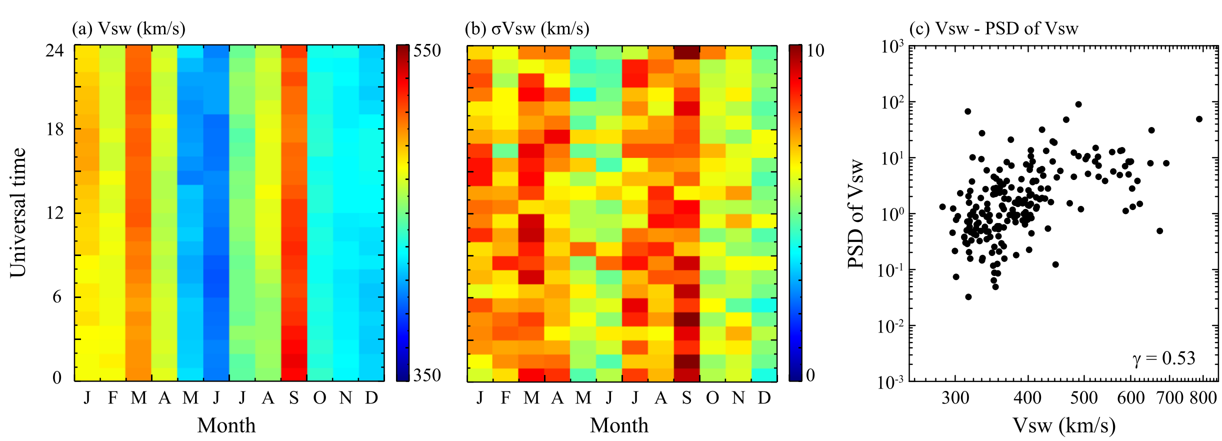

Fig. 5. The distribution of monthly-UT (a) solar wind velocity (V_{sw}) and (b) standard deviation of V_{sw} (σV_{sw}) measured by WIND in 2017. (c) Scatter plot of PSD of V_{sw} (δV_{sw}) over the Pc5 band as a function of V_{sw}.

been considered as the generation mechanism of external compressional waves for FLR.

As mentioned in the introduction, many previous observations in space and on the ground reported that the power of Pc5 waves associated with the KHI is higher at dawn (e.g., Anderson et al., 1990; Nosé et al., 1995; Engebretson et al., 1998; Francia et al., 2005; Takahashi et al., 2012, 2015). It has been suggested that this dawn-dusk asymmetry of the Pc5 power is due to the asymmetric spatial distribution of Alfvén speed in the magnetosphere (e.g., Takahashi et al., 2016; Kim et al., 2018).

In agreement with the previous studies, we found that the Pc5 power was enhanced in the prenoon sector at AGO3 and SPA stations. Both stations showed a similar local time dependence of the Pc5 power. Thus, we suggest that the Pc5 activities at SPA station are generated from the closed field lines. This indicates that SPA station is located equatorward with respect to the cusp.

As shown in Fig. 4a–c, we observed that the Pc5 powers in the prenoon sector at AGO3 and SPA were enhanced in the interval from January to April and in September. These intervals are characterized by high solar wind velocity (Fig. 4a). Since the level of the KHI depends on solar wind velocity, the enhanced Pc5 powers at AGO3 and SPA are associated with high-speed solar wind flow through the KHI on the magnetopause. We also observed that the prenoon power peaks at AGO3 and SPA occur over a broad range of MLT in March and September when V_{sw} was highly enhanced. This indicates that high V_{sw} provides more effectively the destabilization of KHI in a wide region.

The Pc5 powers at MCM and JBS stations in the polar cap region are significantly enhanced near noon, corresponding to the cusp location. Unlikely at AGO3 and SPA, it was enhanced in January. These observations lead us to that the fundamental question: is the generation mechanism of polar-cap Pc5 activity the same as that at SPA and AGO3 in a closed magnetic field lines?

We note that the polar-cap Pc5 activity with a broad maximum power near noon reported in our study is not new. Francia et al. (2005, 2009) also reported that a maximum power of Pc5 waves in the polar cap occurs around noon, consistent with our observations. Such a MLT dependence of polar-cap Pc5 power has been interpreted as FRLs occurring at somewhat lower latitudes, corresponding to a region of the outermost closed field lines, on the dayside (De Lauretis et al., 2016). However, toroidal Pc5 power distribution observed just inside the magnetopause is stronger in the dawnside than in the dayside (e.g., Takahashi et al., 2015, 2016). Such observations in space imply that FLRs of the outermost closed field lines may not be a unique key mechanism for polar-cap Pc5 activity.

It should be noted that the Pc5 activities at MCM and JBS occur at other local times even though their power is much smaller than that near noon when V_{sw} was high. For example, the broadening enhancements of Pc5 power during September in Fig. 4d and e are corresponding to high V_{sw} in Fig. 5a. As an alternative model we proposed that polar-cap Pc5 activities are excited by δV_{sw} imbedded in the solar wind flowing over the polar cap region. It is well known that the FAC is diverted into perpendicular current in the polar cap ionosphere, which is driven by the solar wind electric field ($\mathbf{E}_{sw} = -\mathbf{V}_{sw} \times \mathbf{B}_{sw}$) acting as an MHD generator in the earth's frame. As shown in Fig. 5b and c, the magnitude of δV_{sw} is positively correlated with V_{sw}. Thus, the large time-modulated E_{sw} (δE_{sw}) will be seen in the interval of large δV_{sw}. Such δE_{sw} drives a system of time-dependent perpendicular current in the polar cap ionosphere, and these currents are responsible for producing polar-cap Pc5 activity.

The region 1 current is located between 70° and 80° MLAT. Iijima and Potemra (1976) reported that there are cusp region field aligned currents (hereafter, cusp-FACs), which are confined to the range of ~77°–80° MLAT. The cusp-FACs are observed in the range from 0930 to 1430 MLT. If the cusp-FACs are connected with the region 1 field-aligned current, the Pc5 activity of the polar cap stations, MCM and JBS, located at ~80° MLAT will have a peak power near noon. Therefore, we suggest that polar-cap Pc5 activity observed at MCM and JBS has a direct connection with δV_{sw} changes in the solar wind.

5. Conclusion

We have performed a statistical analysis of Pc5 wave observed at ground stations in Antarctica. We found that the diurnal variations of Pc5 activity depends on geomagnetic latitudes. The polar-cap Pc5 power is larger in the dayside local time sector than in other local time sectors, while Pc5 maximizes in the morning sector at auroral region. Pc5 waves at auroral latitudes are corresponding to closed filed lines and they are generated by KHI associated with solar wind velocity. KHI is strong at dawn and these dawn-dusk asymmetry also shown at wave activity on the ground. In contrast to auroral region, magnetic fields in the polar-cap are connected to open field lines, then the source of polar-cap Pc5 comes from outer magnetosphere. We have examined the dependence of polar-cap Pc5 power on δV_{sw} and found that the Pc5 power is positively correlated with δV_{sw} with correlation coefficients larger than 0.5. From this correlation analysis, we suggest that polar-cap Pc5 waves are generated by time-dependent current flowing in the polar cap ionosphere, which is driven by δV_{sw} –associated δE_{sw}.

Acknowledgments

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jastp.2019.105087.

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