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Characteristics of negative values of polar cap index as an indicator of reversed convection

Tsutomu Nagatsuma

Applied Research and Standards Division, Communications Research Laboratory, Nukui Kitamachi 4-chome, Koganei-shi, Tokyo 184-8795

Abstract: The polar cap (PC) index sometimes shows negative values in the summer hemisphere. The Hall current induced by reversed convection causes the negative values of PC index. This means that the negative PC is an indicator of reversed convection in the polar cap of the summer hemisphere. Using the northern PC index (PCN) for 1995 to 1999, we have statistically examined the occurrence characteristics of negative values of PCN. The results of our data analysis show that a negative value of PCN frequently occurs when the solar zenith angle is less than 75° and when the IMF B_Y and B_Z are positive. These results are consistent with those obtained by the previous studies. Further, we found that the occurrence of negative PCN increases with solar wind electric field projected onto the GSM YZ plane (E_T), if the clock angle is less than 60°. When the clock angle is from 60 to 80°, the occurrence of negative PCN increases with E_T in the cases when E_T is less than 4 mV/m, and decreases with increasing E_T in the cases of E_T greater than 4 mV/m. Further, the occurrence of negative PCN increases with increasing magnitude of IMF projected onto the GSM *YZ* plane (B_T) and decreases with increasing solar wind velocity. These results suggest that the occurrence of reversed convection in the polar cap is not a simple function of IMF clock angle. Their occurrences are also controlled by the magnitude of B_T and solar wind velocity.

1. Introduction

In the Earth's magnetosphere the plasma convection is driven by the solar wind–magnetosphere interaction. Ionospheric currents are driven by the transmission of magnetic tension from the magnetosphere to the ionosphere. Since the behavior of ionospheric currents is reflected on the ground as magnetic field perturbations, we can estimate the condition of plasma convection in the magnetosphere by analyzing magnetic field variations on the ground. The ionospheric current induced by solar wind–magnetosphere interaction leading to plasma convection is named *DP*2 current system (Nishida, 1968). The main contributor to horizontal magnetic field variations in the near-pole region is the *DP*2 current system. Based on this interpretation, Troshichev *et al.* (1979) proposed a polar cap (PC) index. According to the results of Troshichev *et al.* (1988), the PC index has a good correlation with the merging electric field $E_m = V_{SW} B_T \sin^2(\theta/2)$ introduced by Kan and Lee (1979), where V_{SW} is the solar wind velocity, B_T is the projection of interplanetary magnetic field (IMF) onto the GSM *YZ* plane, and θ is a clock angle of IMF.

The PC index sometimes shows negative values in the summer hemisphere. The occurrence of negative PC corresponds to the case of positive IMF B_Z (*e.g.*, Vennerstrøm *et al.*, 1991), since the flow direction of the Hall current induced by the reversed convection is opposite to the two-cell convection pattern (Maezawa, 1976; Friis-Christensen *et al.*, 1985). Reversed convection corresponds to the lobe cell convection driven by a northward IMF merging at the magnetopause with the southward tail lobe field poleward of the cusps that close within the polar cap (Maezawa, 1976; Crooker, 1992). This suggests that the occurrence of reversed convection in the polar cap can be identified using the polarity of the PC index.

Until now, many ionospheric convection models have been produced as functions of each component of the IMF intensity and clock angle (*e.g.*, Weimer, 1995). These models show that the transition from two-cell to four-cell convection pattern occurs at a fixed clock angle. However, the locations of dayside merging regions expected from anti-parallel merging model depend on the clock angle (Crooker, 1979). And even when the clock angle is the same, the solar wind velocity and magnetic field intensity can be different from one event to the next. The intensity of B_T and solar wind velocity controls the efficiency of the dayside merging process (*e.g.*, Hill, 1975; Mitchell and Kan, 1978). It is expected that these differences in solar wind conditions modulate the occurrence of reversed convection.

In this paper, we have statistically analyzed the characteristics of negative values of PC index and have examined the conditions for the occurrence of reversed convection in the polar cap.

2. Observation

Figure 1 shows the yearly variations in the 15-min northern PC index (PCN) and those in the solar zenith angle both from Qaanaaq (formerly Thule). Occurrence of negative PCN is mostly seen in northern summer for the solar zenith angle less than 90°.

A month-UT plot for the occurrence distribution of negative PCN for 1995 to 1999 is shown in Fig. 2. The size of each dot shows the magnitude of negative PCN. Color contours of solar zenith angle at Qaanaaq are overlaid in this figure. Occurrence of negative PCN is mostly distributed from 12 to 22 UT in summer. Since the magnetic local noon of corrected geomagnetic coordinate at Qaanaaq is about 15 UT, negative PCN is mostly distributed from 9 to 19 MLT. Also, this distribution roughly corresponds to the condition for the solar zenith angle less than 75°.

Based on these results, we use for the rest of our analysis PCN data in summer from 1995 to 1999 for the UT range between 12 and 22 UT. For 1995 to 1997, data from the WIND satellite are used to represent the solar wind parameters. For 1998 to 1999, data from the ACE satellite are used.

Figure 3 shows scatter plots of PCN as a function of IMF clock angle, binned for every 1 mV/m of solar wind electric field projected onto the GSM *YZ* plane (E_T) from 0 mV/m to 8 mV/m. Black lines with filled circles show the average values of PCN, binned for every 20° of clock angle from −180 to 180°. The calculated E_m is shown as a blue line.

In general, there is a good correspondence between the average value of PCN and E_m.

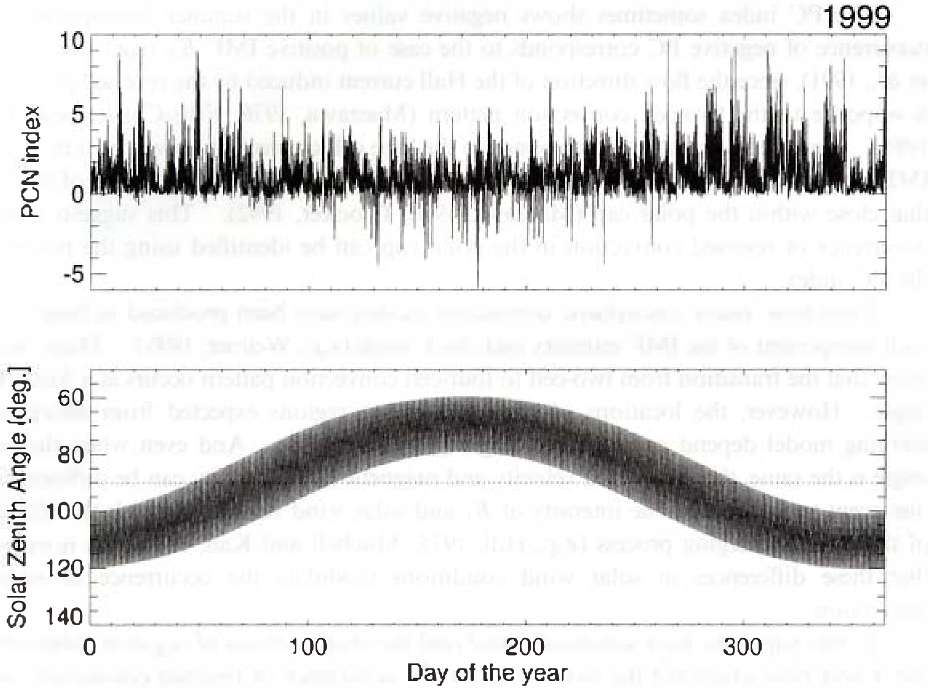

Fig. 1. (Top) Yearly variation of northern PC index (PCN) at Qaanaaq for 1999. (Bottom) Yearly variation of solar zenith angle at Qaanaaq.

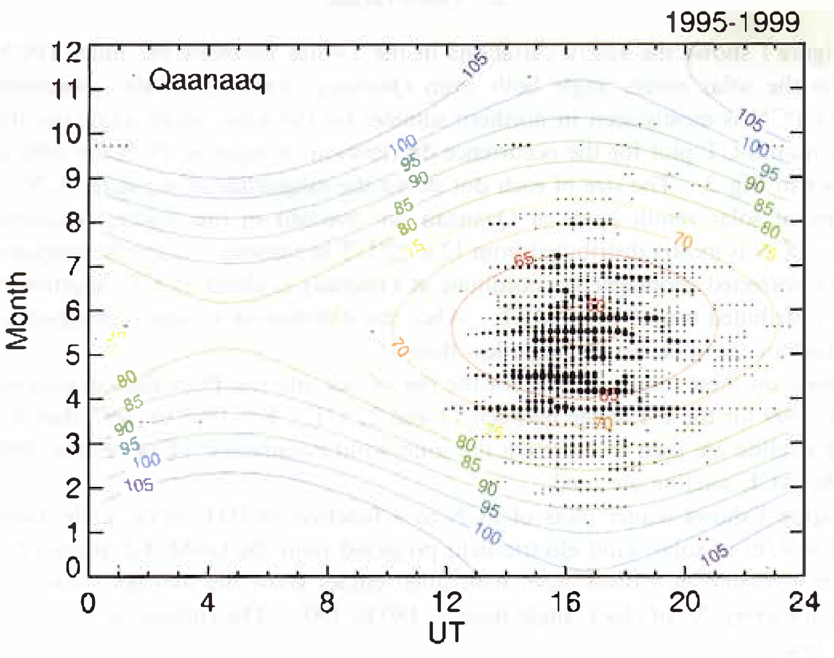

Fig. 2. A month-UT plot for the occurrence distribution of negative PCN. Color contours of solar zenith angle at Qaanaaq are overlaid.

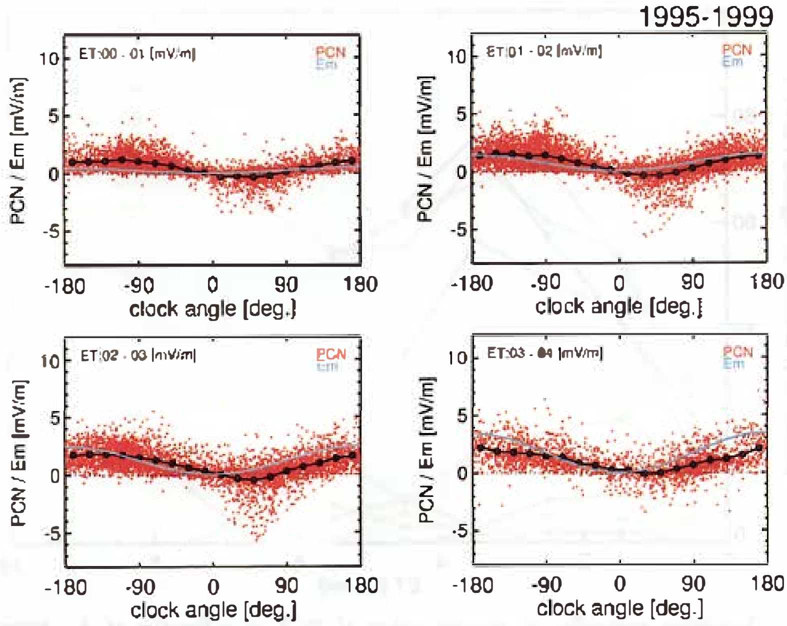

Fig 3a. *Scatter plots of IMF clock angle vs PCN for four ranges of E_T, 00-01 mV/m (top left), 01-02 mV/m (top right), 02-03 mV/m (bottom left), and 03-04 mV/m (bottom right). The black lines with filled circles show the average values of PCN. The blue lines show the calculated merging electric field (E_m).*

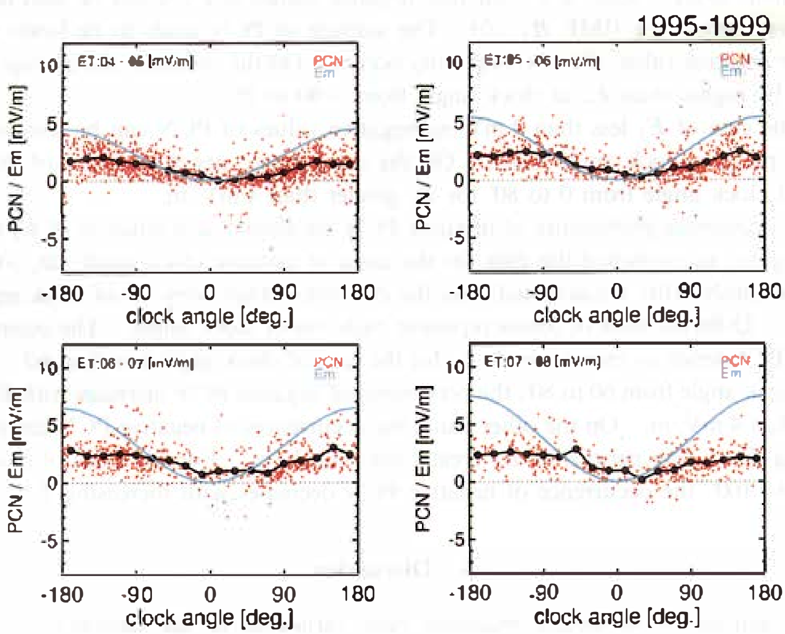

Fig. 3b. *Same as Fig 3a but for 04-05 mV/m (top left), 05-06 mV/m (top right), 06-07 mV/m (bottom left), and 07-08 mV/m (bottom right).*

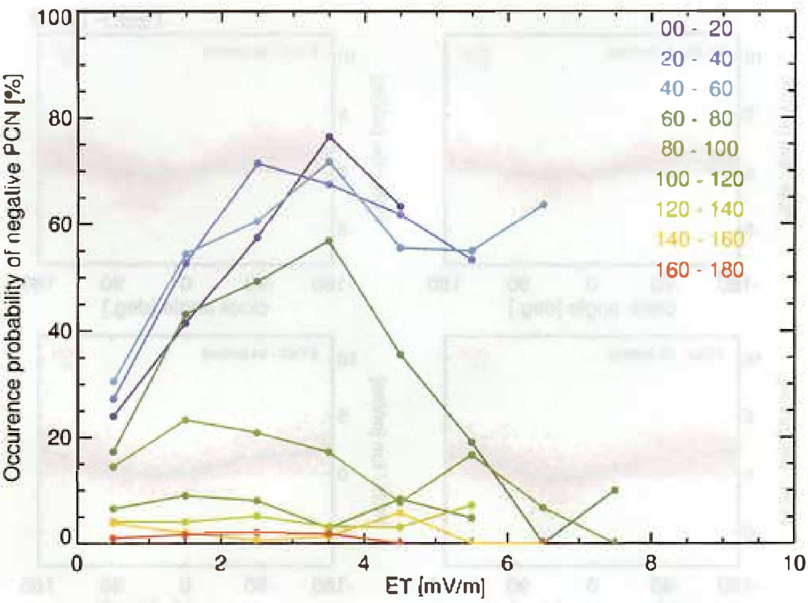

Fig. 4. Occurrence probability of negative values of PCN as a function of E_T, binned for every 20° of clock angle from 0 to 180°.

However, the average of PCN tends to be saturated when E_m is greater than 5 mV/m (Nagatsuma, 2002). Also, it is clear that negative values of PCN can be seen frequently at positive clock angle (IMF $B_Y>0$). The average of PCN tends to be lower than E_m when the negative value of PCN frequently occurs. On the contrary, the average of PCN tends to be higher than E_m at clock angle from -90 to 0°.

In the case of E_T less than 4 mV/m, negative values of PCN can be seen in a wide range of positive clock angle sector. On the other hand, negative values of PCN only appear at clock angle from 0 to 80° for E_T greater than 4 mV/m.

The occurrence probability of negative PCN are shown as a function of E_T in Fig. 4. In this figure, we examined the data for the cases of positive clock angle ($B_Y>0$). The occurrence probability is calculated from the data binned for every 20° of clock angle from 0 to 180°. Different lines of colors represent each bin of clock angle. The occurrence of negative PCN tends to increase with E_T for the case of clock angle less than 60°. For the case of clock angle from 60 to 80°, the occurrence of negative PCN increases with E_T during E_T less than 4 mV/m. On the other hand, the occurrences of negative PCN decrease with increasing E_T during periods of E_T greater than 4 mV/m. For the cases of clock angle from 80 to 100°, the occurrence of negative PCN decreases with increasing E_T.

3. Discussion

The sources of horizontal magnetic field variations in the near-pole regions are supposed to be ionospheric Hall currents in the polar cap and the distant field-aligned currents at the poleward rim of the auroral oval (Vennerstrøm *et al.*, 1991). In the winter hemisphere, Hall currents are negligible since the ionospheric conductivity is low. On the contrary, the effect from the Hall currents is significant in the summer hemisphere with low solar zenith angle, since the ionospheric conductivity is enhanced. The results for the occurrence period of negative PC obtained from our data analysis clearly support this interpretation and are consistent with those from previous studies (Vennerstrøm *et al.*, 1991; Nagatsuma *et al.*, 2002).

The occurrence of negative PCN depends on the polarity of IMF B_Y. This is consistent with the results obtained by Vennerstrøm *et al.* (1991). When B_Y is negative, sunward flow of a lobe cell tends to be formed in the dawn sector. For positive B_Y, sunward flow of a lobe cell tends to form in the dusk sector. Since negative PCN is frequently detected in the afternoon sector by enhanced conductivity, a positive B_Y is a favorable condition. The enhancement of PCN during the period of clock angle from −90 to 0° might be caused by an enhancement of antisunward flow of lobe cell for negative B_Y.

As shown in Fig. 4, the occurrence probability of negative PCN is a function of E_T and clock angle. It seems that the clock angle from 60 to 80° is the transition sector for the occurrence of reversed convection in the polar cap. Since E_T is a product of B_T and the solar wind velocity (V_{SW}), we examined the B_T and V_{SW} dependence separately for the occurrence of negative PCN.

Figure 5 shows the occurrence probability of negative PCN as a function of B_T. Data are sorted by nine bins of clock angle, which are plotted with different colors. At clock angles less than 60°, the occurrence probability of negative PCN tends to increase with increasing B_T. This result is consistent with that obtained by Weimer (1995).

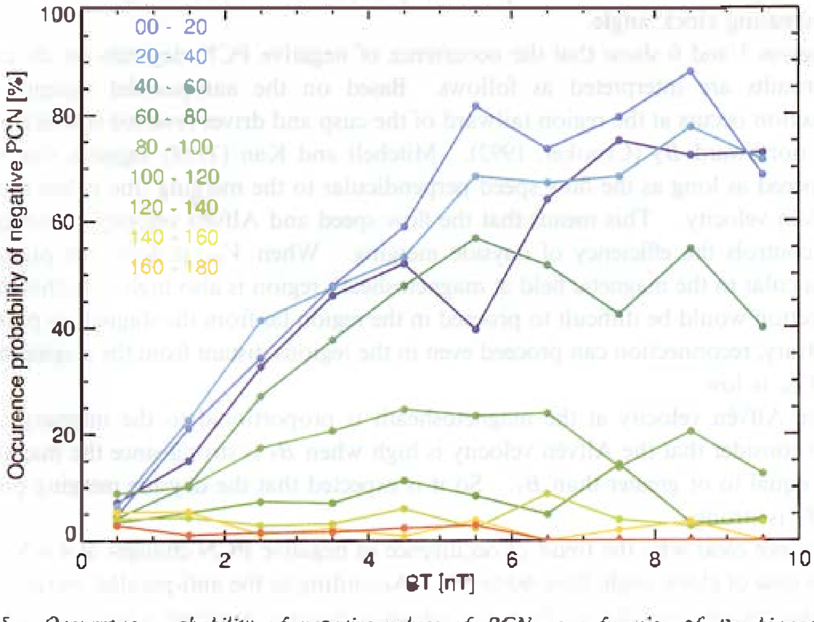

Fig. 5. Occurrence probability of negative values of PCN as a function of B_T, binned for every 20° of clock angle from 0 to 180°.

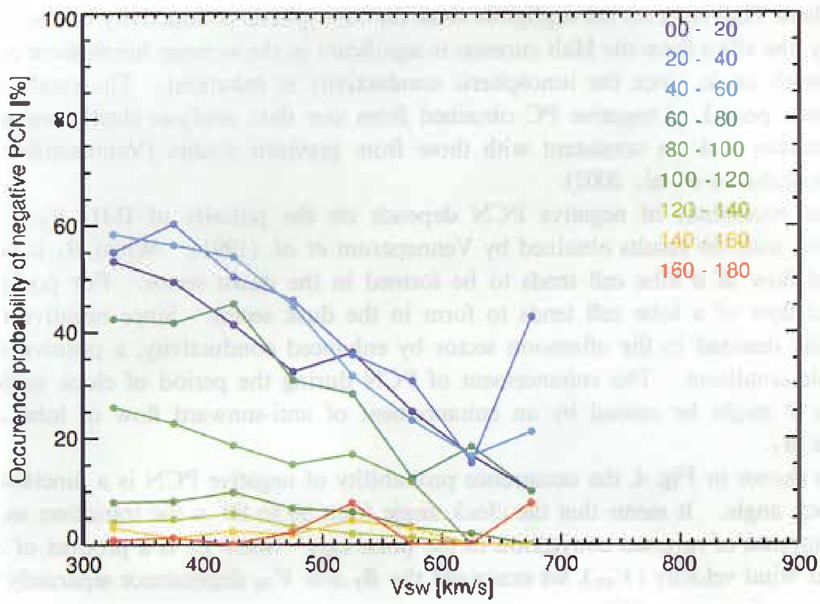

Fig. 6. Occurrence probability of negative values of PCN as a function of V_{SW}, binned for every 20° of clock angle from 0 to 180°.

The occurrence probability of negative PCN as a function of V_{SW} is shown in Fig. 6. Data are sorted in nine bins of clock angle, which are represented by lines of different colors. In general, the occurrence probability decreases with increasing V_{SW} and decreases with increasing clock angle.

Figures 5 and 6 show that the occurrence of negative PCN depends on B_T and V_{SW}. These results are interpreted as follows. Based on the anti-parallel merging model, reconnection occurs at the region tailward of the cusp and drives reversed convection in the case of northward B_Z (Crooker, 1992). Mitchell and Kan (1978) suggests that merging will proceed as long as the flow speed perpendicular to the merging line is less than twice the Alfvén velocity. This means that the flow speed and Alfvén velocity in the magnetosheath controls the efficiency of dayside merging. When V_{SW} is high, the plasma flow perpendicular to the magnetic field at magnetosheath region is also high. In this situation, reconnection would be difficult to proceed in the region far from the stagnation point. On the contrary, reconnection can proceed even in the regions distant from the stagnation point when V_{SW} is low.

The Alfvén velocity at the magnetosheath is proportional to the intensity of IMF. We can consider that the Alfvén velocity is high when B_T is strong since the magnitude of IMF is equal to or greater than B_T. So it is expected that the dayside merging progresses when B_T is strong.

It is not clear why the trend of occurrence of negative PCN changes at 4 mV/m of E_T for the case of clock angle from 60 to 80°. According to the anti-parallel merging model, a merging region most distant from the sub-solar point is expected when the IMF points dawnward or duskward (Crooker, 1979). Under these conditions, the occurrence of reversed convection strongly depends on B_T and solar wind velocity. It may be possible to interpret B_T and the solar wind velocity dependence of the occurrence of negative PCN in the following way. When E_T is less than 4 mV/m, B_T is large and solar wind velocity is low. In this situation, reversed convection can develop even during periods of large clock angle. When E_T is greater than 4 mV/m, large solar wind speed is expected and reversed convection cannot proceed.

4. Conclusion

We have examined characteristics of negative values of PCN index. The results of our data analysis shows that negative values of PCN frequently occur during the solar zenith angle less than 75° and during the IMF clock angle from 0° to 90° ($B_Y > 0$ and $B_Z > 0$). These results are consistent with those in the previous studies. Further, we found that the occurrence probability of negative PCN increases with E_T, if the clock angle is less than 60°. When the clock angle is from 60 to 80°, the occurrence of negative PCN increases with increasing E_T until E_T reaches 4 mV/m. On the other hand, the occurrence of negative PCN decreases with increasing E_T when E_T is greater than 4 mV/m. Further, the occurrence of negative PCN increases with B_T and decreases with increasing solar wind velocity. These results suggest that the occurrence of reversed convection in the polar cap is not a simple function of the IMF clock angle. The occurrence conditions are also controlled by the magnitude of IMF projected onto the GSM YZ plane and by solar wind velocity.

Acknowledgments

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