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Statistical Survey of Arase Satellite Data Sets in Conjunction With the Finnish Riometer Network

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Key Points:
• Arase omnidirectional electron flux and plasma wave data are investigated statistically in conjunction with the Finnish riometer network.
• CNA events associate with Arase electron flux in the energy range >a few keV and plasma waves in 0.5–3 kHz at the ELF/VLF frequency range.
• Study suggests that whistler mode chorus waves are the major driver for EEP responsible for the observed CNA.

Abstract
During disturbed geomagnetic conditions, the energetic particles in the inner magnetosphere are known to undergo precipitation loss due to interaction with various plasma waves. This study investigates the energetic particle precipitation events statistically using coordinate observations from the ground riometer network and the inner-magnetospheric satellite mission, Arase. We have compared cosmic noise absorption (CNA) data obtained from the Finnish ground riometer network located in the auroral/sub-auroral latitudes with the comprehensive data set of omnidirectional electron/proton flux and plasma waves in ELF/VLF frequency range from the Arase satellite during the overpass intervals. The study period includes one and a half years of data between March 2017 and September 2018 covering Arase conjunctions with the riometer stations from all magnetic local time sectors. The relation between the plasma flux/waves observed at the satellite with the riometer absorptions are investigated statistically for CNA (absorption >0.5 dB) and non-CNA (absorption <0.5 dB) cases separately. During CNA events, Arase observed elevated electron flux in the medium energy range (2–100 keV), and plasma wave activity in the whistler-mode frequency range (0.5–3 kHz) of the spectra. Our study provides an estimate of the statistical dependence of the electron flux and plasma wave observations at Arase with the ground reality of actual precipitation.

1. Introduction
Inner-magnetosphere is a dynamic region of the Earth's magnetosphere which consist of various plasma populations, with energies ranging from a few eV to nearly 10 MeV. The energetic particle populations (energy range: 30 keV to 1 MeV) in the inner magnetosphere mainly comprise outer radiation belt electrons, and ring current particles (electrons and ions; e.g., Kanekal and Miyoshi, 2021). These particle populations which are trapped to the Earth's magnetic field can at times escape from the magnetosphere under favorable conditions. One of the important loss mechanisms of the energetic particles is the precipitation into the atmosphere via pitch angle scattering by plasma waves (e.g., Millan and Thorne, 2007; Thorne, 2010).

In addition to these trapped particle populations, the electrons (<100 keV) freshly injected into the inner magnetosphere, from the night side plasma sheet in association with substorm intervals can also result in atmospheric precipitation (Thorne et al., 2010). The cyclotron resonance between gyrating electrons and different plasma waves is considered as one of the important processes responsible for energetic electron precipitation (EEP). Whistler mode chorus waves are known to have a dominant role in the precipitation of much higher energy electrons up to approximately 1 MeV.
The electromagnetic ion cyclotron (EMIC) waves can scatter resonant protons into the loss cone causing precipitation into the atmosphere (Cornwall et al., 1970; Miyoshi et al., 2008; Summers, 2005; Usanova et al., 2010). Compared to whistler mode chorus waves EMICs are more spatially localized to duskside plasmapause (Erlandson & Ukhorskiy, 2001; Sakaguchi et al., 2012; Spasojevic & Fuselier, 2009).

Electrons are the dominant species of these precipitating charged particles and the diffuse aurora is a common visual demonstration of the EEP events. Diffuse auroras are often accompanied by intensity modulations with a periodicity of 2–20 s and are known as pulsating auroras (e.g., Lessard, 2012; Li et al., 2012; Miyoshi, Saito, et al., 2013; Nishimura et al., 2020). As the resonant energy of electrons depend on the magnetic latitude, chorus waves can cause the pitch angle scattering of different energy electrons along the field line. Miyoshi et al. (2010); Miyoshi, Oyama, et al. (2015); Miyoshi et al. (2020) have studied EEP in association with pulsating auroras. They have shown that electrons with wide energy range of tens to hundreds of keV precipitate, in association with pulsating auroras, as a result of the interaction of the electrons with whistler mode chorus waves propagating from the equator along the geomagnetic field lines. Miyoshi et al. (2020) have proposed a model that the relativistic electron microburst is a high-energy tail of the pulsating aurora, which was later confirmed by recent observational studies (Kawamura et al., 2021; Miyoshi et al., 2021; Shimuk et al., 2021).

As higher energy electrons penetrate deeper into the atmosphere, they can result in enhanced ionization in the D region ionosphere. Miyoshi, Oyama, et al. (2015); Oyama et al. (2017) have reported ionization down to 68 and 65 km during EEP events with energies approximately >200 keV and approximately >500 keV, respectively. In a recent study Miyoshi et al. (2021) have shown evidence for the impact of the pulsating aurora associated MeV energy EEP on the ozone chemistry in the polar mesosphere.

Oyama et al. (2017) have studied two EEP events in detail by employing ground and satellite based observations. Utilizing EISCAT electron density measurements, Oyama et al. (2017) have shown that the flux of the precipitating electrons with energies >10 keV has a preferential increase during more disturbed (active precipitation) intervals compared to relatively quieter (before precipitation) time. Similarly an increase in precipitating electron flux at energies >30 keV and >100 keV was observed at NOAA/POES 18 satellite passing close to KAIRA during the EEP event (CNA approximately 1 dB). They found that the energy of the precipitating electrons depends on the MLT, with increase (decrease) in EEP flux for energies >200 keV (<40 keV) with MLT. These higher energy EEPs were found to be coincident with the formation of patchy structure in the diffuse aurora observed at ground. Interaction of the high energy electrons with the lower band chorus waves are considered as the causative mechanism for the observed EEP.

High energy EEP can hence result in increased ionization at mesospheric altitudes (50–85 km). This increased ionization can have a significant impact on HOx and NOx production rate at geomagnetic latitudes between about 55° and 75°, leading to a catalytic effect of ozone depletion (M. Andersson et al., 2014; M. E. Andersson et al., 2012; Verronen et al., 2011). The EEP effect on mesospheric ozone, both in day-to-day changes and in longer term variability is observed and reported (M. Andersson et al., 2014; Verronen et al., 2013). However, the accurate quantification of the effect of EEP on the total solar-driven energetic particle precipitation (EPP) forcing and the associated atmospheric and climate response remains a key challenge. Simulating the changes in the atmospheric chemistry lacks crucial input concerning the magnitude of the EPP forcing related to the ionization caused by the precipitation of energetic electrons. This is mainly because of the limitations of the satellite observations in determining the precipitating flux values from the particle flux observations which comprise both trapped and precipitating electrons. The satellite-based observation lacks accurate determination of the precipitating electron flux values (Tyssy et al., 2016) due to the less angular resolution and large acceptance angle of the on-board electron telescopes. With particles having a range of different pitch angle distribution, it is difficult to estimate accurately the precipitating flux values using satellite.

Previous EEP studies using coordinated observations from satellite and ground has compared the CNA observed by riometers and the energetic electron flux measured by NOAA’s POES series of low earth orbiting (LEO) satellites (Hargreaves et al., 2010; Rodger et al., 2013; Tanaka et al., 2005). They have estimated the CNA using the electron flux values obtained from 0° (precipitating flux) and 90° (trapped flux) telescopes of the medium energy particle detectors (>30 keV) on board satellite. These studies have shown that the CNA estimated from the precipitating electron flux (0° detector) underestimate the actual riometer absorption. Tanaka et al. (2005) showed that compared to precipitating flux, the CNA estimated from trapped electron flux has higher correlation
with observed CNA. Their study shows that CNA expected from the actual pitch angle distribution should be between the two (precipitating and trapped flux) estimates. Hargreaves et al. (2010) and Rodger et al. (2013) have shown that the combination of the precipitating and trapped flux gives a more realistic estimates of the true EEP flux entering into the atmosphere. All these previous studies point out the limitation of 0° telescope in detecting true EEP flux, as it views only a small portion of the inside of bounce loss cone pitch angle range. The actual precipitation may occur with a larger fraction of electrons precipitating outside the range of 0° telescope (Rodger et al., 2013).

The space born observations of EPP events are mainly obtained from LEO satellites in highly inclined orbits. Although they can more directly measure the precipitating flux using the particle detectors aligned along the field lines, these satellite observations often underestimates the precipitation flux and have limited energy resolution. Also, as they are far from the plasma wave populations originating close to the equator, LEO satellites cannot measure directly the plasma waves responsible for these precipitations. Equatorial/near-equatorial magnetospheric satellites on the other hand are ideal for in situ wave measurements but they cannot often distinguish between the trapped and precipitating particles due to the limited angular resolution of the particle telescopes in resolving the small loss cone angles at magnetospheric altitudes. Inner magnetospheric satellite mission, Arase has the capability of identifying precipitating flux using onboard high angular resolution particle detectors. S. Kasahara, Miyoshi, et al. (2018) identified for the first time the precipitating flux inside loss cone caused by the chorus waves at the equator using the Arase observations.

In the present paper, we have used plasma observations from the Arase satellite in the inner magnetosphere and the cosmic noise absorption data from riometers located in the auroral/sub-auroral latitudes to study the EPP events. We have surveyed one and a half years data and statistically investigated the relation between the plasma flux and wave observations at the satellite with the ground CNA during the Arase riometer conjunction intervals. In this study period, the apogee of Arase has swept through all MLT sectors and has satellite riometer conjunction events covering all MLTs. With this comparative study, we intend to resolve the dynamics in the inner magnetosphere, when precipitation is observed at ground. The uniqueness of this study is that, here we have considered all the conjunction events with and without CNA and a general scenario at Arase location during precipitation and non-precipitation events is derived. To the best of authors' knowledge, this is the first study utilizing such a large data set covering all MLTs and statistically comparing the flux and wave observations at satellite with ground CNA.

The following Sections 2 and 3 respectively describe the data and methodology used in the study. Section 4 presents the statistical results. The outcomes of the study are discussed and summarized in Section 5 and finally the results are concluded in Section 6.

2. Data

In this study, the EPP events are investigated using conjugate observations from ground and space platforms. We have surveyed nearly one and a half years (March 2017 to September 2018) of cosmic noise absorption (CNA) data from ground riometers and plasma wave and flux data observed by Arase satellite in the inner magnetosphere.

2.1. Riometer Data

Riometers are instruments which can measure the opacity of the ionosphere to cosmic radio noise. During precipitation events, the enhanced ionization in the ionospheric D region will result in increased absorption of the incoming cosmic radio noise (Hargreaves, 1969). The additional ionization due to EPP can be detected at ground using riometers by subtracting the average sidereal absorption of the radio noise (referred to as quiet day curve) from the actual observations. This enhanced absorption from the background value is referred in this study as CNA. Present paper utilizes CNA data from a latitudinal chain of six riometer stations covering auroral and sub-auroral latitudes operated by Sodankylä Geophysical Observatory in Northern Finland (https://www.sgo.fi/Data/Riometer/riometer.php). The riometer stations and their geographic coordinates along with L shells are shown in Figure 1a. The instruments used are traditional narrow band, wide-beam (60°) riometers, operating at frequencies 30.0 and 32.4 MHz. The riometer signal is sampled at 10 Hz and the CNA data is available at 1 min time resolution.
2.2. Satellite Data

Arase, formally known as Exploration of energization and Radiation in Geospace (ERG; Miyoshi, Shinohara, Takashima, et al., 2018) is a Japanese (JAXA/ISAS) inner magnetospheric satellite mission launched in December 2016. Arase moves in an elliptical orbit with an apogee of 32,110 km (∼5 \( R_E \)) and a perigee at ∼460 km and has an orbital inclination of 31°. We have used the electron/proton flux data and plasma wave (electric/magnetic field) observations obtained from different plasma instruments onboard Arase satellite.

In this study the electron and proton flux data used are the omnidirectional flux. It should be noted that the flux data inside the loss cone (precipitation flux) observed by Arase is not routinely available as it depends on the direction of the ambient magnetic field. It is therefore difficult to perform a statistical study based on the limited precipitation flux data available. The electron flux data used are obtained from Extremely High-Energy Electron Experiments (XEP; 400 keV– a few MeV; Higashio et al., 2018a, 2018b), High-Energy Electron Experiments (HEP-L; 70 keV–1 MeV; Mitani, Hori, et al., 2018; Mitani, Takashima, et al., 2018), Medium-Energy Particle experiments – Electron analyzer (MEP-e; 7–87 keV; S. Kasahara, Yokota, Hori, et al., 2018; S. Kasahara, Yokota, Mitani, et al., 2018), and Low-Energy Particle experiments – Electron analyzer (LEP-e; ∼19 eV–19 keV; Kazama et al., 2017; Wang et al., 2018). The proton flux data used are obtained from Medium-Energy Particle experiments – Ion mass analyzer (MEP-i; Yokota et al., 2018; Yokota et al., 2017; energy range: 10–180 keV/q), and Low – Energy Particle experiments – Ion mass analyzer (LEP – i; Asamura, Kazama, et al. (2018); Asamura, Miyoshi, and Shinohara (2018); energy range: 0.01–25 keV/q). The energy – time spectra of the electron and proton flux are investigated.

The plasma wave observations are obtained from the Onboard Frequency Analyzer (OFA) on Plasma Wave Experiment (PWE) instrument (Y. Kasahara, Kasaba, et al., 2018; Y. Kasahara, Kojima, et al., 2018; Matsuda et al., 2018) onboard Arase satellite. OFA provides the power spectral densities of the electric and magnetic fields in the frequency range from a few Hz to 20 kHz at 1 s sampling.
3. Methodology

The simultaneous observations of CNA data from ground riometer stations and plasma flux/wave data from the Arase satellite in the inner magnetosphere during the satellite-ground conjunction interval are investigated. Through this analysis, we aim to derive a statistical picture of the plasma flux and waves in the inner magnetosphere and its possible relation to observed ground CNA.

In this study, first, we have identified all conjunction events occurred during the study period, March 2017–September 2018. The criteria used for the event selection are, (a) Arase L shell located within ±0.2 of that of the ground station and (b) the geographic longitude of Arase ionospheric footprints (at 100 km) in the northern hemisphere is within ±15° of that of the ground station. The ionospheric footprints of Arase and the Mcllwain L shell values used here are obtained using the IGRF model from Arase Level-2 orbit file (Miyoshi, Shinohara, & Jun, 2018).

An example illustrating the conjunction event of Arase with ground riometers on 15 April 2017 is shown in Figure 1. In Figure 1a, the map shows geographic location of the ground stations and the Arase ionospheric footprints. Figure 1b shows the CNA data from 6 riometer stations, where the red dots indicate the time of Arase conjunction with each station. It can be seen from Figure 1b that Arase has good conjunction with Abisko and Ivalo stations and also there was clear enhancement in the CNA (∼1.5 dB) in both stations around 02:00 UT, indicating enhanced ionization in the lower ionosphere. In this event, Sodankylä and Rovaniemi stations do not have conjunctions with Arase and therefore are not considered. Oulu and Jyväskylä on the other hand have short conjunction periods close to 04:00 and 05:00 UT respectively, however no enhancement in CNA was observed.

Based on the riometer absorption values, the conjunction events identified during the entire study period are then classified into CNA (absorption >0.5 dB) and non-CNA (absorption <0.5 dB) events. Figure 2 shows the MLT distribution of the percentage occurrence of CNA (red bars) and non-CNA (blue bars) events during Arase conjunction with each riometer station. The percentage occurrence is estimated as the ratio between the number of events in each MLT sector and the total number of events and are calculated for CNA and non-CNA events separately. In the considered study period, Arase apogee spans all MLT sectors and hence we have satellite conjunction with riometers covering all MLTs. The percentage occurrence of non-CNA events (blue bars) are more or less uniformly distributed in all MLTs. However, the percentage occurrence of the CNA events (red bars) are higher in the post-midnight to noon MLTs. In the figure, N indicates the total number of CNA and non-CNA conjunction events for each stations.
The dependence of the geomagnetic disturbances on the occurrence of CNA and non-CNA events are investigated by analyzing the Kp index and is shown in Figure 3. The percentage occurrence of the CNA events is clearly dominant during disturbed geomagnetic conditions with Kp ≥ 3, whereas the non-CNA events showed a decreasing occurrence with increasing Kp. We have also checked the dependence of the AE index on the occurrence of the CNA events (figure not shown here) and found that nearly 87% of the CNA events occurred during high AE values (≥200 nT), indicating its association with substorms.

The next step is to investigate the electron/proton flux and the plasma wave spectra observed by Arase in the inner magnetosphere during the conjunction interval. For each Arase conjunction event with a ground riometer station, we have estimated the median spectra for the electron/proton flux and electric/magnetic field power. These median spectra are then categorized into CNA (absorption >0.5 dB) and non-CNA (absorption <0.5 dB) cases. Once we have collected the median spectra for all the events, we have then calculated the weighted median for CNA and non-CNA cases separately. Here the weights of each event is the number of data points in the conjunction time interval. In the present analysis the error bars of the weighted median is shown as standard error (standard deviation divided by the square root of the total number of CNA/non-CNA cases). The standard deviation of the weighted median is estimated as the median of the absolute deviations (MAD) of the weighted median from individual median spectra.

4. Statistical Results of Arase Plasma Flux and Wave Data

In this section we present the statistical results of the Arase plasma flux and wave observations in the inner magnetosphere during CNA and non-CNA events observed at different riometer stations during conjunction intervals.

Figure 4 shows the weighted median of the energy spectra of the electron fluxes in low (LEPe), medium (MEPe), high (HEP), and extreme high (XEP) energy ranges during CNA (red stars) and non-CNA (blue stars) events. Through this combined LEPe, MEPe, HEP, and XEP spectra, we intent to investigate the energy range in which the Arase flux is associated to the riometer absorption. From Figure 4, it can be seen that the deviation between blue (non-CNA events) and red (CNA events) spectra are found to be large in the MEPe, and higher energy part of LEPe observations, indicating significant flux enhancement between a few keV to approximately 100 keV during CNA. This observation suggest enhanced injection of plasma sheet electrons at Arase location during the ground CNA events. The LEPe, HEP, and XEP instruments also showed a marginal yet systematic enhancement in the electron flux during CNA. However, the flux enhancement in the XEP instrument (>500 keV) is found to be higher. These conjugate observations from satellite and ground clearly indicate the association of the ground
CNA with plasma sheet electron (<100 keV) injection at Arase location. The small enhancement in high energy (>100 keV) electrons may also indicate the contribution of outer radiation belt electron enhancements on the observed CNA. Please note that the riometers used in this study are sensitive to precipitating electrons with energies >30 keV.

In Figure 4, it is also interesting to note that the shape of the MEPe electron spectra during CNA events (red) changes as we move toward lower latitudes. At Abisko (Figure 4b), the red spectra had a maximum deviation from blue one close to ∼10 keV. But as we move to lower latitude stations, that is, from Abisko (Figure 4b) to Oulu (Figure 4f), energy of the maximum flux peak shifts to higher energies as indicated by green arrows in Figure 4. This may indicate that higher energy electrons are precipitated to lower latitudes. We have estimated the ratio of the CNA to non-CNA electron flux. The peak values of the flux ratio and the corresponding energies at each riometer L shells are shown in Table 1. It should be noted that the number of CNA events (indicated as N) decreases as we move toward lower latitudes, that is, Abisko has highest number of CNA events and Jyväskylä has zero events. Also N depends on the availability of the good data from each instruments. With Oulu having only four CNA events, its statistical significance has to be considered carefully. Please note that inter-calibrations between different sensors of Arase particle instruments have not been completed yet, so that there is gap of flux between different instruments.

Similar to Figure 4, we have investigated the omnidirectional ion flux spectra in the medium and low energy range observed by Arase during CNA and non-CNA events (Figure 5). It should be noted that we do not expect a direct causality: the Arase ion fluxes are limited to energies <180 keV/q which are incapable of ionizing the altitudes below 100 km (Fang et al., 2013) and hence producing the CNA observed. Instead, this analysis is intended to understand the total proton flux level at Arase when CNA is observed at ground. Figure 4 shows a marginal, although systematic increase in the proton flux in both low and medium energy range. This result may also support the idea of enhanced injection of plasma sheet particles during ground CNA.

Figures 6 and 7 show the power spectra of the magnetic and electric fields respectively during CNA (red) and non-CNA (blue) events in the same format as Figures 4 and 5. Figures also show the median value of the equatorial electron gyro-frequency ($f_{ce}$) estimated at each riometer L shell for the Arase conjunction interval during CNA. Please note that the $f_{ce}$ values are

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**Table 1**

| Station name | L shell | Energy (keV) | Ratio peak e−flux (CNA/non-CNA) |
|--------------|---------|-------------|---------------------------------|
| Abisko       | 5.9     | 10.1        | 25.2                            |
| Ivalo        | 5.8     | 14.3        | 21.1                            |
| Sodankylä    | 5.3     | 35.0        | 20.6                            |
| Rovaniemi    | 5.1     | 24.5        | 38.3                            |
| Oulu         | 4.5     | 35.0        | 24.7                            |
estimated using the magnetic field strength mapped to the magnetic equator, using IGRF model obtained from Arase Level-2 orbit file. Here we examine statistically the presence of VLF (very low frequency) plasma waves at Arase location when CNA is observed at ground. Figures 6 and 7 show very clear and interesting observations of the presence of waves in both magnetic and electric field spectra with a peak power between 0.5 and 3 kHz during CNA events. Also the frequency of the peak power is found to be less than $0.5 f_{ce}$. This observation indicates the presence of whistler mode chorus waves, especially lower band chorus (LBC) in the inner magnetosphere at Arase location during ground CNA events. During non-CNA cases, no significant VLF wave activity is observed.

Figure 5. Same as Figure 4 but for the energy spectra of proton flux in low (LEP-i: 0–10 keV), and medium (MEP-i: 10–180 keV) energy range.

Figure 6. Weighted median of the power spectra of ac magnetic fields observed by Arase satellite during CNA (red) and non-CNA (blue) events over ground riometer stations (a) Abisko, (b) Ivalo, (c) Sodankylä, (d) Rovaniemi, (e) Oulu, and (f) Jyväskylä. The error bars indicate the standard error of the weighted median spectrum. The L shell values and the equatorial electron gyro-frequencies at each riometer stations are indicated in the panels (a)–(f).
Similar to electron flux, we have estimated the ratio of the plasma wave power in the magnetic field between CNA and non-CNA events. The peak values of the power ratio and the corresponding frequencies along with $0.5f_{ce}$ values for each station are shown in Table 2.

Our statistical analysis of particle flux and waves therefore clearly indicates that when riometers observed CNA events, which is a ground truth for EEP, Arase located in the same L shell of the riometer station observed enhanced electron flux in the energy range between a few keV and approximately 2 MeV and also the presence of whistler mode chorus waves in the frequency range 0.5–3 kHz.

5. Summary and Discussion

In this paper CNA data from ground riometers located in auroral/sub-auroral latitudes and simultaneous particle and wave observations from Arase satellite in the inner magnetosphere are investigated statistically to understand the relation between the precipitation observed at ground and the dynamics in the inner magnetosphere.

We have analyzed one and a half years of data during the Arase conjunction interval with the ground riometer stations for both CNA and non-CNA periods. The CNA events investigated here showed a higher occurrence in the post-midnight to noon MLT hours (Figure 2) and during disturbed geomagnetic conditions with $Kp > 3$ (Figure 3) and $AE > 200$ nT (figure not shown). These observations suggests that the CNA events investigated here are predominantly associated with substorm.

It is clearly evident from the study that when precipitation is observed at ground (CNA events), a significant enhancement in the electron flux ($\sim$1 order magnitude) in the medium energy range ($\sim$2–100 keV) is observed by Arase (Figure 4). This observation is in accordance with study by Oyama et al. (2017), who reported a selective increase in the precipitating electron flux with energy $>10$ keV during EEP intervals. The enhanced electron flux at Arase in the medium energy range suggest plasma sheet electrons injected into the inner magnetosphere during ground CNA events (Jaynes et al., 2015; Li, Thorne, Angelopoulos, Bonnell, et al., 2009; Miyoshi et al., 2021; Miyoshi, Oyama, et al., 2015). Here with omnidirectional flux data we cannot discuss the direct causality of the medium energy ($<100$ keV) electrons on the observed CNA. However, the statistical results clearly show that the medium energy electron flux associate well with the ground CNA.

### Table 2

| Station name | L shell | Frequency (kHz) | Ratio peak Bfield power (CNA/non-CNA) | $0.5f_{ce}$ (kHz) |
|--------------|---------|----------------|---------------------------------------|-------------------|
| Abisko       | 5.9     | 1.2            | 7.1                                   | 2.0               |
| Ivalo        | 5.8     | 0.8            | 7.9                                   | 2.1               |
| Sodankylä    | 5.3     | 1.0            | 7.9                                   | 2.7               |
| Rovaniemi    | 5.1     | 1.0            | 17.8                                  | 3.1               |
| Oulu         | 4.5     | 2.8            | 15.8                                  | 4.5               |
indicating that the plasma sheet injection has a direct or indirect effect on the observed CNA. The distribution of Kp (Figure 3) and AE indices (figure not shown here) on the occurrence of CNA events indicate the association of substorm and hence supports the idea of injection of plasma sheet particles.

Figure 4 also shows a change in the shape of the medium energy electron spectra during CNA events with a small shift in the energy of the peak electron flux at different riometer stations. The energy of the peak CNA to non-CNA electron flux ratios are found to increase with decreasing L shell (Table 1). This may indicate higher energy electron precipitation at lower latitudes (i.e., lower L shells), which suggests that the most contributed energy to CNA may depend on L shell. It should be noted that the ground riometers used in this study are sensitive to precipitating electrons with energies >30 keV. A small enhancement in the electron flux is also observed in the high energy part of the spectra mainly at >500 keV indicating the contribution of outer radiation belt electrons on the observed CNA.

The simultaneous plasma wave observations from Arase (Figures 5 and 6) show clear enhancement of the wave power in the frequency range 0.5–3 kHz in both magnetic and electric fields. The peak frequency of the wave is found to be less than half the equatorial gyro frequency of the electrons at each L shell of the riometer stations during the Arase conjunctions (Table 2). These results suggest the presence of whistler mode chorus wave at Arase location during ground CNA events. Many previous studies have identified the role of whistler mode chorus waves on the precipitation of energetic electrons (10s of keV) (Miyoshi, Oyama, et al., 2015; Li et al., 2010). Our observations of higher occurrence of the CNA events in the near-midnight and postmidnight sectors and is the dominant cause of diffuse aurora. Whistler mode chorus waves are known to occur predominantly in the pre-midnight to dawn MLT sector outside the plasmapause location and L shell <8 (Li et al., 2010). Our observations of higher occurrence of the CNA events in the post-midnight to morning MLT (Figure 2) may also suggest the dominant role of whistler mode chorus waves in the precipitation of the energetic electrons.

In the present study, the combined wave and flux observations from Arase clearly portrays a dominant scenario in the inner magnetosphere during ground CNA events. Our study reveals that when CNA is observed at ground, in general there is enhanced injection of the plasma sheet electrons into the inner magnetosphere. These freshly injected plasma sheet electrons (<100 keV) in the night side drift toward noon through dawn MLT and provide free energy source for the generation of whistler mode chorus waves, which in-turn results in the pitch angle scattering of the energetic electrons by whistler mode chorus waves using Arase observations. Thorne et al. (2010) using CRRES and Polar satellite observations together with numerical simulations have shown that the plasma sheet electrons (0.1–50 keV) injected into the inner magnetosphere are predominantly scattered by whistler mode chorus waves in the near-midnight and postmidnight sectors and is the dominant cause of diffuse aurora. Whistler mode chorus waves are known to occur predominantly in the pre-midnight to dawn MLT sector outside the plasmapause location and L shell <8 (Li et al., 2010). Our observations of higher occurrence of the CNA events in the post-midnight to morning MLT (Figure 2) may also suggest the dominant role of whistler mode chorus waves in the precipitation of the energetic electrons.

In the present study, the combined wave and flux observations from Arase clearly portrays a dominant scenario in the inner magnetosphere during ground CNA events. Our study reveals that when CNA is observed at ground, in general there is enhanced injection of the plasma sheet electrons into the inner magnetosphere. These freshly injected plasma sheet electrons (<100 keV) in the night side drift toward noon through dawn MLT and provide free energy source for the generation of whistler mode chorus waves, which in-turn results in the pitch angle scattering of the energetic electrons (10s of keV to few MeV) comprising both plasma sheet and outer radiation belt electrons. Through this study a direct relationship between the enhancement of whistler mode chorus waves at Arase location and the ground CNA is identified.

The present study is limited to the importance of the CNA caused by the EEP due to the pitch angle scattering by the plasma waves. However, one cannot rule out the contribution of other sources on the observed ground CNA. One possible contamination to the CNA analyzed in this study can be caused by auroral absorption (AA). AA is caused by the high-energy tail of auroral electrons at the time of local auroral break up in the expansion phase of an auroral substorm. It should be noted that AA is caused by direct precipitation of substorm injected electrons and not the result of wave-particle interaction in the magnetosphere. In this study, the CNA data from auroral zone stations, Abisko and Ivalo, in the pre-midnight to midnight hours can be contaminated by AA.

Arase satellite was launched with the aim to study the inner magnetospheric dynamics and how energetic particles are born and get lost due to the interaction with various plasma waves. With on board high-angular resolution particle detectors (LEPe and MEPe), Arase satellite is capable of distinguishing the small loss cone at magnetospheric altitudes. Also, unlike LEO satellites in highly inclined orbits, Arase orbiting in the near equatorial plane is ideal for observing the plasma waves originating close to the equator. This provides a unique opportunity to study the precipitating flux and the plasma waves. In the present study, we have utilized Arase omnidirectional flux data, which consist of both trapped and precipitating flux. At Arase altitudes, as the loss cone width is very small (≈1–2°), the major portion of the omniflux will be constituted by trapped particles. The limitation of this study is that using omniflux data we cannot account for the precipitating flux in the magnetosphere responsible for the observed ground CNA. However, it should be noted that the Arase electron flux observations in the loss
cone are not routinely available as it depends on the direction of the ambient magnetic field. Hence it is practically difficult to to perform such a statistical study based on the pitch angle resolved data. Our study utilizing omnidirectional flux data provides an estimate of the change in the total flux at Arase location and also the energy range of the particles corresponding to the enhanced flux during ground precipitation intervals. The clear association observed between medium energy electron flux and ground CNA suggests that the omnidirectional flux data of MEPe can be used as an indicator for CNA caused by EEP. It is important as the availability of precipitating flux (loss cone data) is limited.

A more detailed event study utilizing the precipitating flux within the loss cone and the plasma wave observations from Arase will be carried out in the future, to explore the mechanisms responsible for the precipitation observed at ground in different MLT sectors.

6. Conclusions

EEP events are studied statistically using CNA data from ground riometers and the omnidirectional electron flux and plasma wave data from Arase satellite in the inner magnetosphere covering observations from all MLT sectors. The observed CNA events are found to have preferential occurrence in the post-midnight to noon MLT and also during disturbed geomagnetic conditions, suggesting its association with substorms. The statistical results show the association of ground CNA with the enhanced electron flux in the medium energy range, a few keV to 100 keV at Arase, indicating plasma sheet electron injection. Also the CNA events are found to be associated with enhanced plasma wave power in the frequency range 0.5–3 kHz at Arase location. The whistler mode chorus wave driven EEP is considered as the dominant causative mechanism responsible for the observed CNA. The study suggest that omnidirectional flux data of MEPe can serve as an indicator for CNA caused by EEP.

Data Availability Statement

Science data of Arase mission are available from ERG Science center operated by ISAS/JAXA and ISEE/Nagoya University (http://ergsc.isee.nagoya-u.ac.jp/, Miyoshi, Hori, et al., 2018). The study utilized Level-2 omnidirectional flux data of LEP-e v02.02 (Wang et al., 2018), MEP-e v01.02 (S. Kasahara, Yokota, Hori, et al., 2018), HEP-L v01.03 (Mitani, Hori, et al., 2018), KEP v01.00 (Higashio et al., 2018b), LEPI v03.00 (Asamura, Miyoshi, & Shinohara, 2018), MEP-i v02.01 (Yokota et al., 2018), and PWE/POF Level-2 v02.01 power spectrum data (Y. Kasahara, Kojima, et al., 2018) and orbit Level-2 v02 (Miyoshi, Shinohara, & Jun, 2018) data. The riometer data are obtained from the Sodankylä Geophysical Observatory (http://www.sgo.fi) server and is available upon request.

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