Earth, Planets and Space

EXPRESS LETTER Open Access

Solar and geomagnetic activity dependence of 150-km echoes observed by the Equatorial Atmosphere Radar in Indonesia

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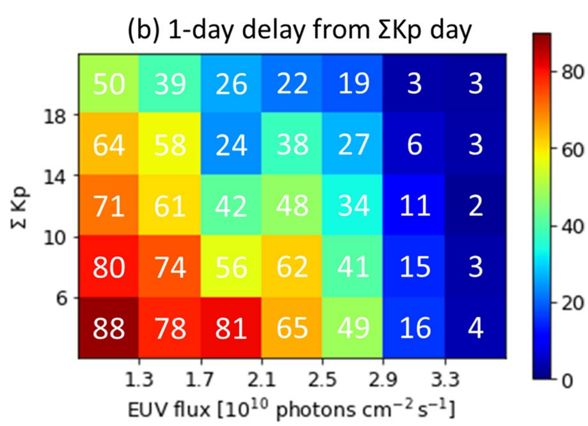
Abstract

The occurrence characteristics of 150-km echoes in low-latitude regions are studied using the Equatorial Atmosphere Radar (EAR) in Indonesia. The long-term observation of the 150-km echoes by the EAR enables us to study the occurrence characteristics of 150-km echoes statistically. It is shown that the occurrence rate of the 150-km echoes observed by the EAR shows a semiannual variation with two peaks in solstices and a negative correlation with both the EUV flux and ΣKp index, that is, the solar and the geomagnetic activity. Geomagnetic activity correlates with the occurrence rate of 150-km echoes observed one day after when the ΣKp was measured. However, the occurrence rate is always low during the high solar activity period regardless of the geomagnetic activity. While the seasonal variation and the solar activity dependence of the occurrence of 150-km echoes are consistent with previous studies, this is the first time a negative correlation with geomagnetic activity is reported.

Keywords: Equatorial ionosphere, 150-km echoes, Equatorial Atmosphere Radar

Graphical Abstract



Introduction

150-km echoes frequently observed by VHF radars in equatorial and low-latitude regions have been a puzzling phenomenon for more than a half century (Balsley 1964). They are observed from the direction perpendicular to

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the geomagnetic field and generally show a necklace-like pattern in range-time-intensity plots and a narrow spectral width (e.g., Kudeki and Fawcett 1993). While 150-km echoes have been considered to be generated by the unstable growth of field-aligned irregularities (FAIs), another mechanism named naturally enhanced incoherent scattering (NEIS) was proposed in association with the echoes from off-perpendicular directions (Chau et al. 2009). The two types of echoes actually coexist and have been named type A and type B (Chau and Kudeki 2013). The type A is associated with NEIS process in which the spectral width is proportional to that of signal-to-noise ratio (SNR), and the type B is related with FAIs in which the spectral width is very small regardless of SNR (Patra 2011; Chau and Kudeki 2013; Patra and Chaitanya 2016). On the other hand, Patra et al. (2020) proposed that both types of echoes are primarily of common origin linked with the NEIS process and atmospheric gravity waves play an important role in driving the 150-km echoes as originally proposed by Kudeki and Fawcett (1993). Recent high-resolution observation by the Jicamarca VHF radar revealed that the 150-km echoes were likely modulated by gravity waves (Reyes et al. 2020), whereas it does not mean that gravity waves play a critical role in generation of 150-km echoes.

In a last few years, there were great advances in understanding the generation mechanism of the 150-km echoes based on numerical simulations and theoretical investigations. Oppenheim and Dimant (2016) showed that photoelectrons can drive electron waves and ion density irregularities that radars could observe as 150-km echoes based on kinetic simulations. The spectrum of electron waves that could be observed by a VHF radar is enhanced in the direction perpendicular to the geomagnetic field. This model explains the daytime occurrence and spectral characteristics of 150-km echoes consistently. Longley et al. (2020) proposed the photoelectron-driven upper hybrid instability as the generation mechanism of 150-km echoes, which can also explain multiple gaps of radar echoes where the upper hybrid frequency equals integer multiples of the electron gyrofrequency (Lehmacher et al. 2020; Reyes et al. 2020). It was also shown that a solar flare has a strong impact on the 150-km echoes (Pedatella et al. 2019). There is no doubt that the solar radiation plays a critical role in the generation of 150-km echoes.

While 150-km echoes had been considered to be specific within the equatorial electrojet belt for several decades, they have been detected at various off-equatorial stations (e.g., Patra and Rao 2006; Patra et al. 2008; Yokoyama et al. 2009; Rodrigues et al. 2011). It has been known from various observations that the occurrence characteristics of 150-km echoes largely depend on the locations of observatories. Tsunoda and Ecklund (2004) showed the maximum occurrence during the June solstice period at Pohnpei, Federated States of Micronesia. Chau and Kudeki (2006) also showed the maximum during the June solstice period at Jicamarca and no correlation with magnetic activity. The occurrence during the December solstice period at the two locations was quite low. On the other hand, the occurrence during the December solstice period was comparable to that during the June solstice in Brazil (Rodrigues et al. 2011) and Asia (Patra et al. 2012). There is no clear explanation of the seasonal variation depending on the locations.

Another unresolved problem is solar activity dependence of the occurrence characteristics. Based on the photoelectron-driven mechanism, one could infer that more photoelectrons are generated when the solar flux increases, resulting in higher occurrence of 150-km echoes. However, Patra et al. (2017) showed that the occurrence of 150-km echoes observed by the Gadanki radar and the Equatorial Atmosphere Radar (EAR) in Indonesia was inversely correlated with the solar activity, which may not be explained by the NEIS mechanism proposed by Oppenheim and Dimant (2016). Patra et al. (2017) suggested that more collisions of photoelectrons with ambient electrons during the high solar activity period may contribute to damp large amplitude waves generated by the photoelectrons.

To further understand and verify the proposed generation mechanism of 150-km echoes, it is important to reveal the occurrence characteristics of 150-km echoes. In this study, we reanalyzed the long-term observations of 150-km echoes by the EAR and classified the occurrence of 150-km echoes by solar and geomagnetic activity because previous statistical studies did not pay attention to the geomagnetic activity (e.g., Patra et al. 2012; Patra et al. 2017). The present results clearly show that the occurrence of 150-km echoes have negative correlations with both solar and geomagnetic activity.

Data

The 47-MHz EAR is located at Kototabang, Indonesia (0.20°S, 100.32°E, 10.36°S dip latitude) and has been operated since 2001. The EAR has an active phased-array antenna system that allows rapid beam steering on a pulse-to-pulse basis with a peak transmitter power of 100 kW (Fukao et al. 2003). The observations of 150-km echoes by the EAR were conducted intermittently from August 2007 to July 2010 (Patra et al. 2008; Yokoyama et al. 2009), then daily observations started in July 2010 and continued until May 2020 (e.g., Patra et al. 2017; Pavan Chaitanya et al. 2017, 2018) The radar beams were directed to be perpendicular to the geomagnetic field lines and regularly adjusted by taking the secular variation into account based on the International

Geomagnetic Reference Field (IGRF) model (Alken et al. 2021). Those data are available at the EAR website with detailed observation parameters (http://www2.rish.kyoto-u.ac.jp/ear/data-fai/). All observations of 150-km echoes were visually checked and counted as a date of occurrence if echo patches with a signal-to-noise ratio of over −6 dB were observed in an altitude range of 130–170 km and a time range of 0900–1500 LT. The threshold SNR value was determined to best detect 150-km echoes and not to be suffered by background noises. A typical necklace shape of 150-km echoes is not considered as a necessary condition. Even a small patch of backscatter echoes that appeared in the time and altitude ranges was counted as 150-km echoes.

A long-term data set enables us to study the dependence of the occurrence rate of 150-km echoes on both solar and geomagnetic activity. For the index of solar activity, we used the EUV flux (0.1–50 nm) measured by Solar EUV Monitor (SEM) on the Solar and Heliospheric Observatory (SOHO) satellite to be consistent with the previous study by Patra et al. (2017). For the index of geomagnetic activity, we used Kp index obtained from World Data Center for Geomagnetism, Kyoto. Eight Kp indices in a day are added to be ΣKp per day.

Results and discussion

All 150-km echoes observed by the EAR are considered as type B generated by field-aligned irregularities because the EAR is not as powerful as the Jicamarca or Gadanki radars and is not able to detect type A echoes due to NEIS (Chau and Kudeki 2013). The monthly occurrence rates of the 150-km echoes observed by the EAR from August 2007 to May 2020 are shown in Fig. 1. It is clear that the occurrence characteristics have two maxima in solstices and two minima in equinoxes, which is consistent with previous analyses of the EAR data (Patra et al. 2012; Patra et al. 2017). The variation shows an obvious semiannual pattern with the same maximum occurrence rate in January and July.

Figure 2a, b show the scatter plots of the occurrence rate of 150-km echoes against EUV flux and ΣKp index, respectively. Each dot corresponds to the averaged indices and the occurrence rate for 1 year to remove the seasonal dependence and to be consistent with the result reported by Patra et al. (2017). The occurrence rates clearly show negative correlation with the EUV flux and ΣKp index. While the negative correlation with the solar activity is consistent with the previous study by Patra et al. (2017), the negative correlation with the geomagnetic activity is presented for the first time. As the Kp index may tend to be large during the high solar activity period, the two factors should not be investigated independently. Furthermore, the impact of geomagnetic disturbances on the ionosphere may be delayed for a few days. The delay effect cannot be seen in Fig. 2b because the indices are averaged for one year.

Ionospheric responses to geomagnetic disturbances may appear instantaneously or delay for a few days (e.g., Maruyama et al. 2005). Figure 3 shows a matrix of the occurrence rate of 150-km echoes against the EUV flux on the same day and ΣKp index on (a) the same day, (b) 1 day before, and (c) 2 days before. The number in each cell denotes the occurrence rate in percentage within the range of the two indices. It is again clearly shown that the occurrence rate show the negative correlation with the two indices, but the correlation with the EUV flux is more significant than that with the ΣKp index. The negative correlation with the EUV flux can be clearly discerned at any levels of ΣKp index. The negative correlation with ΣKp index can be clearly discerned especially in 1-day delay case shown in Fig. 3b. In the lowest EUV flux range (the leftmost column), the occurrence rate is 88% and 50% with the lowest and highest ΣKp ranges, respectively, while the correlation

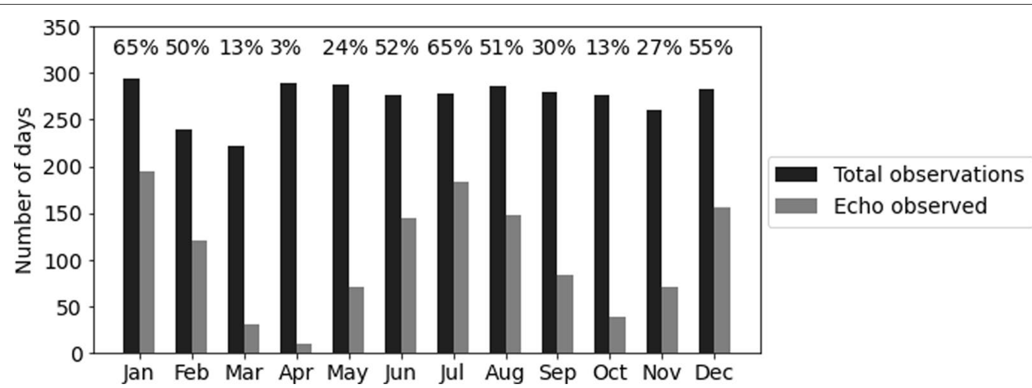

Fig. 1 Monthly occurrence characteristics of 150-km echoes observed by the EAR from August 2007 to May 2020

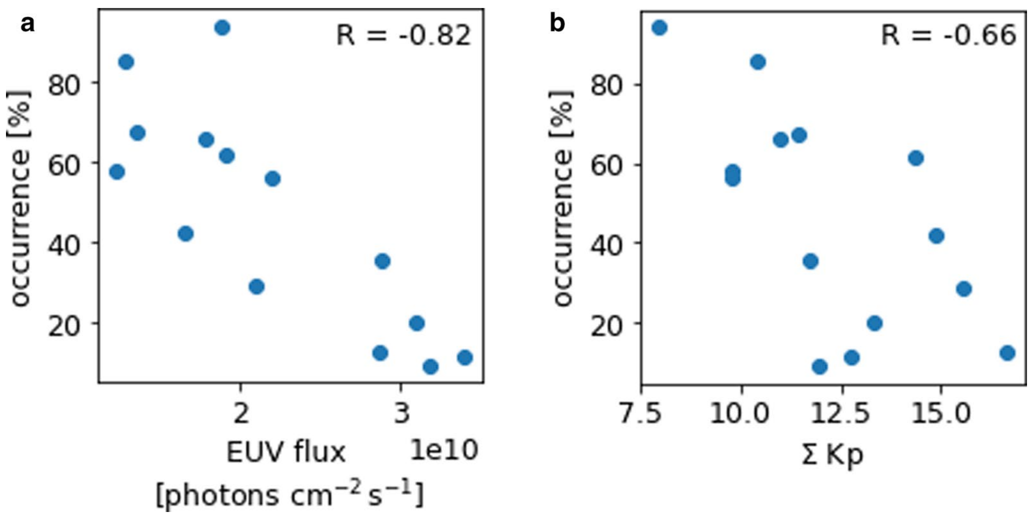

Fig. 2 Scatter plot of the occurrence rate of 150-km echoes against **a** EUV flux and **b** ΣKp index. Each dot corresponds to the averaged indices and the occurrence rate for 1 year

is weaker in Fig. 3a, c. In the highest EUV flux range (the rightmost column), the occurrence rate is very low regardless of the ΣKp index. It might be possible that the geomagnetic activity itself has a seasonal variation so that the above results could appear. However, even though the data during only the solstice month is used, the same ΣKp dependence can be observed (not shown), which means that the dependence on ΣKp index is not an artifact due to the seasonal variation of geomagnetic activity. It can be concluded that the solar activity is a major factor that controls the occurrence of 150-km echoes and the geomagnetic activity is a minor factor that weakly impacts on the 150-km echoes.

The photoelectron-driven upper hybrid instability proposed by Longley et al. (2020) can explain many aspects of 150-km echoes. However, the occurrence characteristics of the 150-km echoes presented here, that is, higher occurrence in solstices than in equinoxes and negative correlation with solar and geomagnetic activity, are puzzling and cannot be directly explained by the proposed mechanism. Under the conditions of small solar zenith angle in equinoxes and during the high solar activity period, the solar EUV flux would become strong and generate more photoelectrons. Although the photoelectron model does not claim a simple relation between the solar EUV flux and 150-km echoes, it is worth noting that the total photoelectron density, that is, the solar EUV flux, is not a key factor in the photoelectron model. There must be extra factors that control the generation of 150-km echoes such as an energy distribution of photoelectrons. Further numerical and theoretical considerations may be required to understand the occurrence characteristics.

The occurrence characteristics of 150-km echoes may help to understand its generation mechanism. Although the observations of 150-km echoes often show the manifestation of gravity waves (Reyes et al. 2020), it does not mean that gravity waves are a source of 150-km echoes. If 150-km echoes were primarily driven by a certain process of neutral atmosphere such as atmospheric gravity waves, the dependence on geomagnetic activity would not be so significant. In other words, electrodynamics should be more significant than the dynamics of neutral atmosphere in the generation of 150-km echoes. Electric fields in the equatorial region can be modulated by geomagnetic disturbances via prompt penetration or disturbance dynamo mechanisms (e.g., Maruyama et al. 2005). The fact that geomagnetic activity correlates with the occurrence rate of 150-km echoes observed 1 day after when the ΣKp was measured implies that overshielding or disturbance dynamo electric field may play a role in suppressing the occurrence of 150-km echoes. However, electric fields do not explicitly appear in the derivation of photoelectron-driven upper hybrid instability (Longley et al. 2020). Electric fields may play an indirect or a secondary role in the generation of 150-km echoes, that is, amplification or attenuation of the seeded upper hybrid instability initiated by photoelectrons. In addition, we have to take the semiannual variation with two maxima during the solstice period of the occurrence rate of 150-km echoes into consideration, which makes a thorough interpretation quite difficult. It may be possible to link the occurrence of 150-km echoes with the global SQ and equatorial electrojet current system that should

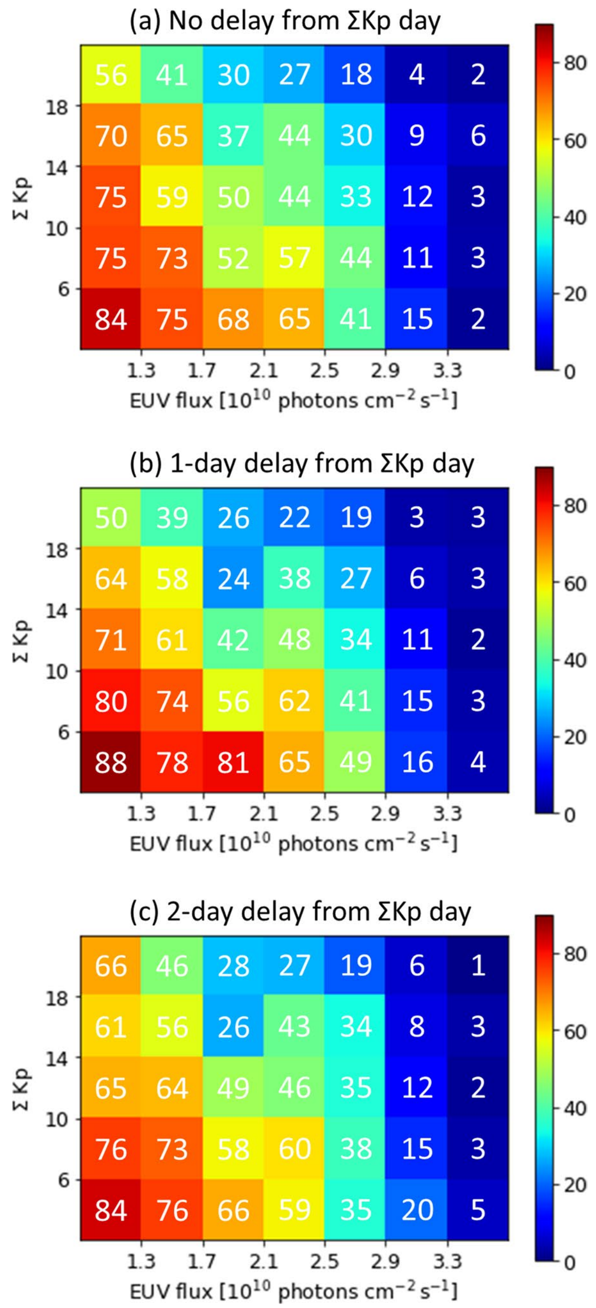

Fig. 3 Matrix of the occurrence rate of 150-km echoes against the EUV flux on the same day and ΣKp index on **a** the same day, **b** 1 day before, and **c** 2 days before. The number in each cell denotes the occurrence rate in percentage within the range of the two indices

also be affected by the solar and geomagnetic activity as well as seasons and longitudes (Yamazaki and Maute 2017). Although the photoelectron-driven mechanism is a strong candidate for the generation mechanism of 150-km echoes, there must be other factors that have yet to be discovered.

Conclusions

Based on the long-term observation of the 150-km echoes by the EAR in Indonesia, the occurrence characteristics of the 150-km echoes have been investigated. It has been shown that the occurrence rate of the 150-km echoes shows a semiannual variation with two peaks in solstices and the negative correlation with the EUV flux. Geomagnetic activity correlates with the occurrence rate of 150-km echoes observed after one day when ΣKp was measured during the low and medium solar activity period. However, the occurrence rate is always low during the high solar activity period regardless of the geomagnetic activity. While the seasonal variation and the solar activity dependence of 150-km echoes are consistent with previous studies, the geomagnetic activity dependence is a new finding of the present study and suggests electric fields may play a secondary role in the generation of 150-km echoes. Although there is no doubt that the photoelectron-driven upper hybrid instability mechanism is a strong candidate for the generation of 150-km echoes, the statistical results imply a complex generation mechanism and not fully explained by the proposed theory. Further studies are required to discover unknown factors that control the occurrence of 150-km echoes such as the global SQ and equatorial electrojet current system.

Acknowledgements
This research was carried out by the collaborative research program of the Research Institute for Sustainable Humanosphere (RISH), Kyoto University. The operation of EAR is based upon the Agreement between RISH and LAPAN signed on September 8, 2000.

Author contributions
TY and MY prepared the manuscript and supervised the research direction. RT dealt with the data and conducted the statistical analysis. All authors read and approved the final manuscript.

Funding
This research was partially supported by JSPS KAKENHI Grant Number 20H00197.

Availability of data and materials
The EAR data is available at RISH, Kyoto University (http://www2.rish.kyoto-u.ac.jp/ear/data-fai/). Kp index data is available at World Data Center for Geomagnetism, Kyoto (http://wdc.kugi.kyoto-u.ac.jp/). Solar EUV data was available at Solar EUV Monitor (SEM) on the Solar and Heliospheric Observatory (SOHO) (https://dornsifecms.usc.edu/space-sciences-center/download-sem-data/).

Declarations

Competing interests
The authors have no competing interests.

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Received: 27 December 2021 Accepted: 10 July 2022
Published online: 22 July 2022

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