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Slightly-deformed clouds of enhanced mesospheric sodium and potassium concentration over the SAMA region: a case study

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This work investigates a slightly-deformed cloud of enhanced mesospheric sodium (Na) and potassium (K) layers registered on 24 June 2023 by the dual-beam Na/K LIDAR system operating over the low-latitude sector of São José dos Campos - Brazil (23.1°S; 45.9°W), a region under the influence of the South Atlantic Magnetic Anomaly (SAMA). In this event, these peculiar metal clouds presented a strong and quick intensification with a vertical extension of ~4 km and a duration of only a few minutes. At the same time, evidence of Energetic Particle Precipitation (EPP) was observed in the low-latitude ionosphere. Such a record of the metal layers is rare and presents unique characteristics since it seems to be the Na and K cloud that precedes the C-structures. This suggests that, unlike previous observations over the Brazilian sector, the slightly deformed clouds of metal are formed much near the line of the sight of the LIDAR, which makes this event quite rare and intriguing to study.

KEYWORDS

Na and K layer, Es layer, tidal wind, SAMA, energetic particle precipitation

1 Introduction

The metal layers in the mesosphere and lower thermosphere (MLT) are located between ~80 km and 110 km, and their main source is meteoric ablation. Among the different metals present in the atmosphere, sodium (Na) is one of the easiest to study due to the large resonance scattering cross-section and higher concentration, and for this reason, many scientific works for different latitudes can be found using these metallic layers (Slipher, 1929; Bowman et al., 1969; Clemesha et al., 1979; Clemesha et al., 1982; Simonich et al., 1979; Simonich et al., 2005).

Based on LIDAR observations of the mesospheric Na layer at the low latitude sector of the southern hemisphere, Clemesha et al. (1978) showed, for the first time, the presence of thin layers of enhanced concentration superimposed on the regular background. Some years later, a more detailed study revealed that these thin layers of Na and other metals, known as sporadic neutral layers (Ns), are most frequently located between 90 and 100 km. The layers presenting a thickness between about 100 m and several kilometers, densities between about 10^2-10^5cm^{-3}, usually are superposed on a background layer (Clemesha, 1995). Additionally, the occurrence of Ns appears to have a latitudinal dependence, being more frequent at high and low latitudes (especially in the case of sodium) than at mid-latitude (e.g., Hansen and Von Zahn, 1990; Clemesha, 1995) and is strongly linked to the appearance of ionosphere sporadic E (Es) layers on ionograms. They last a few minutes to hours and generally do not exhibit rapid height changes (Clemesha et al., 1999). The studies of Ns layers of other metals, such as potassium (K), began later (Eska et al., 1998). Specifically in the Brazilian sector, the first measurements were made only in 2017 (Andrioli et al., 2021). Compared to Na, the concentration of K is lower (about ten percent of Na); therefore, its detection is not as easy as in the case of Na. However, efforts have been made to investigate the behavior of both metals, which, although they belong to the same group (alkali metals), present distinct characteristics.

Although the basic metal features described in previous paragraphs are observed and discussed for different latitudes, some anomalies can also occur in the metallic layers. In this context, this work is developed. While the regular Ns layers generally have a vertical width of the order of 1 km, last from a few minutes to a few hours, and decrease in height with time without rapid temporal variations, the anomalous layers can present higher intensities, ascending instead of descending and can have a different shape. For example, Andrioli et al. (2024) discussed the possiblility of indirect effects of energetic particle precipitation (EPP) in the peculiar enhancement in K and Na. They also reported the ascending movement of K and Na instead of the expected descending movement.

Regarding the shape of metal layers, some studies have discussed the occurrence of an unusual structure such as “C”-structures. For instance, Kane et al. (2001) investigated a rare sporadic Na layer that resembled the rare ‘C-type’ Na layer observed over Arecibo, Puerto Rico. They proposed that this non-conventional Na layer structure in the LIDARgrams could be associated with the field-aligned 3-meter irregularities and the Kelvin Helmholtz Instabilities (KHI). Sridharan et al. (2009) also studied the occurrences of the C-structures in Na metal layer over the Indian sector and, similar to Kane et al. (2001), associated these complex structures with KHI under the influence of a strong wind shear. Sarkhel et al. (2015), in turn, discussed a possible deformation in the KH-billow structure to explain an unusual Na layer (λimage’ structure) over the same sector. The dynamic instability impacts on billow-like structures in the Na layer due to the instabilities process in the atmosphere, were also discussed by Sarkhel et al. (2012) to explain the abnormal structures in the Na layer.

On the other hand, Clemesha et al. (2004) proposed a different mechanism to explain the C-type structures. They believed that the observed structures might result from the wind-shear distortion of preexisting Na clouds and that the advection of the resulting sheared structure over the LIDAR by the same wind formation is what could produce the observed C-shaped structures. Using the data of a narrow band Na density and temperature LIDAR and a high-resolution simultaneous Na and K LIDAR over the low latitude sector of Brazil, Andrioli et al. (2022) investigated the C-structures similar to that studied by Clemesha et al. (2004). They identified a low correlation between C shape layers and Es layers occurrences. They also found a strong wind shear at the altitude and time that the C-structures appeared. In agreement with these authors, the low correlation between C-structures and Es layers indicates that these phenomena cannot be associated with field-aligned ionospheric irregularities and KHI. Therefore, the mechanism proposed by Clemesha et al. (2004) seems to be more plausible to explain this phenomenon.

The present work shows, for the first time, the moment in which a cloud of enhanced Na and K is possibly formed. This unique register, made by the LIDAR located at São José dos Campos (Brazil), indicates that these enhanced metal clouds were formed above the field of view of the laser and are different from what was published until this moment. The enhanced cloud was observed within the central height of the layer (~94 km) and not at the topside of the background layer as generally C-type occur. Therefore, this unique event corresponds to the formation of a metallic cloud that, perhaps under the influence of an appropriated wind shear, could also form the rare C-structures to be advected to another place. We will discuss the event of metal layers, considering the mesospheric winds and the ionospheric layers in the interval in which the main event is observed and in the hours that precede and follow it.

2 Results

2.1 Abnormal Na and K layers on 23–24 June 2023

The sporadic K and Na layer registered by the China-Brazil Joint Laboratory for Space Weather (CBJLSW) Dual-bean Na-K LIDAR at São José dos Campos–SJC – (23.1°S; 45.9°W) on the night of June 23–24, 2023, is studied here. This period corresponds to a recovery phase of a magnetic storm, which is associated with a complex solar wind structure, including Interplanetary Shocks and a sequence of High-speed Solar Wind Streams (HSSs) that reached the L1 Lagrangian point on 15, 19, and 23 June (https://kauai.ccmc.gsfc.nasa.gov/DONKI).

The Na/K LIDAR is based on the resonance fluorescence scattering mechanism using two laser beams centered at 589 nm (Na) and 770 nm (K). The equipment has a time and height resolution of 20 s and 96 m, respectively. A combination of 10 consecutive profiles in time is used here to infer the Na and K densities at the mesosphere and lower thermosphere region (MLT) with a temporal resolution of 3.3 min (for more details about the method used to calculate the Na and K concentrations, see Andrioli et al., 2020). Figure 1 presents the K (panel a) and Na (panel b) concentrations on the studied night over SJC in logarithm scale for better identification of the shape, because the huge values occurred on the studied night over SJC.

The sudden increase in the density of both the metal layers reached an impressive value of 2,000 cm^{-3} for K and about 20,500 cm^{-3} for Na (see Figure 3D to found these values in linear scale). As reported by Andrioli et al. (2021), the typical average peak density for K and Na over SJC is 300 and 6,000 atoms cm^{-3}, respectively. Therefore, the density values on June 24 were ~7 and

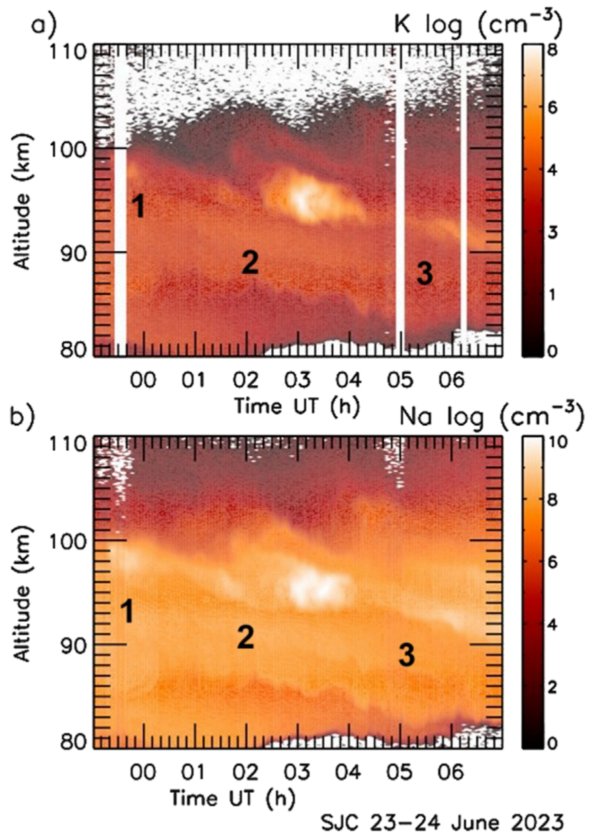

FIGURE 1
Height time-intensity profiles contour of **(a)** K and **(b)** Na density concentrations in logarithm scale layer on 23–24 June 2023 at São José dos Campos (UT = LT+3h).

3.5 times more intense for K and Na, respectively. It is relevant to mention that this high concentration of K has never been registered before at São José dos Campos. Compared to the background layer's typical values, the K and Na layers' concentration was 31 and 9 times more intense, respectively. Another small and quick intensification in the metal layer is also evident during the descending movement of the main layer, as seen between 23:00 and 00:00 UT, and 05:00 and 06:00 UT (denoted by numbers one and three while number two is the time and position of the phenomena studied here). The possible origin of these intensifications will be briefly discussed in the following sections.

A very peculiar behavior is observed in the metal layers regarding their shape, intensity, duration, and altitude in which they are formed. It can be observed that near 03:00 UT, both K and Na layers exhibited concentrations much higher than the background layer, along with a peculiar format that appears to be related to an enhanced cloud of Na and K with a minimal deformation preceding the formation of the C-structures. Besides that, it can be noted that the vertical extension of these layers was about 4 km. According to Clemesha et al. (1999), regular sporadic neutral layers have a vertical dimension of ~1 km and last from a few minutes to a few hours. In contrast, in the event studied here, the layers were 3–4 times wider and lasted only from 10 to 20 min. Furthermore, both anomalous layers were formed at around 94 km, close to the centroid of the primarily layer (91 km and 93 km, respectively of K and Na) which is another distinct feature since the occurrence of peculiar structures, like the C-structures, have been detected at the top of (in our case, 101 km for K and 102 km for Na), or even separated from the primary (see more detail at Sarkhel et al., 2015; Andrioli et al., 2022; Sridharan et al., 2009).

2.2 Ionospheric behavior on 23–24 June 2023

To understand the unusual metal layers presented in Figure 1, the behavior of the ionosphere is discussed based on Digisonde data over Cachoeira Paulista (CPL, 22.7°S, 45.0°W), which is located 100 km apart from SJC. A careful visual analysis of ionograms collected on the night of June 23–24, 2023, revealed interesting features of the ionosphere over CPL since the hours that preceded the event in the metal layers. Figure 2A shows the presence of an extra-ionization at night as indicated by the abnormal occurrence of an E-layer at about 150 km from 22:50 UT to 23:10 UT (red rectangle), with a critical frequency of ~2.4 MHz. Similar to what is observed in the F-layer (above 220 km), the ordinary (red) and the extraordinary (green) traces of the E-layer are evident, mainly at 22:50 UT. Around this time interval, a weak intensification is seen in the Na and K in Figure 1, as indicated by the number "1". The nocturnal E layer in this event was registered from 22:20 UT on 23 June until 00:40 UT on 24 June; however, only some ionograms were selected to show here (Figure 2).

At about 01:30 UT, a perturbation is noted at the higher frequencies of the F layer (vertical red arrow). After this, between 01:40 UT and 02:20 UT, an incurved trace in the F-layer base can be observed (red circle) at the same time in which new modifications started to be seen in neutral layers (number "2" in Figure 2). In agreement with some works (Santos et al., 2016a; Santos et al., 2016b; Abdu et al., 2013), this incurved trace, which is quite common during the daytime but rare at night, is also strong evidence of an extra-ionization at lower heights of the ionosphere. Such curvature indicates that electromagnetic signals emitted to ionosphere sounding are delayed, and this only occurs in the presence of an increase in the electron density in the lower heights. After the sequence of the incurved trace, new modifications in the ionosphere are seen and precisely concurrent with the abrupt changes observed in metal layers. At 02:30 UT (Figure 3), a new stratification in the F-layer (red arrow) at ~300 km was observed and occurred simultaneously to the occurrence of a new Es layer with a certain degree of range spreading, which suggesting the possible formation of the auroral sporadic E-layer. Note that this spreading Es layer superimposed on another flat Es (Es_f) formed some minutes earlier (blue arrow). Both the Es layer types persisted throughout the entire studied period. From 02:50 UT onwards, the Es layer completely blocked the reflection from the F-layer. Furthermore, the ionograms showed that the spreading Es layer presented a new configuration as indicated by the inclined red lines in this figure. As Resende et al. (2023) discussed recently, this feature suggests a possible influence of the gravity waves, which destabilize the environment and create inhomogeneous layers in ionograms. The signatures of these waves are very clear in both Na and K layers, which are considered good traces of this kind of

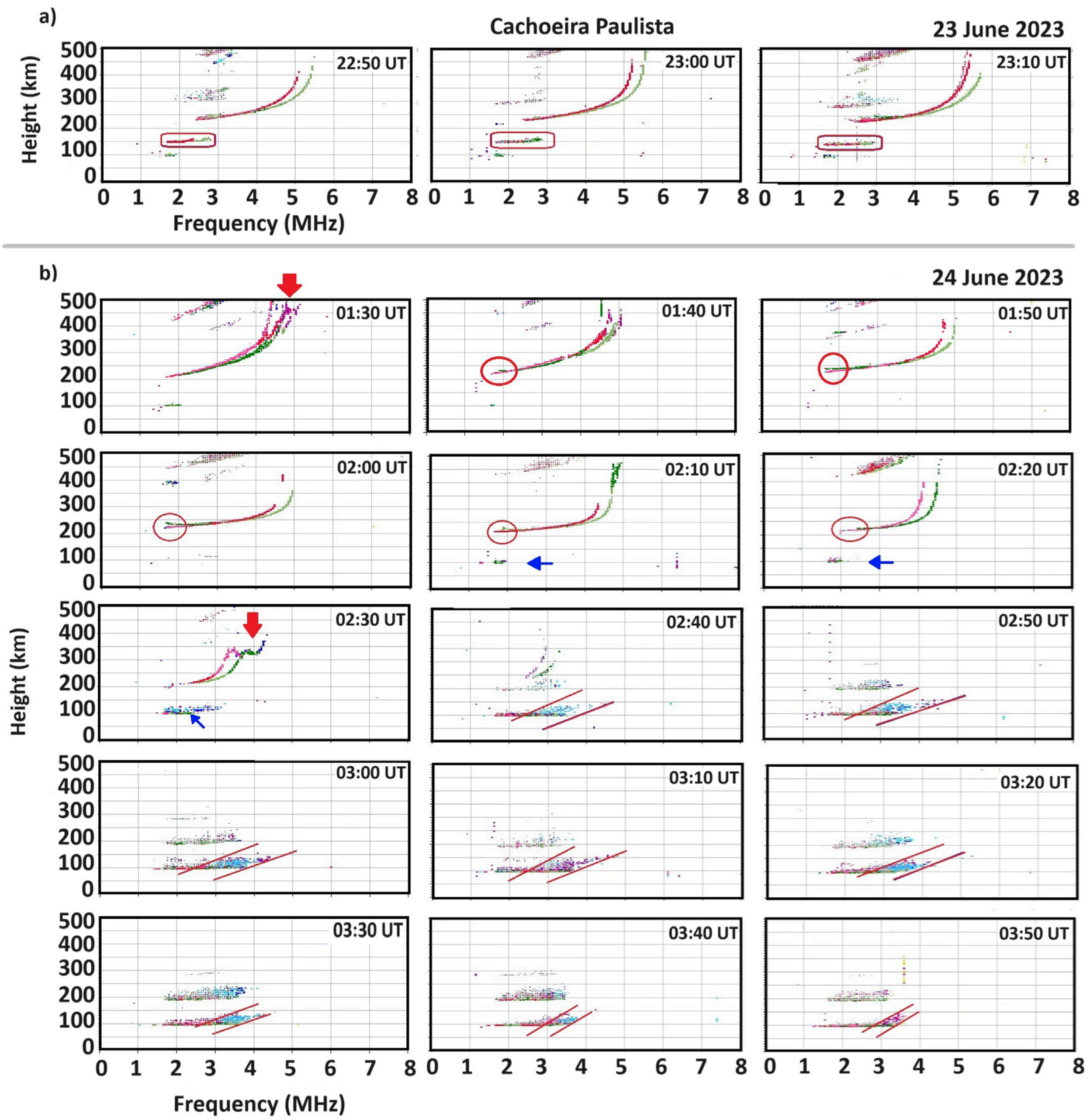

FIGURE 2
The ionograms over Cachoeira Paulista show **(a)** the presence of an atypical E-layer and **(b)** the incurved trace in the F-layer base (from 01:30 UT to 01:50 UT), the stratification in the F-layer (02:30 UT), and the presence of spread Es layer.

fluctuation as observed in Figure 1 at about 100 km, at the same height in which the inclined Es layers are observed. It is relevant to state that some similar ionogram modifications (not shown here) have been observed in Santa Maria- Brazil (29.7° S, 53.7° W), a region located in the center of SAMA (Moro et al., 2019). This indicates that the increased ionization observed in Cachoeira Paulista and Santa Maria, both located in regions influenced by the SAMA, can be directly linked to the impact of Energetic Particle Precipitation (EPP). The EPP can form the auroral sporadic E-layer (Esa), a layer typically observed at auroral stations. In the low-latitude sector, the Esa layer is triggered by electron precipitation from the inner radiation belt, influenced by solar wind structures (Da Silva et al., 2022; Da Silva et al., 2023). Therefore, the relationship between the intensity of the neutral layers and EPP will be briefly discussed since this topic remains an active area of investigation.

3 Discussion

This work presents a sudden intensification within the metals main layer, a unique phenomenon over the low-latitude Brazilian sector

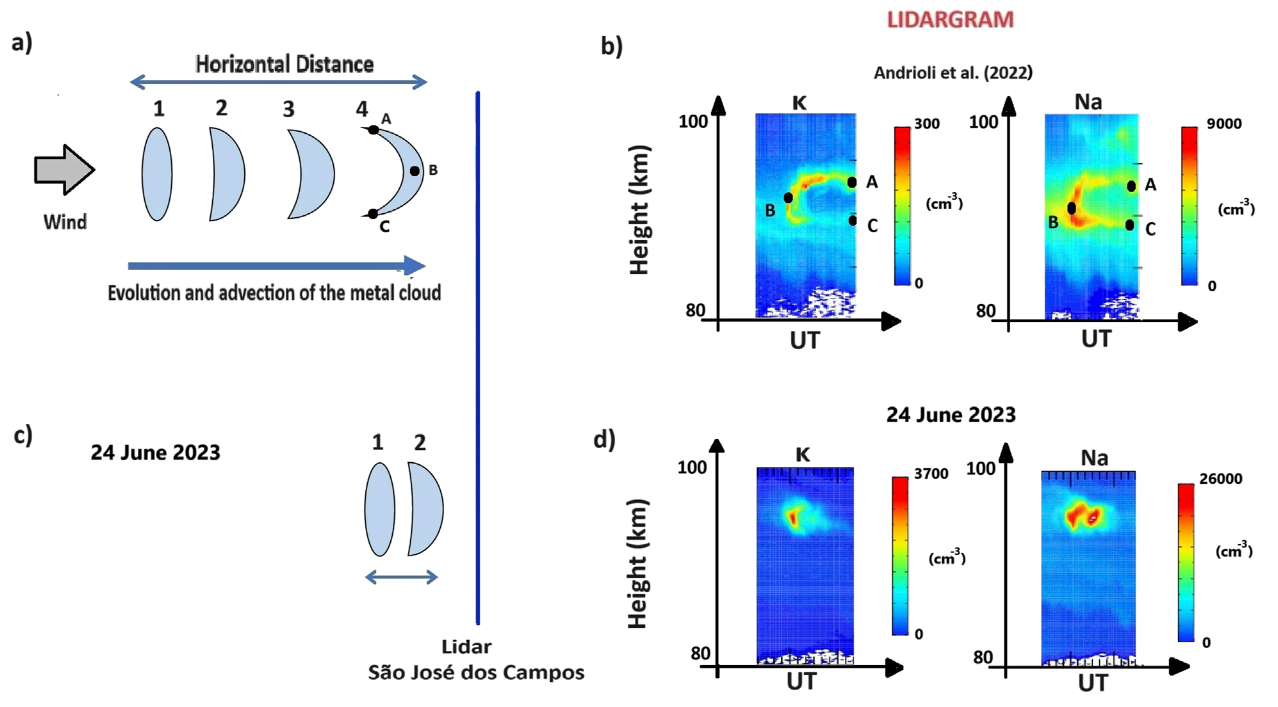

FIGURE 3
Schematic illustration showing **(a)** the deformation of the initial cloud of metals until stage 4 (C-structure), **(b)** example of C-structures in Na and K **(c)** a cloud being formed near the LIDAR's beam over SJC **(d)** cloud of enhancement metal of K and Na on June 24.

that resembles a slightly deformed cloud of enhanced mesospheric Na and K. As mentioned by Clemesha et al. (2004), if the C-structures are rare and might be observed anywhere over a path of several hundred kilometers downwind from the location of the initial cloud, the observation of the undistorted (or slightly distorted) initial cloud, visible over a much more restricted area, would be even rarer. As mentioned by Clemesha and co-authors (2004), only six well-developed C-structure events were detected in 766 h of observations. Andrioli et al. (2022), in turn, reported three C-structures over 82 nights in the first data set analyzed and nine over 185 nights in the second data set. Based on these works, the frequency of occurrence of C-structure is around 5% of the nights. Moreover, in all the reported studies, the C-structures were well developed (stages 3 or 4 in Figure 3A), different from the present work which the enhanced metal cloud seems to be slightly distorted, highlighting the importance of the case study discussed here. Additionally, other anomalous characteristics are also seen as the intensity, duration, and height in which the Na and K layers are formed.

Although the anomalous K and Na layers observed in this study should not be classified as C-layers but rather as precursor clouds to their formation, understanding the mechanisms underlying these layers is essential for contextualizing the uniqueness of the event analyzed in this work. In this regard, two key aspects will be discussed: (i) the abnormal shape and (ii) the intensities of the observed metal layers.

As mentioned in the introduction, the KHI mechanism, wave breaking, and field-aligned ionospheric irregularities are some of the mechanisms proposed to explain the C-layers. However, Clemesha et al. (2004) disagree that such structures are caused by the abovementioned mechanisms and suggest that the wind-shear distortion of an initial cloud of enhanced sodium concentration produces this kind of layer. The authors used a very interesting illustration to explain how they believe the C-structures are formed (see their Figure 7). As the mechanism they proposed seems to be very plausible in explaining our case, we adapted their illustration as indicated in Figure 3.

Figure 3A shows an example of a cloud of metal layer in four stages: the initial undeformed cloud (stage 1) and its evolution under the influence of wind (stages 2 and 3) until it reaches the LIDAR beam (indicated by the vertical blue line) with the C-format (stage 4). In agreement with Clemesha et al. (2004), an appropriate wind could deform the initial cloud and transport it towards the LIDAR. If the maximum wind amplitude is at the center of this cloud, the vertical time evolution of the metal over the LIDAR location (LIDARgram) will first show the central part of the cloud, represented by the letter "B" in this figure, followed by the upper and lower part of the cloud (letters A and C), thus forming the perfect structure in "C" shape for both K and Na. This is what exactly was observed by Andrioli et al. (2022), as indicated in Figure 3B. However, the case studied here has different aspects since the structure recorded by the Na/K LIDAR over SJC presented a minimum deformation, a very short duration, and a density much higher than those reported by Andrioli et al. (2022) for the same sector. In this case, the metal's concentration on June 24 was ~10 times higher for K and ~3 times for Na (Figures 3B,D). This spectacular increase was never registered on 8 years of K measurement in the Brazilian sector and only in two cases (Andrioli et al., 2024 and in the study case here) in a total of over more than 50 years of data of Na.

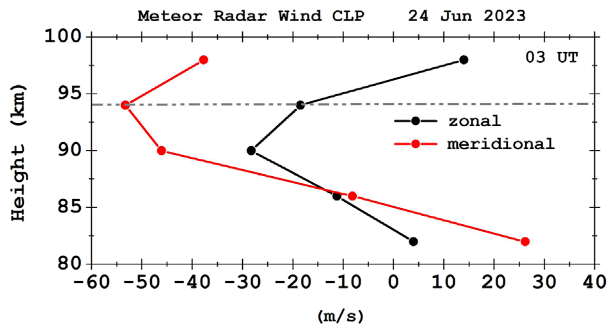

FIGURE 4
Meridional (positive to north) and zonal wind (positive to east) components over CPL on June 24 at 03:00 UT.

Following the same reasoning, a possible explanation for the anomalous shape of the structure studied here is that it was formed as close as the LIDAR as indicated by stages 1 or two otherwise (see Figure 3C). Otherwise, we would expect a C-structure since the winds on June 24 presented normal conditions to move this enhanced cloud in the LIDAR direction. As can be seen in Figure 4, the meridional (red line)/zonal (black line) wind component reached ~ −55/−20 m/s around the time in which strong structures were formed (~03 UT). Additionally, it can be noted that the maximum amplitude of the meridional wind coincides with the height of the observed abnormal layers (~94 km, dashed gray line). The values of wind in this event are similar to those observed by Andrioli et al. (2022) and Clemesha et al. (2004). However, in the cases studied by these authors, the C-structures in mesospheric Na and K layers were registered, and this happened because the initial cloud (indicated by number one in Figure 3A) was created in a more distant region and advected by the wind in the direction of the LIDAR. Considering that the changes in ionograms over CPL (Figure 2) occurred simultaneously to changes in metal layers over SJC, and considering a wind velocity of 50 m/s and a distance of ~100 km between SJC and CPL, we can say that if this enhanced cloud had been created in a region further away from the LIDAR, it probably would arrive in SJC deformed in ~30 min in the form of C- structure. As this is not what we observe in our data, we strongly believe the enhanced Na and K cloud was formed much near the line of sight of the LIDAR.

Regardless of the source of generation of the recorded metal clouds, their irregular shape cannot be explained solely by the processes involved in their generation. To investigate this, the neutral wind measurements collected by an all-sky interferometric radar located at CPL were used. This radar is based on a transmitter antenna that emits pulses at a frequency of 35.24 MHz and five receiver antennas. For each meteor echo, the radial velocity of the wind is calculated, and the height and azimuth are determined by correlating the signals from the different antennas and by analyzing the pulse delay. This radar provides data with a typical time resolution of 1 h and a height resolution ranging from 2 to 3 km (Batista et al., 2004). Figure 4 shows that the maximum of the meridional component to the south occurs very close to the peak of the cloud density. Besides that, above and below this maximum, the meridional component, despite being directed to the south, is further north, creating a relative shear. This condition would justify a non-homogeneous drift of the metal concentration by altitude in the volume above the LIDAR beam. As mentioned by Kane et al. (2001), the neutral Na (and also K) can act as a passive tracer of wave activity above~ 85 km (i.e., tracer of neutral atmosphere dynamics). This means that once the intensified cloud is created, it can be blown away by the wind, as proposed in the mechanism of Clemesha et al. (2004) in Figure 3A.

Figure 5 shows the column abundances of Na and K on 23–24 June 2023 for different ranges of heights. We could observe that during the event, the amount of Na and K was doubled and quadrupled, respectively. This is a clear evidence of a fresh injection of Na and K metals in the MLT region during this event, probably caused by EPP. The total column density of potassium K (upper panel) and sodium Na (lower panel) shows an abrupt increase at about 03 UT for the altitudes from 90 to 100 km. Therefore, this case cannot be considered as the vertical redistribution of the enhanced metal cloud of preexisting Na and K, but rather the enhanced metal cloud itself before its redistribution/deformation by the wind.

Another interesting aspect of the event studied here is the anomalous intensity observed in Na and K. As previously mentioned, the ionograms in Figure 2 provide evidence of EPP in the ionosphere on the day of the event, as the formation of the nocturnal E-layer (E_n), spread Es layers (Es_a), and incurved F layer base (IT_F). These evidences were not restricted to CPL, a region very near to SJC, but also Santa Maria (SM), which is a region located in the center of the SAMA. Figure 6 summarizes the intervals in which such modifications in ionospheric layers caused by EPP were seen in ionograms. The vertical dashed ink lines indicate the times when the strong intensification was seen in metal layers (~02:30 UT) and instances in which other lower intensifications were observed, as those denoted by numbers one and 3. The notation Es_{a+g} is used to indicate that the Es layer was affected both by EPP and gravity waves, as it will be mentioned later.

As can be seen in Figure 6, the ionosphere was disturbed by the EPP, mainly in the times that preceded the main event in Na and K. Based on recent work, one of the factors that could contribute to the anomalous intensification of the metal layers is triggered by the set of chemical reactions involving the EPP. Although the first impact of EPP in the atmosphere is to produce an extra ionization, the connection with the neutral layers is in the ion-molecular neutralization mechanism through successive chemical reactions up to the final release of the neutralized metallic atom (Plane et al., 2015). It is important to emphasize that some mechanisms have been used to explain the connection between EPP and metal layers over high latitudes. However, for the low latitudes under the influence of the SAMA, the first discussions started with the work of Andrioli et al. (2024). Therefore, more studies need to be done to elucidate the mechanism responsible for the peculiar increase of K and Na layers in the low latitudes sector.

Finally, our results also showed an Es layer from 02:30 UT with a certain degree of inclination and spreading. Regarding inclination, some authors have claimed that this characteristic can be related to gravity wave propagation (see, for example, Resende et al., 2023; Cohen et al., 1962). Regarding spreading of the Es layer, besides the EPP, Resende et al. (2022) suggest that the gravity waves' influence makes the environment unstable and creates inhomogeneous layers in ionograms (Es_{a+g}). In this context, the author mentioned that

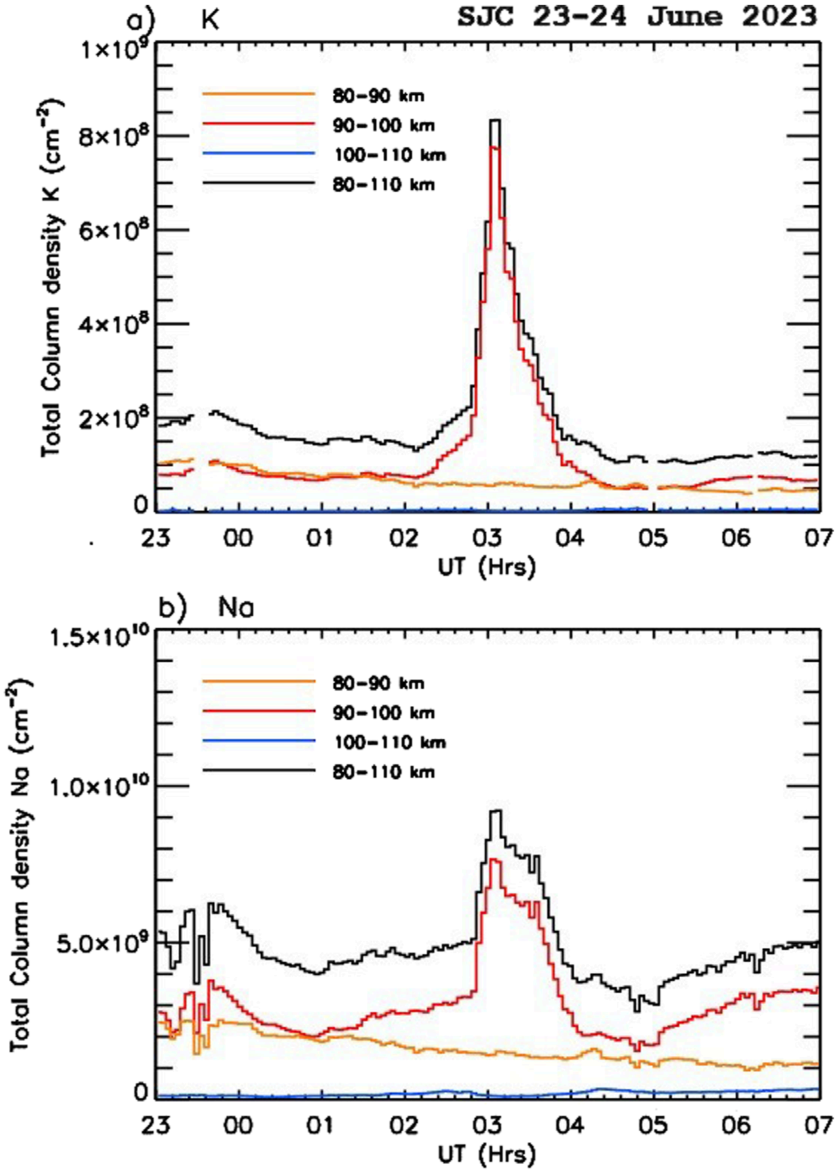

FIGURE 5
Total column density of K **(a)**, and Na **(b)**, on 23–24 June 2023, for different ranges of heights.

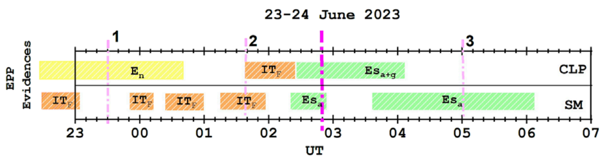

FIGURE 6
EPP evidence on ionosphere over Cachoeira Paulista and Santa Maria on 23–24 June 2023.

KHI, which stands out as one of the most classical instabilities in fluid mechanics, is a leading candidate to impact the Es layer together with the EPP occurrence. The gravity wave propagation, in this case, is supported by the fluctuations clearly seen in the top of metal layers in Figure 1 at about 100 km of height, the same height at which the Es layers are observed. A more detailed study is needed to understand the simultaneous impacts of EPP and KHI in the Es layers and the possible relation of these events with the metal layers.

4 Conclusion

We have presented, for the first time, a new structure observed at about 94 km in the atmospheric Na and K layers as registered by the dual-beam LIDAR over the low latitude sector of São José dos Campos–Brazil. Following the same mechanism proposed by Clemesha et al. (2004), we believe that the structures observed correspond to a practically pré-C metal visible over a very restricted area where the LIDAR was operating. Based on the meteor wind data during the same period, it was possible to that the slight deformation in Na and K layers seems to be caused mainly by the meridional wind since there is a strong shear in this wind component near the altitude at which the neutral layers are formed. Simultaneous changes observed in the neutral and ionized atmosphere suggest that the studied events may be related to each other through the impacts of the EPP in the SAMA region. However, more investigations and observations are needed to understand this type of event better.

Data availability statement

The datasets presented in this study can be found in online repositories. The names of the repository/repositories and accession number(s) can be found below: https://zenodo.org/records/13869322.

Author contributions

AS: Conceptualization, Formal Analysis, Investigation, Writing–original draft, Writing–review and editing. GY: Supervision, Writing–review and editing, AP: Supervision, Writing–review and editing. VA: Formal Analysis, Investigation, Software, Writing–review and editing. PB: Writing–review and editing, CB: Investigation, Writing–review and editing. LR: Writing–review and editing, IB: Writing–review and editing. LAS: Writing–review and editing. JM: Writing–review and editing. JS: Writing–review and editing. JSu: Writing–review and editing. MA: Writing–review and editing. CW: Funding acquisition, Project administration, Resources, Writing–review and editing. HL: Funding acquisition, Project administration, Resources, Writing–review and editing. ZL: Funding acquisition, Project administration, Resources, Writing–review and editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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