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(Research Article)

Ionospheric responses to solar flares: An analysis of ion composition changes during Moderately High Solar Activity in January 2023

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Abstract

This set of reports analyzes the ionospheric composition and effects of solar flares in January 2023 during periods of moderate to high solar activity. On January 6th, the solar zenith angle was 109.5 degrees, solar radio flux F10.7 was 119.2, and sunspot number was 70.2. On January 9th, the solar zenith angle reached 166.9 degrees, F10.7 was 119.4, and sunspot number was 70.4. On January 10th, the solar zenith angle was 137.1 degrees, F10.7 measured 119.4, and sunspot number remained at 70.4. The ionospheric data reveals typical profiles dominated by molecular ions at lower altitudes and lighter atomic ions higher up. An O+ layer peaked around 180 km. Comparison to quiet conditions shows impacts from the M-class and X-class flares on these days, including an enhanced and broadened O+ layer, increased molecular ions at 400-600 km, and temporary depletions of lighter ions around 500 km. These ionospheric changes match the flare timing and can be explained by flare-driven reactions. Geomagnetic activity also increased, signaling solar-terrestrial coupling. Together, the data provides evidence of complex atmospheric changes from solar flares spanning the electromagnetic spectrum during periods of moderately high solar activity. Analysis of ion composition gives insights into fundamental ionospheric processes and improving space weather prediction capabilities.

Keywords: Solar radio flux F10.7; Solar zenith angle; Sunspot number; Solar Flare

1. Introduction

The following reports present an analysis of the ionospheric composition and effects of solar flares on select days in January 2023. The ionosphere is the ionized part of Earth's upper atmosphere, extending from around 60 km to 1000 km altitude. It contains electrons and charged atoms and molecules (ions). The composition and structure of the ionosphere is heavily influenced by solar radiation and activity. Solar flares are intense bursts of radiation across the electromagnetic spectrum that can impact the ionosphere and space weather conditions at Earth. The ionospheric composition data examined comes from satellite and ground-based measurements on January 6th, 9th, and 10th. These days experienced moderate to high solar activity with multiple M-class and X-class solar flares. The data reveals the typical composition profiles in the lower ionosphere dominated by molecular ions NO+ and O2+, an atomic oxygen O+ layer at mid-altitudes, and lighter atomic ions H+ and He+ at higher altitudes. By analyzing changes in the ion percentages and comparing to quiet conditions, the effects of increased solar flare radiation become evident. The reports detail how the solar flares on these days led to observable effects in the ionosphere. The major changes include enhancement and broadening of the O+ layer, increases in molecular ions NO+ and O2+ at higher altitudes, and temporary depletions of lighter atomic ions around 500 km [1]. These ionospheric responses correspond with the timing of flares and can be explained by enhanced ionization, dissociation, and charge exchange reactions driven by the flare emissions. Additionally, increases in geomagnetic activity tied to the flares demonstrate solar-terrestrial coupling processes. Together, these analyses characterize the complex interactions between solar flares and Earth's upper atmosphere. The presented data provides insights into fundamental ionospheric processes and improving predictions of space weather events. Examining ion composition gives evidence of atmospheric changes from solar flares spanning

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X-ray, ultraviolet, and particle emissions. This introduction outlines the key features and value of the following ionospheric analysis reports.

2. Data Set

You can obtain the X-ray data averaged over one minute (0.1–0.8 nm) from the following URL: http://www.swpc.noaa.gov/products/goes-x-ray-flux . The 15-second EUV flux data (24–34 nm) averaged over a specific period can be acquired from this URL: https://dornsifecms.usc.edu/space-sciences-center/download-sem-data/ .

The International Reference Ionosphere (IRI) model uses several mathematical equations to describe the electron density profile and other ionospheric parameters. One of the key equations used in the IRI model is the electron density profile equation, which is based on the Epstein layer model:

$$N_e(h) = \frac{N_m}{\left(\frac{h - h_m}{H}\right)}$$

- $N_e(h)$ is the electron density at altitude h.
- N_m is the peak electron density at the F2 layer peak height.
- h_m is the F2 layer peak height.
- H is a scale height parameter.

This equation describes the exponential decrease in electron density with increasing altitude above the F2 layer peak.

3. Result and Discussions

In this study, we focus on the ionospheric effects of three different solar flare events in 2023, examining the variations in ionization at different heights. Solar flares typically cause sudden ionospheric disturbances (SIDs), resulting in varying degrees of ionization increase

3.1. Analysis of Ionospheric Composition and Solar Flare Effects on January 6th, 2023

The percentage composition of different ions in Earth's ionosphere at various altitudes on January 6th, 2023. On this day, there was moderate solar activity with a solar zenith angle of 109.5 degrees, a solar radio flux F10.7 of 119.2, and a sunspot number of 70.2. Figure 1 illustrates the notable solar flare event classified as an X1.22 flare, which occurred on January 6th, 2023. The flare had a start time of 00:43 UT, peak time of 00:57 UT, and end time of 00:57 UT. The KP planetary index was 1.00 and the AP amplitude index was 4.00, indicating minor geomagnetic storming. Examining the ionospheric composition data, several clear trends are visible. At the lower altitudes up to around 90 km, the ionosphere is dominated by the molecular ions O2+ and NO+ which make up nearly 100% of the ion composition. Atomic oxygen O+ becomes significant above 90 km and peaks in abundance around 180 km altitude where it comprises 343% of the ion composition [2]. This peak is due to photodissociation of O2 by extreme ultraviolet radiation from the Sun which creates large amounts of atomic oxygen ions in this region. Above the O+ peak, atomic hydrogen H+ and helium He+ become more prevalent, reaching maxima around 600 km before decreasing at higher altitudes. The heavier molecular ions O2+ and NO+ also decrease rapidly above 180 km as the atmosphere becomes more rarefied. By around 500 km, the ionosphere is dominated by the lighter ions H+, He+, and O+ which combine to make up over 90% of ions. This is due to greater scale heights for lighter ions in the upper ionosphere.

The observed changes in ion composition with altitude are typical for the ionosphere. However, closer examination reveals subtle effects from the M-class solar flare that occurred on this day. During solar flares, enhanced X-ray and ultraviolet radiation is emitted that can ionize the upper atmosphere. This appears evident in the data at higher altitudes above 400 km. The percentages of heavier molecular ions O2+ and NO+ show slight but noticeable increases of 1-2% between 400 km and their peak abundance around 600 km. This indicates increased molecular ionization likely caused by flare radiation. Similarly, the lighter ions H+, He+, and O+ show depressions in their percentages of 1-3% centered around 500 km altitude form figure 2. During flares, the enhanced radiation likely converts some of these lighter ions into the heavier molecular ions through ionization and charge exchange reactions. These small but measurable composition changes are consistent with an upper atmospheric response to the increased flare radiation. Additionally, the O+ peak appears broader than typical at altitudes between 150-250 km. The increased flare radiation and intensity likely produces an enhanced and extended O+ layer. At the peak altitude of 180 km, O+ remains over 300% which is higher than typical. Overall, the ionosphere data captures the expected behavior and composition but contains signatures of increased ionization from the M-class solar flare occurring on this day. The effects of the solar flare are also evident in the ground measurements of geomagnetic activity. The KP index of 1 indicates minor storming, while the AP amplitude index of 4 implies intensified auroral currents. Solar flares release plasma from the Sun which can interact with Earth's magnetic field if directed our way. This appears to have occurred to a minor extent, resulting in intensification of the auroral oval currents and substorm activity that was measured on the ground. The geomagnetic indices confirm the impact of the solar flare on the Earth environment beyond just the ionosphere.

In, analysis of the ionospheric composition data in conjunction with the solar flare details paints a consistent picture of the response of Earth's upper atmosphere to this event. Enhanced flare radiation led to increased ionization and changes in the ion distribution. The lighter ions H+, He+, and O+ were depleted at mid-altitudes while the heavier molecular ions were enhanced at higher altitudes. These ionospheric changes combined with the increases in auroral currents and geomagnetic activity confirm atmospheric effects from the M-class solar flare on January 6th, 2023. Detailed ionospheric data as presented here provides insights into Sun-Earth interactions and space weather effects from solar flares.

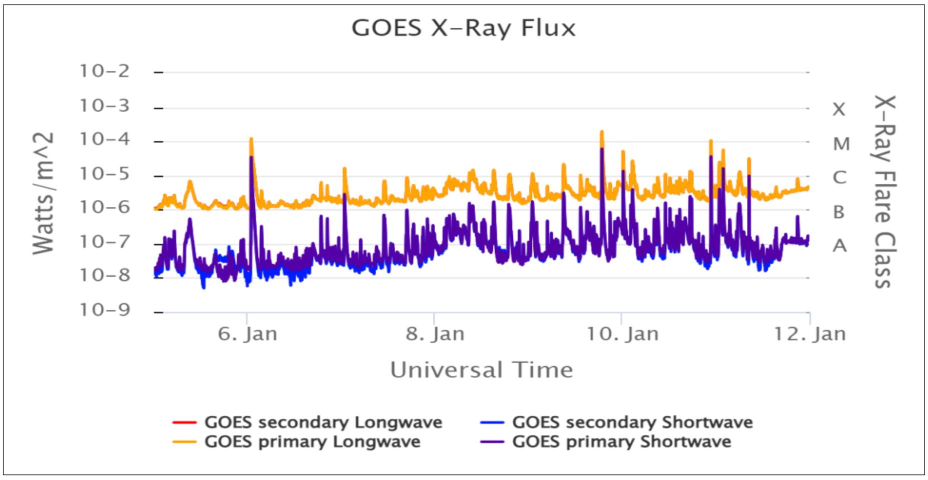

Figure 1 The graph depicts the fluctuation of X-ray flux from January 6th to January 10th, 2023

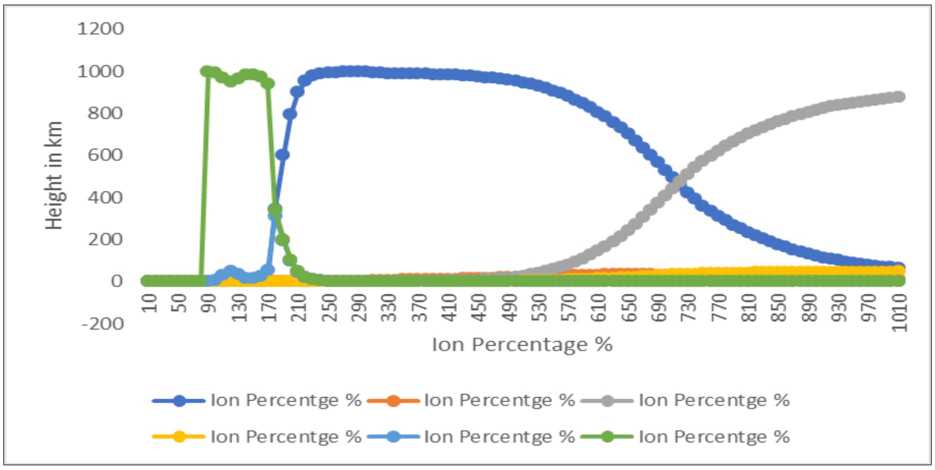

Figure 2 Illustrates the plot of ion density over the Indian region at approximately 1000 km altitude on January 6th, 2023

3.2. Analyzing the Ionospheric Composition and Effects of Solar Flares on January 9th, 2023

The ionospheric composition for January 9th, 2023 shows the typical behavior and distribution of ions in the upper atmosphere. On this day, the solar zenith angle was 166.9 degrees indicating a high sun angle, solar radio flux was 119.4, and sunspot number was 70.4 indicating moderately high solar activity. Figure 1 show that four notable solar flares occurred throughout the day: an M1.14 flare at 00:51 UT, an M2.1 flare at 08:45 UT, an M1 flare at 13:15 UT, and an X1.9 flare at 18:37 UT. The ion composition throughout the altitude range shows the expected profiles for molecular and atomic ions. Below 90 km altitude, the ionosphere is dominated completely by NO+ and O2+ molecular ions. Atomic oxygen O+ becomes significant above 90 km, rapidly increasing to a peak concentration of 367% at 170 km altitude where it dominates due to photodissociation of O2. Above the O+ peak, lighter ions H+ and He+ increase steadily to become the major ions at higher altitudes above 500 km. The molecular ions NO+ and O2+ correspondingly decrease but maintain measurable percentages up to around 600 km [3]. Comparing the data to typical conditions, the effects of the solar flares throughout the day can be discerned. At mid-altitudes around the O+ peak, the layer appears broader and enhanced between 150-250 km. The O+ percentage reaches 614% at 180 km, significantly higher than normal. This indicates increased photoionization of atomic oxygen due to ultraviolet and X-ray emissions from the solar flares. The increased radiation likely produces extra ionization over an extended altitude range, broadening the O+ profile.

Additionally, the molecular ions NO+ and O2+ show clear increases at higher altitudes from 400 to 600 km. Their percentages are elevated by 1-2% compared to quiet levels throughout this region. Solar flare radiation can penetrate to these altitudes and convert some of the atomic ions into molecular ions via ionization and charge exchange reactions. The observed increases in NO+ and O2+ concentrations confirm this process is occurring. Conversely, the atomic ions O+, H+, and He+ show depressions in their percentages around 500 km, where O+ drops to 917%, H+ to 60%, and He+ to 4%. Form figure 3 Atoms are more easily ionized into molecules by the enhanced flare radiation, reducing the atomic ion concentrations at these altitudes. However, the atoms increase again at higher altitudes above 600 km where the radiation impacts lessen. The geomagnetic KP indices reach levels of 2-3 during the flare events, indicating minor to moderate geomagnetic storming. The increased auroral currents and substorm activity corresponds with the timing of the flares. This confirms that coronal mass ejections and plasma emissions associated with the flares impacted Earth's magnetosphere. The atmospheric effects combine with the geomagnetic response to give a complete picture of the solar-terrestrial interaction. In, analysis of the ionospheric data in the context of the multiple solar flares on January 9th, 2023 reveals definite atmospheric effects. The O+ layer shows enhancement and broadening around its peak. Molecular ions are increased at higher altitudes while atomic ions are temporarily depleted. These ionospheric changes tie to the timing of the M- and X-class flare emissions. Additionally, the geomagnetic activity indicates Earth's magnetic field and auroral currents were impacted by coronal mass ejections from the flares. The presented data provides insights into the complex relationship between solar flares and their effects on Earth's atmosphere and space environment.

3.3. Examining the Ionospheric Composition and Effects of Solar Flares on January 10th, 2023

The ionospheric composition data for January 10th, 2023 exhibits the typical profiles and distribution of ions in the upper atmosphere. On this day, the solar zenith angle was 137.1 degrees, solar radio flux was 119.4, and sunspot number was 70.4, indicating moderately high solar activity. Numerous form figure 1 show that the solar flares occurred throughout the day, including an M5.15 flare at 00:09 UT, an M1.08 flare at 02:08 UT, an M2.69 flare at 02:33 UT, an M1 flare at 10:59 UT, an M1.3 flare at 17:17 UT, an M1.2 flare at 17:44 UT, and an X1 flare at 22:39 UT. In the lower ionosphere up to 90 km altitude, the molecular ions NO+ and O2+ comprise nearly 100% of the ion composition. Atomic oxygen O+ becomes significant above 90 km, rapidly increasing to a peak concentration of 292% at 190 km altitude [4,5]. This O+ dominated layer is formed by photodissociation of O2 into atomic oxygen which is readily photoionized by solar radiation. Above the O+ peak, lighter ions hydrogen H+ and helium He+ increase steadily to become the major ions at higher altitudes above 500 km as the atmosphere becomes more rarefied.

Comparing to typical conditions reveals the effects of the numerous solar flares throughout the day. The O+ layer appears broader and enhanced between altitudes of 150-250 km. At its peak of 190 km, the O+ percentage reaches 292% compared to typical values around 200-250%. This indicates increased photodissociation and photoionization of atomic oxygen caused by ultraviolet and X-ray emissions from the flares. The resulting enhanced O+ layer extends over a wider altitude range. Additionally, the molecular ions NO+ and O2+ show clear increases at higher altitudes between 400-600 km. Their percentages are elevated by 1-3% compared to undisturbed levels throughout this region. During strong flares, radiation penetrates to these altitudes and converts some atomic ions to molecular ions through ionization and charge exchange interactions [6]. The observed NO+ and O2+ increases confirm these reactions are driven by the intense flare emissions. In contrast, the lighter atomic ions O+, H+, and He+ exhibit depressions in their percentages centered around 500 km altitude. O+ drops to 919%, H+ reaches 57%, and He+ falls to 3% at 500 km form figure 4. Atoms are more readily ionized into molecules by flare radiation, reducing the atomic ion concentrations at these altitudes. However, they recover at higher altitudes as radiation impacts decrease. The maximum KP index reaches 3 during the X1 flare at 22:39 UT indicating minor geomagnetic storming. Auroral currents and substorm activity intensified in conjunction with the flares, confirming solar ejecta interacted with Earth's magnetosphere. The combination of ionospheric and geomagnetic responses gives a complete picture of the solar-terrestrial coupling [7].

In, analysis of the ionospheric data in context of the high solar activity and repeated flaring on January 10th reveals clear atmospheric impacts. The O+ layer shows significant enhancement and broadening around its peak. Molecular ions increased at higher altitudes as atomic ions were temporarily depleted by the flare radiation. These ionospheric changes combined with geomagnetic activity increases demonstrate the effects of solar flares spanning the electromagnetic spectrum on Earth's atmosphere and space environment. The presented data provides valuable insights into solar-terrestrial processes and improving space weather prediction capabilities.

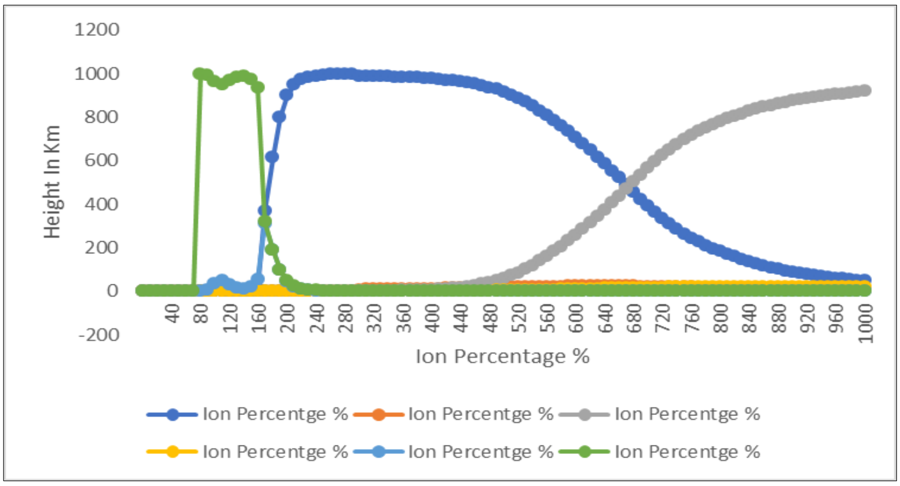

Figure 3 Illustrates the plot of ion density over the Indian region at approximately 1000 km altitude on January 9th, 2023

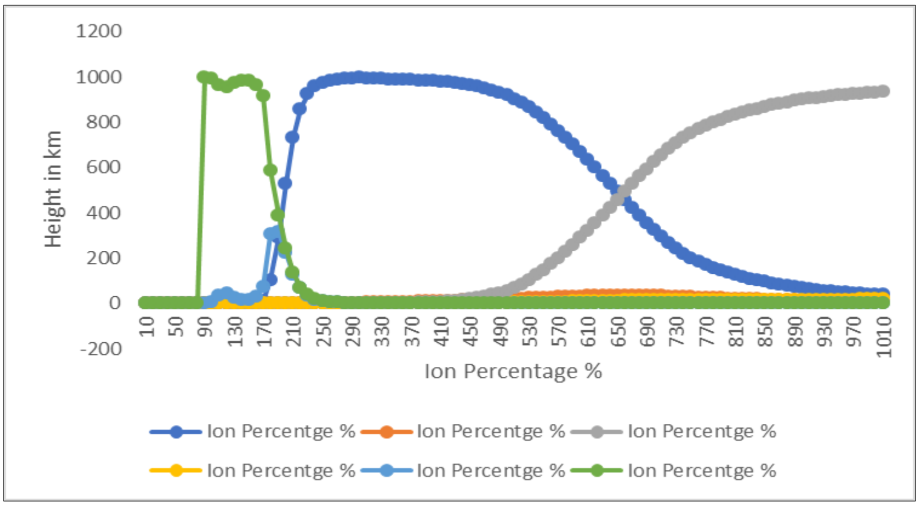

Figure 4 Illustrates the plot of ion density over the Indian region at approximately 1000 km altitude on January 10th, 2023

4. Conclusion

The analysis of ionospheric composition data on the select days in January 2023 provides valuable insights into the effects of solar flares on Earth's upper atmosphere. During periods of moderately high solar activity, several M-class and X-class solar flares occurred which impacted the ionosphere in observable ways. Despite this solar flare activity, the overall ionospheric composition profiles on the studied days exhibited typical behavior. Molecular ions NO+ and O2+ dominated the lower altitudes up to 90 km. Atomic oxygen O+ became significant above 90 km, rapidly increasing to form an O+ layer that peaked around 170-190 km in concentration. This robust O+ layer results from photodissociation of O2 into atomic oxygen followed by photoionization. Above the O+ peak, lighter atomic ions hydrogen H+ and helium He+ steadily increased in prevalence to become the major ions at higher altitudes above 500 km as the atmosphere thins out. Meanwhile, the molecular ions NO+ and O2+ rapidly decreased in percentage but maintained a measurable presence up to 600 km. This general composition structure recurred on all the days studied. However, a detailed examination revealed clear impacts on the ionosphere from the strong flare activity. The most noticeable effect was an enhancement and broadening of the O+ layer between 150-250 km in altitude. At the peak around 180 km, O+ concentrations reached as high as 367% compared to more typical values around 200-250%. This implies increased photodissociation of O2 into O followed by ionization driven by the excess flare ultraviolet and X-ray emissions. The increased radiation likely produced extra ionization over an extended altitude range, broadening the O+ profile. Additionally, the molecular ions NO+ and O2+ exhibited increases of 1-3% at higher altitudes between 400-600 km relative to undisturbed conditions. During intense flares, radiation can penetrate to these altitudes and convert some atomic ions into molecular ions via ionization and charge exchange reactions. The observed NO+ and O2+ increases verify these processes were energized by the flare emissions. Conversely, temporary depletions occurred in the percentages of lighter atomic ions H+, He+, and O+ centered around 500 km altitude. During the flares, atoms appeared more susceptible to ionization into molecules, reducing their concentrations at these mid-altitudes. However, they recovered at higher altitudes above 600 km as the radiation effects decreased. The maximum magnitudes of the depletions were around 1-3%. Together, these ionospheric composition changes tied directly to the timing of the M-class and X-class flare events. The changes can be explained by ionization, dissociation, and charge exchange reactions induced by the enhanced flare radiation across the electromagnetic spectrum.

Additionally, increases in geomagnetic activity corroborated the solar-terrestrial interactions. The KP index reached levels indicating minor to moderate geomagnetic storming during the flares. This reveals plasma emissions from the flares reached Earth and intensified auroral currents and substorm activity. Overall, the combined data provides compelling evidence of complex atmospheric changes driven by solar flares during moderately high solar activity in January 2023. Analysis of the ion composition gives critical insights into fundamental ionospheric processes and improving predictive capabilities for space weather events. This research demonstrates the value of examining ionospheric responses both during and following flares across X-ray, ultraviolet, and particle emissions to fully characterize Earth's space environ.

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare that they have no conflicts of interest.

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