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Impact of CR Forbush Decreases on Upper Atmospheric Pressure and Temperature in Saudi Arabia

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Abstract

The objective of this research is to investigate the effects of cosmic ray Forbush Decreases (FDs) exceeding 7% in magnitude, occurring between 1985 and 2016, on upper atmospheric pressure and temperature at Abha and Tabouk. Employing the super epoch analysis method, the study concentrated on altitudes of 5 km and 10 km, uncovering significant variations. Seasonal and synoptic-scale variations were considered and excluded when necessary across eight 9-day periods. Both locations showed considerable fluctuations in pressure and temperature before and after the events. At 5 km altitude (21 events), Abha experienced more pressure increases both before (9 vs. 7) and after (12 vs. 11) the events compared to Tabouk. For temperature, Abha recorded more increases before the events (5 vs. 1), while Tabouk showed more decreases (19 vs. 15). Post-event, Tabouk had more temperature increases (13 vs. 10). At 10 km altitude (20 events), both regions experienced more decreases than increases in pressure and temperature before the events and more increases afterward. Notably, Abha experienced more pressure increases both 4 days before (9 vs. 7) and after the events (12 vs. 11) than Tabouk. For temperature, Abha recorded more increases before the events (5 vs. 1), while Tabouk showed more decreases (19 vs. 15). Post-event, Tabouk had more temperature increases (13 vs. 10). These findings underscore both similarities and differences in atmospheric responses to FDs between Abha and Tabouk. Both locations exhibited cooling trends before and warming trends after the events, with Tabouk demonstrating a more pronounced warming trend post-event. These results enhance our understanding of the atmospheric dynamics linked to FDs and assist in predicting weather patterns associated with these phenomena.

Keywords

Forbush Decrease, Upper Air Temperature, Saudi Arabia, Climate Change,

Solar Activity

1. Introduction

Solar activity processes such as geomagnetic storms propagate through the interplanetary medium and can affect the magnetosphere, the ionosphere, and even the Earth's surface. These processes either directly affect the magnetosphere through the deposition of energized electrons which bombard the upper atmosphere producing aurorae or indirectly through modulation of CR particles which change the chemical and physical properties of the atmosphere [1]-[10].

Solar variability modulates the cosmic ray (CR) flux on different timescales. The CR flux measured on Earth is anticorrelated with the variations in the solar activity (sunspot number) on an 11-year timescale. Shorter timescale variations are also observed during the Forbush decreases [11] [12].

Cosmic Ray Forbush Decreases (FDs) are events characterized by a temporary reduction in cosmic ray intensity due to solar phenomena like coronal mass ejections. The interest in Forbush decreases stems from the recognition that CRs play a role in the Earth's atmospheric processes including the influence of air pressure and temperature (e.g., [13]-[15]).

The mechanisms by which Forbush decreases influence upper air temperature and pressure are complex and involve multiple atmospheric processes. One hypothesis involves the role of CRs in cloud formation. Svensmark and Friis-Christensen (1997) suggested that variations in CR flux could affect the nucleation and growth of ice particles in clouds, influencing the radiative properties of clouds and their interaction with incoming solar radiation, leading to changes in atmospheric temperature [16].

Another proposed mechanism focuses on the global electric circuit and the role of atmospheric electricity [17] which can potentially affect the dynamics of weather systems and the distribution of temperature and pressure in the upper atmosphere.

When FDs occur, there is a reduction in atmospheric ionization, which affects chemical processes crucial for maintaining pressure and temperature balances, notably those involving ozone. Ozone is vital for absorbing ultraviolet (UV) radiation and maintaining the thermal structure of the atmosphere. A decrease in ozone due to lower ionization can lead to cooling in the stratosphere, influencing atmospheric stability and temperature gradients. This cooling effect can alter atmospheric pressure patterns [18] [19]. At high altitudes, changes in ozone and temperature can impact pressure gradients, which are essential for driving wind patterns and atmospheric circulation. These altered pressure gradients can influence weather systems by shifting storm tracks and modifying the distribution of heat and moisture globally (e.g., [20]-[22]). Furthermore, the cooling of the stratosphere enhances atmospheric stability, affecting vertical air movements and cloud formation. These changes can impact temperature gradients, which are critical for driving large-scale atmospheric circulation patterns [23] and [7].

The impact of Forbush decreases on upper air temperature and pressure has been a subject of particular interest. Research in this area has sought to understand how changes in CR flux might influence atmospheric conditions (e.g., [13] [16] [17] and [24]).

Diverse results between increase and decrease before and after the FD events have been revealed.

However, studying the effects of FDs on temperature and pressure is complex due to the intricate interactions between extraterrestrial factors and atmospheric dynamics. The variability in CR intensity and the numerous factors influencing atmospheric conditions make it challenging to isolate the specific impacts of FDs. More observations and investigations are essential to deepen our understanding of these processes.

This study aims to determine whether there will be any significant impact on temperature and pressure before and/or before Forbush decreases at altitudes of 10 km and 15 km at two sites in Saudi Arabia: Tabouk in the north and Abha in the south. By examining these diverse geographical locations, we aim to contribute valuable insights into the regional variations in the impact of FDs on atmospheric dynamics.

2. Data and Methodology

Our study employed epoch analysis to explore the influence of FDs on upper air pressure and temperature, focusing on events from 1985 to 2005. We utilized daily radiosonde data, including pressure and temperature measurements, from two altitudes—10 km and 15 km—at two locations in Saudi Arabia: Tabouk in the North and Abha in the South. These sites were chosen for their data availability, diverse climatic conditions, altitudes, and potentially varied responses to FDs.

To control for seasonal and synoptic-scale variations, we normalized historical data and applied techniques such as moving averages and regression analysis. Statistical tests, including t-tests and ANOVA, were conducted to determine significance, while regression models were used to isolate the effects of Forbush decreases from other meteorological factors.

The superposed epoch method was applied to the pressure and temperature data, examining the period from 4 days before to 4 days after each event. This method helped identify the statistical relationship between cosmic ray intensity and atmospheric pressure, particularly focusing on the day of minimum cosmic ray levels during FDs to minimize confounding factors. We selected and analyzed FDs with magnitudes over 7% during the study period, excluding solar proton events to avoid misinterpretation. Events with data gaps exceeding 48 hours were also excluded.

Based on these criteria, 21 Forbush decrease events were analyzed at the 10 km altitude, and 20 events were examined at the 15 km altitude. The chosen Forbush decrease events are listed in **Table 1**. **Figure 1** provides a visual representation of the epoch analysis results for the Forbush decrease event on August 26, 1998, showing (a) pressure and (b) temperature changes four days before and after the event at both locations.

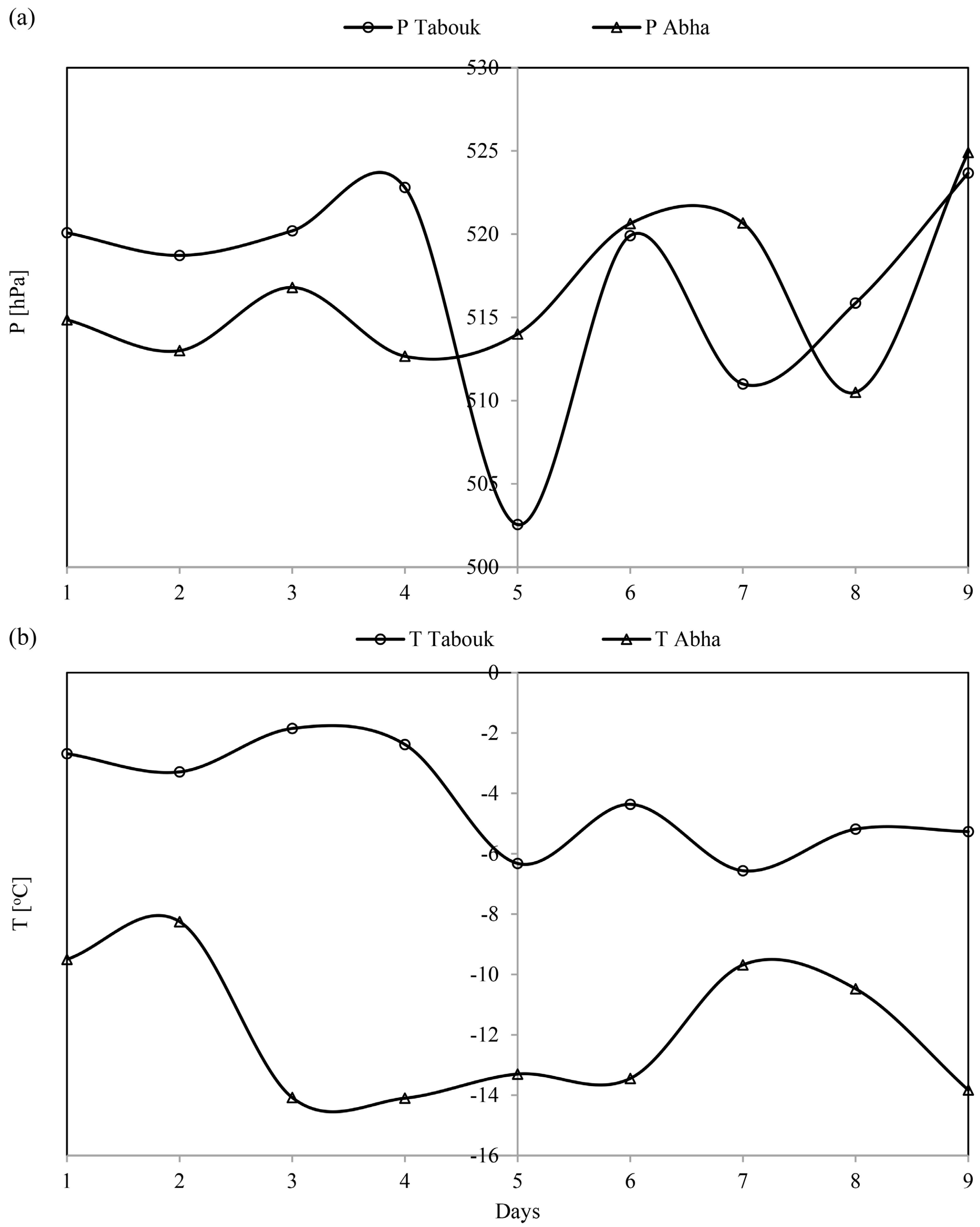

Figure 1. The epoch analysis results for the Forbush decrease event on August 26, 1998, showing (a) pressure and (b) temperature changes four days before and after the event at both locations.

Table 1. List of Forbush decrease events analyzed in this study at altitudes of 5 km and 10 km.

Altitude	FD	Date	FD	Date
5 km	FD1	04/10/1997	FD12	25/09/2001
	FD2	05/01/1998	FD13	30/12/2001
	FD3	05/04/1998	FD14	01/10/2002
	FD4	26/8/1998	FD15	11/10/2002
	FD5	24/09/1998	FD16	01/06/2004
	FD6	11/08/1998	FD17	22/07/2004
	FD7	18/2/1999	FD18	27/07/2004
	FD8	06/11/2000	FD19	08/05/2005
	FD9	27/3/2001	FD20	15/05/2005
	FD10	11/04/2001	FD21	16/07/2005
	FD11	28/4/01		
10 km	FD1	04/10/1997	FD11	28/4/2001
	FD2	05/01/1998	FD12	25/9/2001
	FD3	05/04/1998	FD13	24/11/2001
	FD4	26/8/1998	FD14	01/10/2002
	FD5	24/9/1998	FD15	10/11/2002
	FD6	11/08/1998	FD16	06/01/2004
	FD7	18/2/1999	FD17	27/7/2004
	FD8	11/06/2000	FD18	08/05/2005
	FD9	27/3/2001	FD19	15/5/2005
	FD10	11/04/2001	FD20	09/10/2005

3. Results

3.1. Variations of Pressure and Temperature at 5 km

3.1.1. Tabouk

Figure 2 depicts the frequency of pressure and temperature increases and decreases for each of the four days preceding and following the Forbush Decrease (FD) event at the Tabouk site.

In the period surrounding the FD event at 5 km in Tabouk, distinct patterns in pressure and temperature shifts were observed. Four days before the event, there were more pressure decrease events (15) than increases (6), while temperature showed a strong cooling pattern with 19 decreases and only 2 increases. This cooling trend continued on Day −3, with 20 temperature decrease events and just 1 increase, alongside a similar pressure pattern of 15 decreases and 6 increases. By Day −2, pressure began to stabilize, showing 10 increase events and 11 decreases, whereas temperature remained predominantly cooling with 19 decreases and 2 increases. A significant shift occurred on Day −1, where pressure saw 18 increase events and only 3 decreases, indicating rising pressure. Temperature showed some warming with 6 increases but remained cooler overall with 15 decreases.

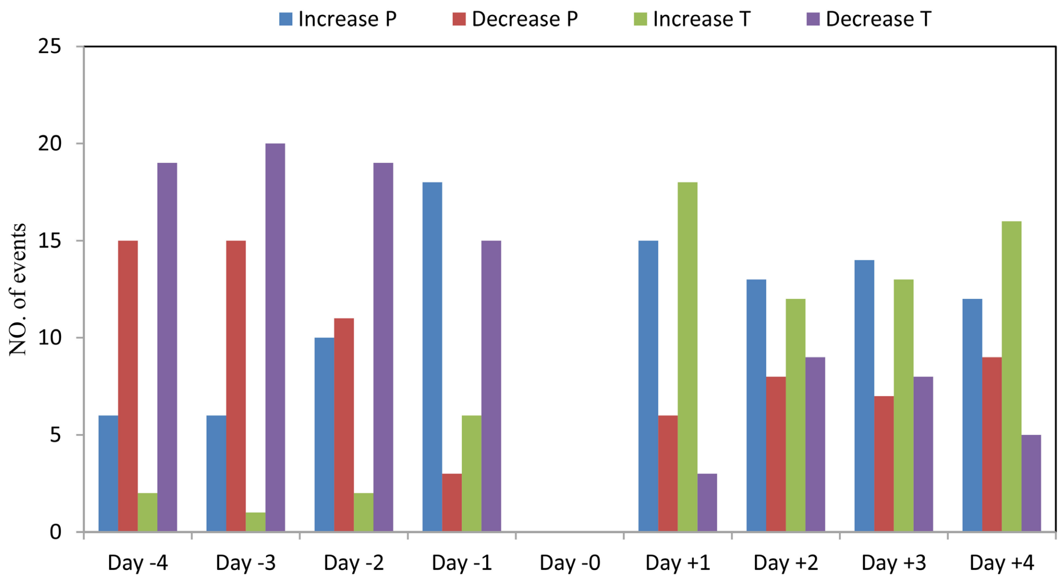

Figure 2. Histogram shows the number of events showed increase and decrease during the four days prior the FDs and Four days post the FDs at Tabouk at 5 km.

Following the event, Day +1 experienced a marked rise in pressure, with 15 increase events and 6 decreases, and a significant warming trend in temperature, with 18 increases and just 3 decreases. This warming continued on Day +2, with pressure showing 13 increases and 8 decreases, and temperature displaying 12 increases against 9 decreases.

Days +3 and +4 maintained this pattern, with pressure showing more increases than decreases (14 to 7 and 12 to 9, respectively). Temperature continued its warming trend, with 13 increases to 8 decreases on Day +3, and a notable 16 increases to 5 decreases on Day +4.

Figure 3 provide a comprehensive analysis of the pressure (**Figure 3(a)**) and temperature (**Figure 3(b)**) changes observed for every Forbush decrease events at the Tabouk site. The data reveal a complex pattern of atmospheric responses, with significant variations in both pressure and temperature magnitudes.

Before the FDs, the pressure changes exhibited a wide range, with increases up to 24.88 hPa and decreases down to 20.63 hPa. Specifically, 11 events showed a pre-event pressure increase, with notable magnitudes such as FD1 (15.07 hPa), FD3 (13.6 hPa), FD15 (14.96 hPa), and FD18 (24.88 hPa). Conversely, 10 events showed a pre-event decrease, with significant magnitudes such as FD4 (17.53 hPa), FD11 (20.63 hPa), and FD14 (13.5 hPa).

After the events, the pressure changes continued to show variability, with increases ranging from 8.26 hPa to 29.35 hPa and decreases from 14.73 hPa to 22.71 hPa. Twelve events showed a post-event pressure increase, with significant magnitudes such as FD4 (21.11 hPa), FD11 (29.35 hPa), FD15 (15.1 hPa), and FD18

(8.26 hPa). Significant post-event decreases were noted for FD5 (15.67 hPa), FD6 (22.71 hPa), and FD9 (14.73 hPa). These post-event changes may indicate a recovery phase or a continuation of the atmospheric adjustments initiated by the Forbush decreases.

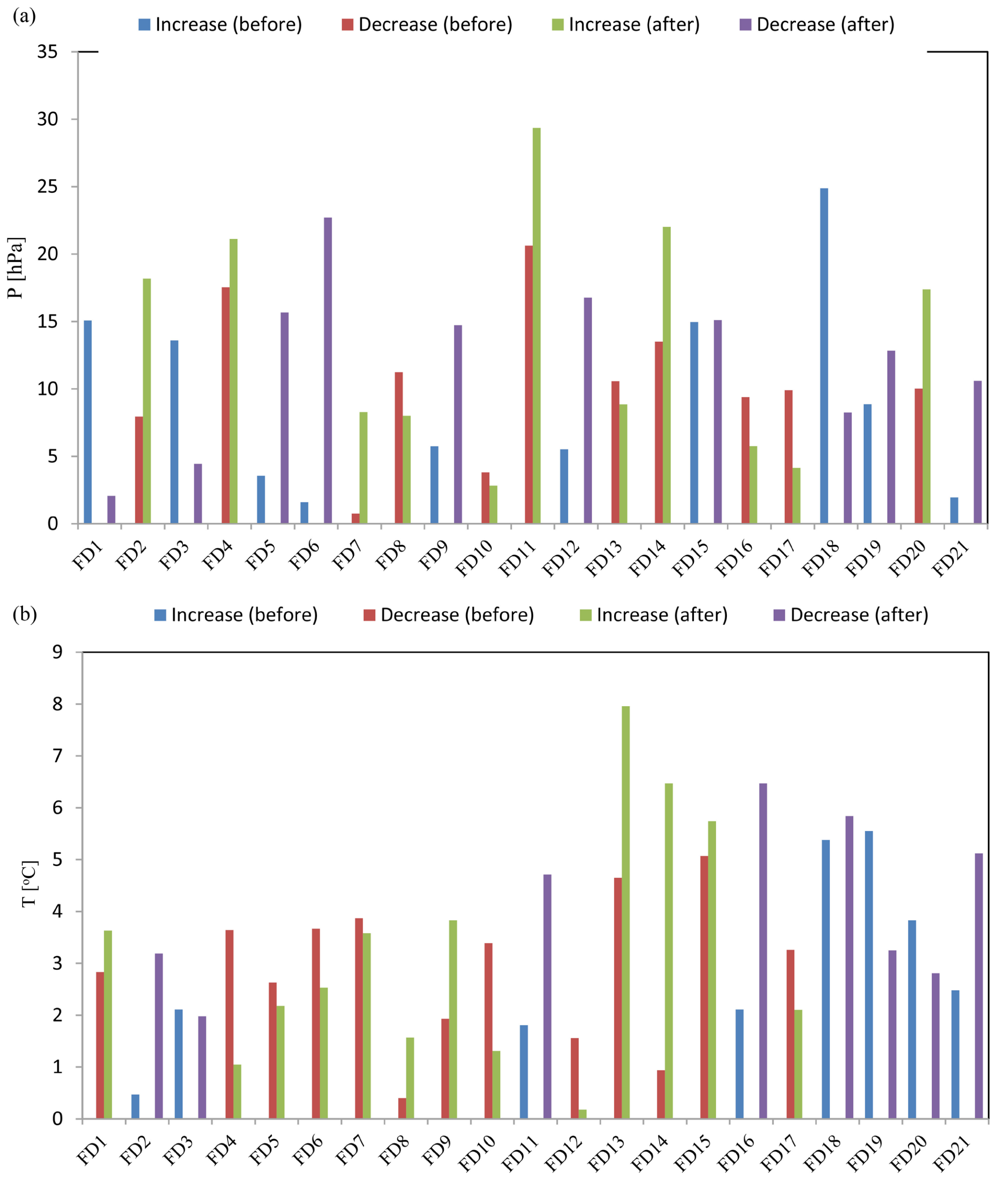

Figure 3. Indicate the magnitude of changes in (a) pressure and (b) temperature for each Forbush decrease event at the Tabouk site at 5 km altitude.

The temperature data (**Figure 3(b)**) present an equally complex picture. Before the events, the temperature changes ranged from decreases of up to 4.65˚C to increases of up to 5.55˚C. Specifically, 8 events showed a pre-event increase in temperature, with substantial magnitudes such as FD3 (2.11˚C), FD15 (5.07˚C), FD18

(5.38˚C), and FD19 (5.55˚C). A larger number of events, 13, exhibited a pre-event decrease, with significant magnitudes such as FD1 (3.63˚C), FD4 (3.64˚C), FD7 (3.87˚C), and FD13 (4.65˚C).

After the events, the temperature changes ranged from a single decrease of 3.19˚C to increases of up to 7.96˚C. A significant majority of events, 17, showed an increase in temperature, with notable magnitudes such as FD11 (4.71˚C), FD13 (7.96˚C), FD15 (5.74˚C), and FD18 (5.84˚C), suggesting a post-event warming trend. Only one event, FD2 (3.19˚C), showed a post-event decrease in temperature, indicating that post-event cooling is relatively rare.

3.1.2. Abha

Figure 4 depicts the frequency of pressure and temperature increases and decreases for each of the four days preceding and following the FD events at the Abha site.

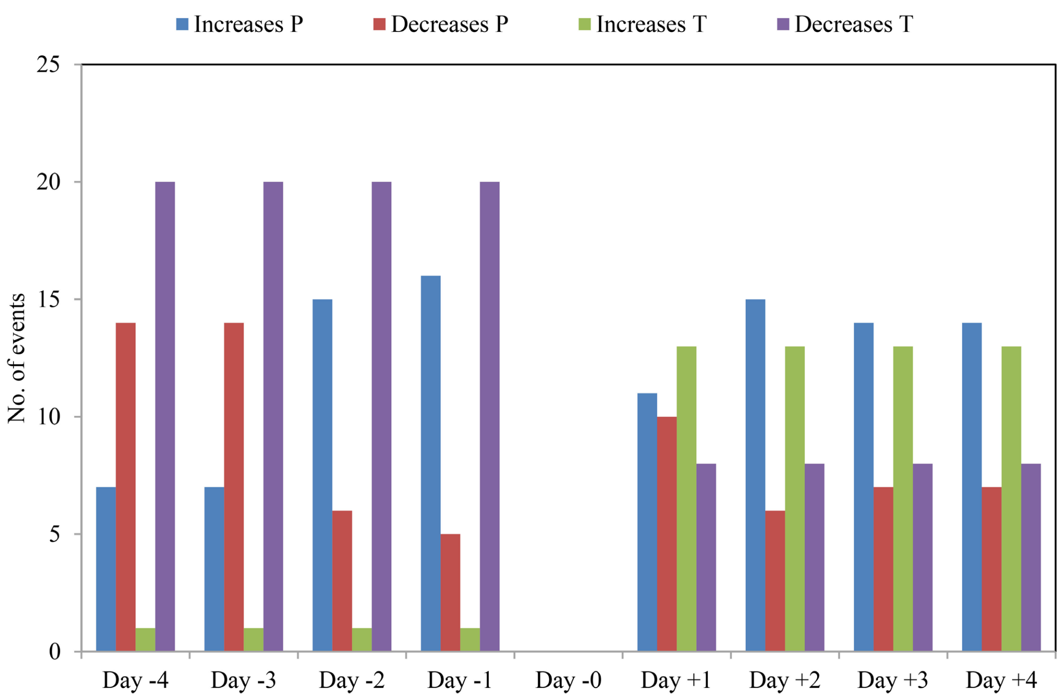

Figure 4. Histogram shows the number of events showed increase and decrease during the four days prior the FDs and Four days post the FDs at Abha at 5 km.

Four days before the event, pressure data showed 7 increase events compared to 14 decrease events. Temperature data mirrored this cooling trend, with 20 decrease events and only 1 increase. On Day −3, the same pattern persisted, with 7 pressure increases against 14 decreases and a continued strong cooling in temperature, with 1 increase and 20 decreases. By Day −2, a significant shift in pressure occurred, with 15 increase events and 6 decreases, suggesting rising pressure conditions. However, temperature remained mostly unchanged, with 1 increase and 20 decreases. Day −1 continued the upward pressure trend with 16 increases and 5 decreases, while temperature still showed only 1 increase against 20 decreases, maintaining the cooling. Following the event, Day +1 saw a more balanced pressure pattern with 11 increases and 10 decreases, while temperature shifted dramatically, showing 13 increases and 8 decreases, indicating a warming trend.

On Day +2, pressure increased again with 15 events versus 6 decreases, and temperature maintained its warming with 13 increases and 8 decreases. This pattern persisted through Days +3 and +4, with pressure showing 14 increases against 7 decreases each day, and temperature consistently recording 13 increases to 8 decreases.

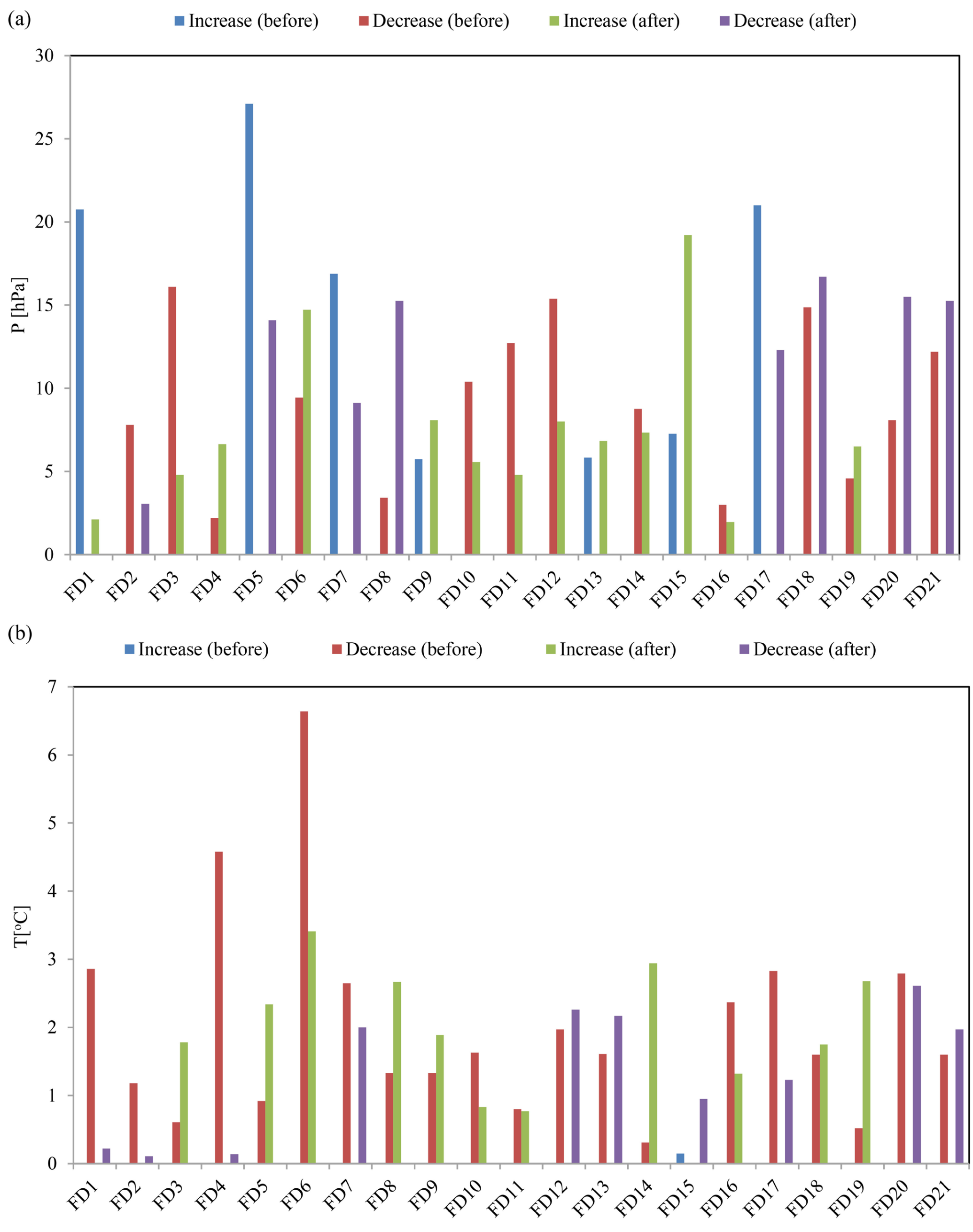

Figure 5. Indicate the magnitude of changes in (a) pressure and (b) temperature for each after Forbush decrease events at the Abha site at 5 km altitude.

Figure 5 illustrate the magnitude of pressure (Figure 5(a)) and temperature (Figure 5(b)) changes before and after each Forbush decrease event.

Before the Forbush decreases, the pressure changes exhibited a wide range, with increases up to 27.11 hPa and decreases down to 2.2 hPa. Specifically, seven events showed a pre-event pressure increase, with magnitudes ranging from 5.74 hPa to 27.11 hPa, while fourteen events demonstrated a decrease, with magnitudes ranging from 2.2 hPa to 16.1 hPa. For instance, FD1 experienced a significant increase in pressure of 20.75 hPa before the event, while FD3 showed a substantial decrease of 16.1 hPa. Additionally, FD5 had a notable pre-event pressure increase of 27.11 hPa, and FD13 showed a decrease of 15.39 hPa. This variability suggests that the atmospheric conditions leading up to these events are diverse, potentially influenced by a range of factors including local weather patterns and larger-scale atmospheric dynamics.

After the events, the pressure changes continued to show variability, with increases ranging from 4.79 hPa to 19.2 hPa and decreases from 2.11 hPa to 16.71 hPa. Eleven events showed a post-event pressure increase, with magnitudes ranging from 4.79 hPa to 19.2 hPa, while nine events showed a decrease, with magnitudes ranging from 2.11 hPa to 16.71 hPa. For example, FD15 exhibited a notable post-event pressure increase of 19.2 hPa, while FD18 showed a significant decrease of 16.71 hPa. Additionally, FD20 had a post-event pressure increase of 15.5 hPa, and FD11 showed a decrease of 9.12 hPa. These post-event changes may indicate a recovery phase or a continuation of the atmospheric adjustments initiated by the Forbush decreases.

The temperature data present an equally complex picture. Before the events, only one event (FD15) showed a slight increase in temperature (0.15˚C), while the remaining twenty events exhibited decreases, ranging from 0.31˚C to 6.64˚C. For instance, FD6 experienced a substantial pre-event temperature decrease of 6.64˚C, and FD4 showed a decrease of 4.58˚C. This predominance of pre-event cooling suggests that the atmospheric conditions leading up to the FDs are often characterized by cooler temperatures, possibly due to increased cloud cover or precipitation.

After the events, the temperature changes showed an even wider range, with increases from 1.96˚C to 19.2˚C and decreases from 2.11˚C to 15.5˚C. Thirteen events showed a post-event temperature increase, with magnitudes ranging from 1.96˚C to 19.2˚C, while eight events showed a decrease, with magnitudes ranging from 2.11˚C to 15.5˚C. For example, FD15 exhibited a significant post-event temperature increase of 19.2˚C, while FD19 showed a substantial decrease of 6.5˚C. Additionally, FD8 had a post-event temperature increase of 15.25˚C, and FD21 showed a decrease of 15.25˚C. The post-event warming in many cases may be attributed to the clearing of skies or the return of solar radiation, while the post-event cooling could be due to lingering effects of the FDs or other atmospheric processes.

3.2. Variations of Pressure and Temperature at 10 km

3.2.1. Tabouk

Figure 6 shows the increase and decrease in pressure and temperature in the four days leading the FD events and the four days post FD event in Tabouk.

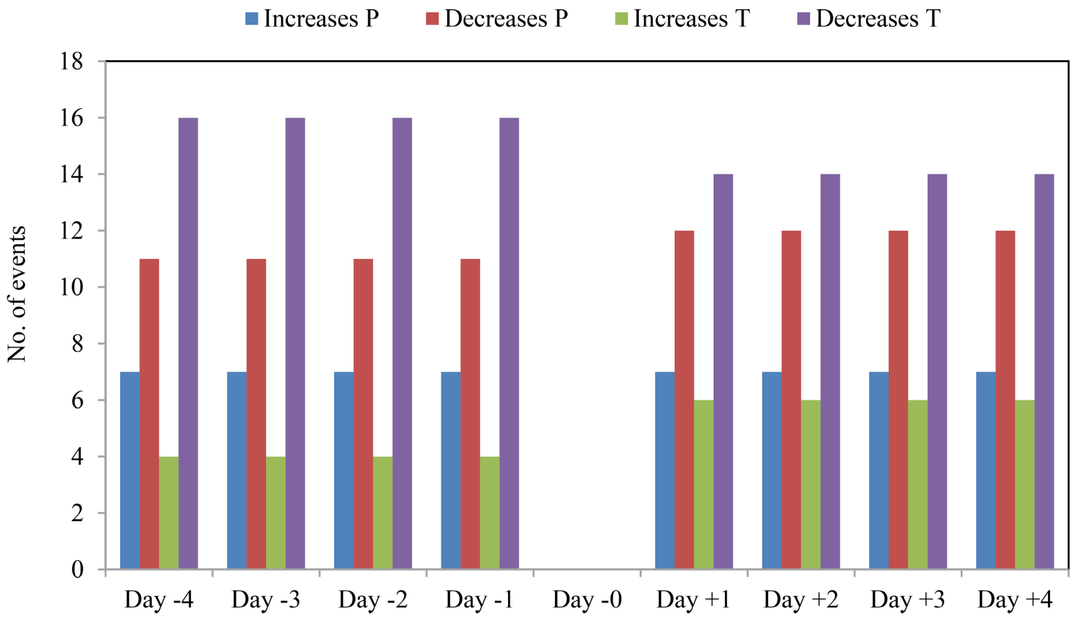

Figure 6. Histogram shows the number of events showed increase and decrease during the four days prior the FDs and Four days post the FDs at Tabouk at 10 km.

In the four days leading up to the event (Days −4 to −1), each day saw 7 events with increased pressure and 11 with decreased pressure, indicating a trend toward lower pressure. Similarly, temperature changes showed only 4 events with increases and 16 with decreases, suggesting cooler conditions.

Following the event, from Day +1 to Day +4, each day showed 7 events with increased pressure and a slight increase to 12 events with decreased pressure, reflecting ongoing atmospheric adjustments with a predominance of pressure decreases. For temperature, Day +1 saw no changes, while Days +2 to +4 showed 6 events with increases and 14 with decreases, indicating a gradual warming trend, though decreases remained more common.

Figure 7 illustrate the magnitude of pressure (Figure 7(a)) and temperature (Figure 7(b)) changes before and after each Forbush decrease event.

Before the events, there were 7 instances of pressure increases and 11 decreases, with significant rises like FD6 (9.25 hPa) and notable drops such as FD5 (8.2 hPa) influenced by local conditions.

After the events, 7 instances of increases and 12 decreases were observed. Increases like FD3 (7.917 hPa) suggest pressure rebounds, while decreases such as FD13 (11.333 hPa) indicate atmospheric adjustments. Overall, the pressure response to FD events is diverse, affected by local and geographical factors.

The temperature changes ranged from notable increases, like FD8 (3.9˚C) before events, to significant decreases, such as FD5 (6.52˚C). Before the Forbush decrease events, there were 16 instances of decreased temperature and only 4 increases, indicating a cooling trend, likely due to increased cloud cover.

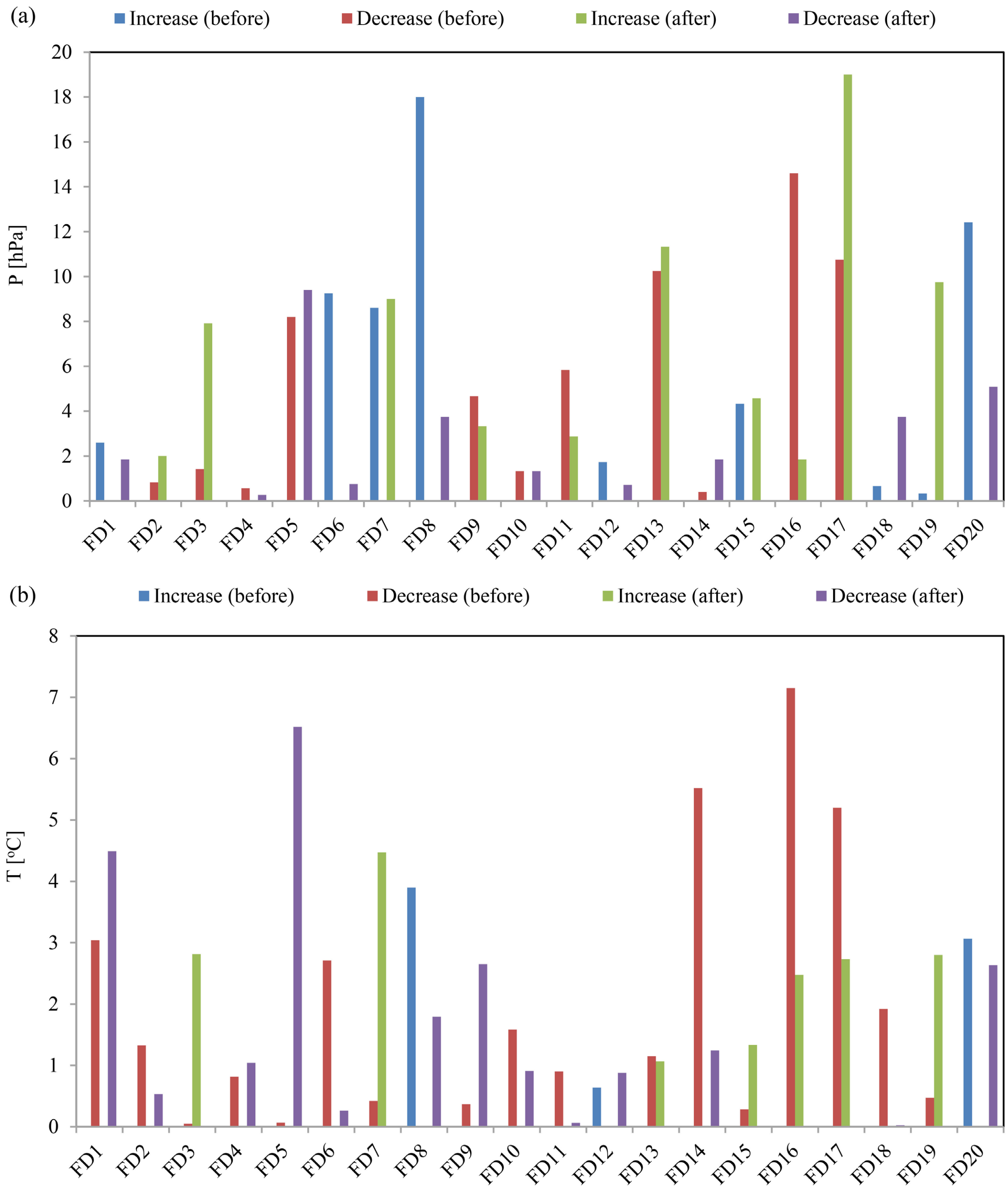

Figure 7. Indicate the magnitude of changes in (a) pressure and (b) temperature for each after Forbush decrease events at the Tabouk site at 10 km altitude.

After the events, the trend continued with 14 decreases and 6 increases. Notable post-event rises, like FD3 (0.05˚C) and FD20 (3.067˚C), suggest temperature rebounds, while significant drops, such as FD5 (2.65˚C), reflect atmospheric adjustments.

3.2.2. Abha

Figure 8 shows the increase and decrease in pressure and temperature in the four days leading the FD events and the four days post FD event in Abha.

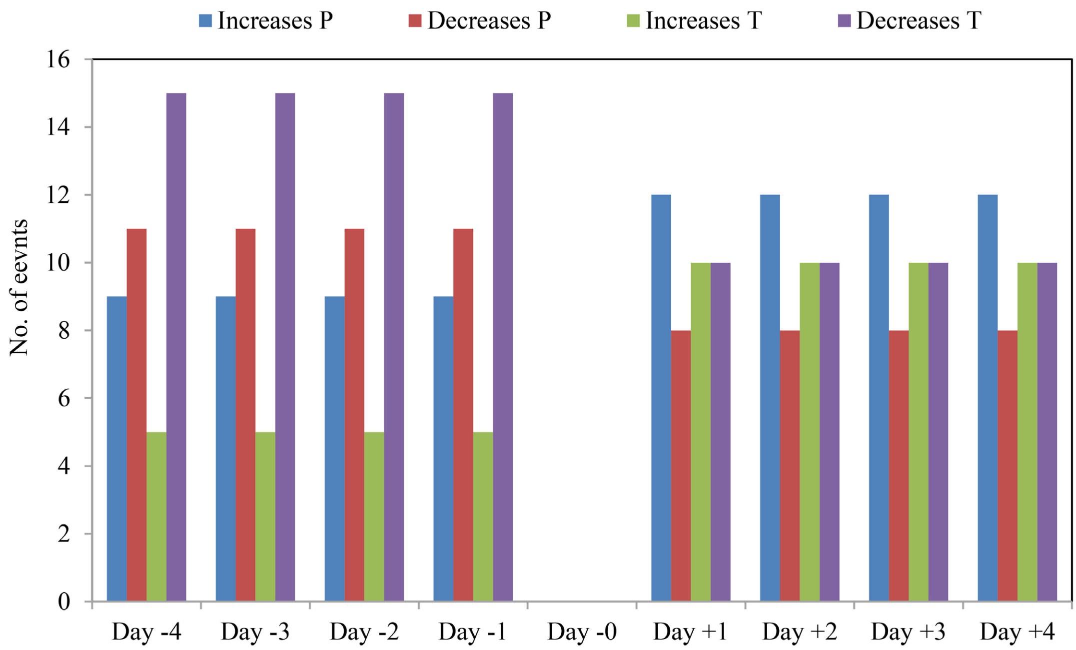

Figure 8. Histogram shows the number of events showed increase and decrease during the four days prior the FDs and Four days post the FDs at Abha at 10 km.

From Days −4 to −1, pressure increased in 9 events and decreased in 11, while temperature increased in 5 events and decreased in 15. Day 0 showed no changes in either pressure or temperature. From Days +1 to +4, pressure increased in 12 events and decreased in 8, whereas temperature had an equal number of increases and decreases at 10 each. This indicates a shift towards higher pressure post-event, with balanced temperature changes.

Figure 9 illustrate the magnitude of (**Figure 9(a)**) pressure and temperature (**Figure 9(b)**) changes before and after each Forbush decrease event.

The range of pressure changes before the events varied significantly. Notable increases were seen in 9 events with significant rises like FD1 (1.27 hP), FD4 (4.33 hP), and FD16 (14.11 hP). Conversely, decreases were prominent in 11 events with substantial drops such as FD5 (10.45 hP) and FD18 (16.71 hP).

After the events, pressure changes included increases in 16 events with significant rises like FD12 (7 hP) and FD17 (10 hP). Decreases were evident in 6 events with notable drops such as FD19 (6.49 hP) and FD20 (4.5 hP).

Before the events, temperature increases were noted in 5 events. Significant rises included FD6 (6.96˚C) and FD14 (3.93˚C). Conversely, decreases occurred in 15 events with notable drops like FD3 (1.06˚C) and FD7 (4.43˚C).

After the events, temperature increases were observed in 10 events. Notable rises included FD11 (3.28˚C) and FD6 (3.21˚C). Decreases were evident in 10 events with significant drops like FD6 (6.96˚C) and FD4 (4.48˚C). These variations highlight the atmospheric adjustments occurring around FD events.

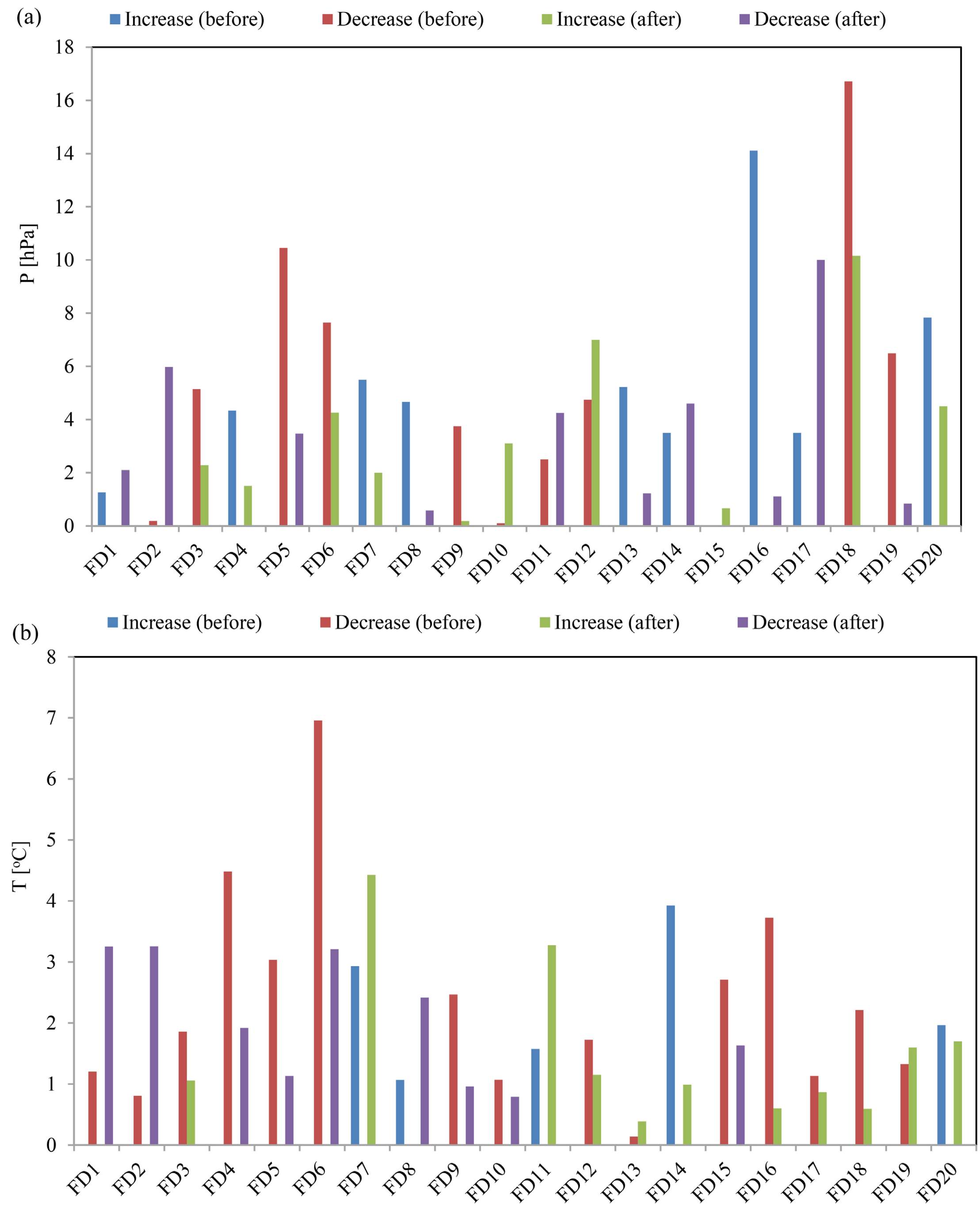

Figure 9. Indicate the magnitude of changes in (a) pressure and (b) temperature for each after Forbush decrease events at the Tabouk site at 10 km altitude.

4. Discussions

The investigation into the effects of FDs on upper atmospheric pressure and temperature at Abha and Tabouk revealed a spectrum of outcomes, with both increases and decreases observed surrounding these events. This variability is consistent with findings from some prior studies but diverges from others, underscoring the intricate nature of atmospheric responses to FDs. For example, [14] studied the pressure variations at different altitudes above Sodankyla (Finland, latitude 67˚) and found that FDs are associated with a pressure increase throughout the troposphere, peaking on the 3rd to 4th day post-event. Conversely, a decrease in temperature was noted in the troposphere during the initial days of the FD. In contrast, Vovk *et al.* [25] identified different effects near the South Pole, where pressure at Vostok Station (Antarctica) increased during solar proton events but decreased during FDs. Veretenenko and Pudovkin [24] examined the lower atmosphere's response to FDs, noting significant shifts in surface pressure and temperature, potentially linked to the modulation of internal gravity waves by atmospheric electricity changes associated with FDs. Egorova *et al.* [26] investigated the influence of cosmic ray variations on atmospheric pressure and temperature in the region of the Southern geomagnetic pole, specifically using data from the Vostok station in Antarctica. The research focuses on the effects of Forbush decreases—periods of reduced cosmic ray flux—and solar proton events on the atmosphere. They found that the onset of a Forbush decrease is followed by a significant warming of the lower atmosphere (up to 10 degrees Celsius) at altitudes below 6 - 7 km, with a duration of about one day. Forbush decreases are accompanied by a reduction in atmospheric pressure at all altitudes below 20 km, with the greatest reduction at higher altitudes. The warming of the troposphere and the decrease in pressure in the lower stratosphere and troposphere lead to a reorganization of the wind system over the polar region within 0 - 6 days. Lam and Rodger (2003) concluded that there is no statistically significant correlation between the onset of moderate to strong geomagnetic storms and changes in winter tropospheric isobaric temperature or height over the South Pole.

[16] found that the reduction in cosmic rays during FDs could alter the electrical properties of the atmosphere, influencing cloud formation and precipitation processes, thereby affecting temperature and pressure patterns. The mechanisms by which Forbush Decreases (FDs) impact upper air temperature and pressure are complex and involve various atmospheric processes. One theory, proposed by [27], suggests that CRs play a role in cloud formation. Changes in CR flux can alter cloud properties and their interaction with solar radiation, thereby affecting atmospheric temperatures. Another mechanism involves the global electric circuit, where atmospheric electricity can alter weather dynamics, impacting the distribution of temperature and pressure. During FDs, reduced atmospheric ionization affects chemical processes essential for maintaining pressure and temperature balance, particularly those involving ozone. Ozone variations affect temperature near the tropopause, influencing stability and moisture transport. Increased ozone cools near-surface air, while lower ozone density can lead to warming due to enhanced greenhouse effects from moisture in the upper troposphere [19].

However, in addition to the nature of the FDs and factors that cause them (type locations and CME), local factors such as topography and regional weather conditions along with large-scale phenomena, may also influence the effects of FDs on both the upper and lower atmospheres significantly influence these outcomes, as observed in our study and others.

5. Conclusion

This study investigated the effects of Forbush Decreases (FDs) exceeding 7% magnitude between 1985 and 2016 on upper air pressure and temperature at Abha and Tabouk. At 5 km altitude, Abha experienced 7 pressure increases and 14 decreases before the events, shifting to 11 increases and 9 decreases afterward. Temperature patterns at Abha showed predominantly decreasing trends pre-event (1 increase, 20 decreases), reversing to mostly increases post-event (13 increases, 8 decreases). Tabouk displayed similar pressure variations (11 increases, 10 decreases pre-event; 12 increases, 9 decreases post-event) but demonstrated a more pronounced temperature response, particularly post-event with 20 increases and only 1 decrease. At 10 km altitude, both locations exhibited similar patterns, characterized by predominant decreases in both pressure and temperature before events, transitioning to increases afterward. Notably, Tabouk showed a stronger warming trend post-event. These findings underscore the complexity of atmospheric responses to FDs and emphasize the importance of localized studies in understanding these atmospheric interactions.

Statements & Declarations

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Competing Interests

The authors have no relevant financial or non-financial interests to disclose.

Author Contributions

All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by Abdullrahman Maghrab ,Alghamdi Mayso, Aldosari Abdulah, and Almutairy Mohammed. The first draft of the manuscript was written by Abdullrahman Maghrabi and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Declaration of Generative AI and AI-Assisted Technologies in the Writing Process

During the preparation of this work the author used pop ai in order to improve the language and readability. After using this tool, the author reviewed and edited the content as needed and take(s) full responsibility for the content of the publication.

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