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Exploring the Effects of Martian Seasons on Surface Features, Climate, and Atmospheric Behavior: A Comprehensive Review

Jobanpreet singh *

Department of Aerospace Engineering, School of Mechanical engineering,

Lovely Professional University, Jalandhar, Punjab, India

Abstract: Mars has specific orbital and axial characteristics that give rise to seasons unlike those encountered on Earth. This paper explores seasonal changes on the Red Planet and demonstrates how deep such changes are about features on its surface, climate, and atmospheric dynamics. It analyses temperature, pressure in the atmosphere, and dust activities as descriptors which show influences towards some phenomena such as polar ice caps, dust storms, and surface weathering. The paper further discusses the interaction between Martian seasons and the thin atmosphere of the planet-the seasonal sublimation of CO2 at the poles and its implications for the Martian climate, revealing insights into how these seasonal changes affect Mars' potential for future human exploration and habitability through a comprehensive examination of recent data from missions to Mars. Thus, this review gives a greater insight into the Martian environment and acts as an argument supporting further studies on seasonal dynamics to advise future missions and searches on other planets for life.

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1. Introduction

Mars is sometimes called the "Red Planet." Scientists have been interested in this planet for centuries, finding similarities and stark differences with Earth. One of the most interesting attributes of Mars is its seasonal cycle, which, although somewhat comparable to Earth's, is sculpted by a different set of planetary characteristics. Its year has almost twice as long as Earth's duration-687 Earth days-and a significant axial tilt of 25.19°; Mars, therefore, experiences seasons in a unique and dramatic way. Mars has a much thinner atmosphere and is more distant from the sun than Earth; its extreme temperature fluctuations and a fragile climate system mark it as significantly different **[1]**. Mars's seasons are interesting from the scientific point of view, but critical implications will be faced for future missions to the planet; therefore, how such seasons impact the atmosphere, surface, and potential habitability will be most crucial in planning long-term human exploration and colonization. For instance, the seasonal sublimation of carbon dioxide at the poles influences the variations in the atmospheric pressure and compositions, which causes global dust storms and variability of weather. Seasonal influences may also be felt on the surface, for instance in the ways dunes are shifted, polar ice caps maybe moving either backward or forward and even possible past or present water activity. Martian seasons differ from Earth seasons, as well as the most dramatic and important environmental changes that result from them. Making use of data produced from recently conducted missions to Mars-most notably rovers such as Curiosity and Perseverance and orbiters such as MAVEN--we will attempt to take an all-around view of how seasonal effects function for Mars today. Ultimately, studying Martian seasons promotes interest in the related study of the planet's past for scientific reasons and the future possibilities when such a discovery might support life **[2]**.

*Department of Aerospace Engineering, School of Mechanical engineering Lovely Professional University, Jalandhar, Punjab, India.
Corresponding Author: jobansohi1234@gmail.com.
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2. Martian Seasons

Mars, the fourth planet from the Sun, has a seasonal cycle dramatically different from Earth's, mainly because of the orbital and axial characteristics of the planet. This length of Mars year is the most significant seasonal distinction of Mars, being nearly twice the length of our year at 687 Earth days. This means that Martian seasons take much more time to come and go than on Earth, should one use Earth months as a measure. Thus, for instance, a whole Martian winter may last almost twice as long as one Earth winter. A Martian year is the consequence of an elliptical orbit around the Sun and its orbit is more elliptical than that of Earth. Though Earth orbits almost in a perfectly circular orbit, the Martian orbit is elliptic; this means that the distance between the planet and the Sun varies much during its yearly cycle. The distance contributes to Mars having more extreme seasons than those found on Earth. The temperatures increase marginally when Mars is nearer to the Sun, while being afar from the Sun at aphelion makes temperatures go a bit lower. These orbital eccentricities, along with the tilt of the planet's axis, cause Martian seasons not only to vary in length but also in magnitude.

Mars' axial tilt of 25.19° is the main influencing factor for season changes on the planet. The Earth's axial tilt is 23.5°, which makes seasonal changes relatively soft and predictable; the axial tilt of the planet increases the differences in temperature and atmospheric pressure considerably on Mars. The tilt determines the amount of sunlight received by each hemisphere during a Martian year. Like Earth's seasons, it is just much more extreme. When the northern hemisphere of the planet is summer, it would be tilted to the sun, making it slightly warmer. The opposite is true for the south hemisphere when it's winter. During southern summer and northern winter, the reverse occurs. The combination of a longer orbit and greater axial tilt really gives rise to much more dramatic seasonal shifts than those we experience on Earth. This has an important influence on the surface and atmosphere of Mars: polar ice caps, dust storms, and composition of the atmospheric gases reflect fluctuations in their observable features. This knowledge would be of aid in planning missions to Mars' environment because seasonal changes are driven directly by these characteristics of Mars' orbit and axial tilt, and astronauts may experience these conditions during their mission **[3].** In short, while the principles of Mars' seasons are essentially the same as those on Earth-such as the tilt of the planet's axis and its orbit around the Sun-the elongated orbit and greater axial tilt of Mars result in seasonal changes that are much more extreme and of a longer duration. These differences lead to some pretty neat science, but they have a major effect on the potential and ability of Mars to support future human exploration.

3. Comparison of Martian and Earth Seasons

Comparing the seasons on Mars to those on Earth would immediately suggest that, although seasonal cycles of the sort occurring with axial tilts for both planets are present, Mars's seasons are far more extreme in time and intensity. Basic differences derive from the different orbital characteristics, axial tilts, and distances of the two planets from the Sun. While Earth's seasons are familiar to us, the planet's season on Mars brings challenges and wonders that not only are dramatically longer but also more intense. The first major difference between Earth's and Mars' seasons is their length. A year on Mars, as mentioned earlier, lasts 687 Earth days, making each of its four seasons considerably longer than Earth's fig.2. To put it simply, Martian Spring, summer, fall, and winter last about 167 days on Earth, where, for instance, in Earth seasons, which usually last three months, or approximately 90 days. That means, therefore, one Martian summer would last about twice as long as an Earth summer. This, in its turn, will directly affect the planet's environmental dynamics. Long seasons allow the Martian weather system to acclimate over months rather than sharply change from one season to another, as is the case on Earth.**[4][5].**

The difference is that temperature fluctuations are different due to Mars being farther from the Sun and having a much colder overall climate. The average temperature on the planet is approximately -60°C (-80°F), though it may decline to as low as -125°C (-195°F) near the polar regions during winter, while at the equator summer may reach temperatures as high as 20°C (68°F). Earth's temperature range, however, extends a good deal more. Temperatures on Earth can go as low as -50°C (-58°F) at the poles during winter and may go higher than 50°C (122°F) during the summer in some desert regions [6]. The close orbit of Earth to the Sun, and its more modest axial tilt, would prevent extreme, freezing situations Mars is subjected to in its winter. Since Martian temperature differences are much greater than those on Earth, the atmosphere is not thick enough to hold heat. The atmosphere, mostly nitrogen and oxygen on Earth, serves as an insulating blanket and usually prevents extreme diurnal temperature swings. The atmosphere on Mars is too thin, comprising mostly carbon dioxide. It offers minimal insulation, so the temperature greatly changes from day to night. A day on Mars, called a sol, is nearly identical to an Earth Day, about 24.6 hours. Yet the range of temperatures throughout a sol can be quite extreme.

Temperatures at midday near the equator can be as warm as nearly 20°C (68°F). Night, however, could drop to -100°C (-148°F).

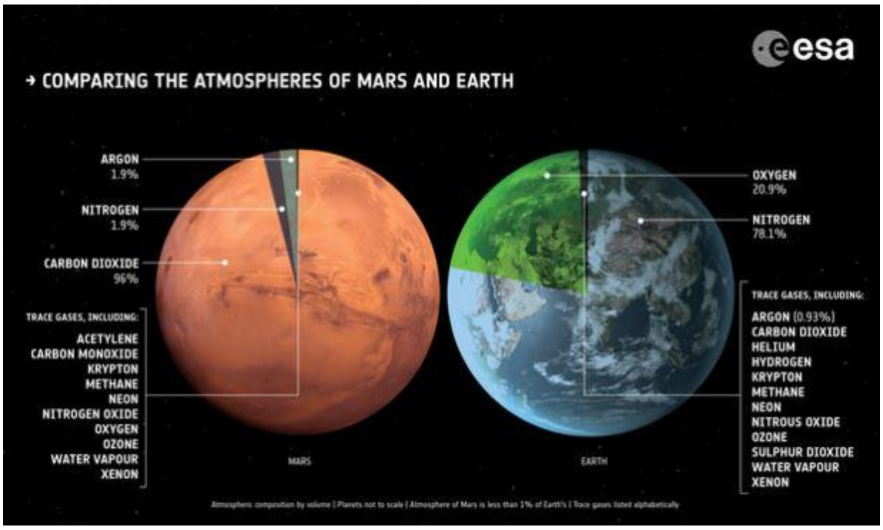

Fig.1 Comparison of Martian and Earth Seasons [Source: ESA][18]

Seasons on Mars can dramatically affect its surface features. Polar ice caps are one of the primary markers of such seasonal changes. At a Martian winter, frozen carbon dioxide covers up poles. With an upsurge in summer, this carbon dioxide, however, sublimates, or directly transforms from a solid to a gas. The seasonal advance and retreat of the ice caps is an interesting component of the seasonal cycle of Mars but also forms an important component within the climate of Mars. While combined with the thin atmosphere, the changing size of the ice caps affects atmospheric pressure on Mars and global dust activity. This contrasts with Earth's polar ice, which also migrates seasonally although not nearly to the extent. Earth's ice sheet, especially in Antarctica and Greenland, sublimates much less dramatically than on Mars. They usually melt and refreeze upon changes in temperature with the ice retreating slowly. The dust storms on Mars also indicate the extreme nature of seasons on Mars. On Martian summer, the rate of such occurrences of dust storms, from local whirlwinds to mighty global dust events, is high. Such a storm can change the look of the surface for days or weeks while spreading dust over vast areas, blocking everything from view. On Earth, a much thicker atmosphere and stable weather systems prevail, so it never saw anything of this type and scale of dust storms.**[7][8]**

Quite naturally, differences in the duration and strength of seasons on Mars as opposed to those on Earth have a rather great influence on those atmospheres. On Earth, changes are mild, and the atmosphere absorbs the temperature shifts slowly. Strong atmospheric dynamics, oceans, and vegetation all tend to stabilize Earth's climate over the course of its year. Mars has no such stabilizing influences. The Martian atmosphere is thin, mainly carbon dioxide in composition, and of course does not possess the heat-retaining properties of Earth's atmosphere. This means seasonal changes on Mars directly affect atmospheric pressure, especially in the summer months due to CO2 sublimation from the polar ice caps, increasing density and pressure differences responsible for more aggressive weather patterns, including massive storms of dust and wind pattern changes. seasons in Mars and Earth are basically due to the axial tilts; however, the duration, intensity, and the effects of the seasons on Mars are much more extreme than on Earth. Mars's seasons last hundreds of days and bring with them large temperature shifts, dramatic changes in features across the surface, and extreme atmospheric behaviors characterizing this planet's environment **[9]**. Knowing the difference is central to the determination of scientists, as it influences how we study Martian climate or search its surface and how we plan for future missions.

4. Impact of Martian Seasons on Surface Features

Seasonal changes at the surface of Mars have many different significant impacts on its surface features. They influence all dune motions, ice deposits, dust storms, and the dynamics of the polar ice caps. The surface phenomena are not only interesting to investigate but also critical to the understanding of the geological history of the planet and its potential past water activity. Mars has an extremely thin atmosphere and extreme seasonal conditions, causing extreme changes within the surface environment of this planet and the resultant shaping of the topography.

The most notable aspect of the planet Mars regarding seasons is that it affects polar ice caps. Mars has two polar ice caps; one located in the northern hemisphere called Planum Boreum and the other one in the southern hemisphere called Planum Australe. During the Martian winter, temperatures plummet dramatically, and carbon dioxide in the atmosphere freezes and collects on the surface, forming an ice layer several meters thick. The process of this seasonal phenomenon differs from the Earth's polar regions, where frozen water makes up the primary form of frozen material. Carbon dioxide (CO_2), in the frozen state, constitutes the majority of the polar ice caps on Mars fig.3. In the warm seasons, since temperatures rise across the planet, the frozen material sublimates. Sublimation, in this case, affects seasonal variability in the atmospheric composition and thereby influences both atmospheric pressure and circulation. The growth and recession of these ice caps over the course of the Martian year also lead to small changes in the ground topography, as the ice can build up sufficiently to cause small-scale movements in the soil below.**[10]**

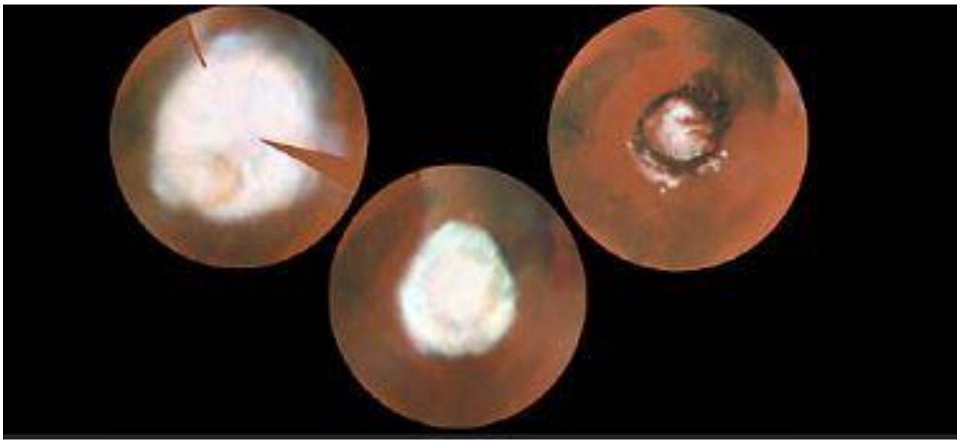

Fig.2 Seasonal Martian Polar Ice Caps Due to CO_2 Sublimation and Deposition [Source: Hubble Website] [17]

In addition to the ice caps, Martian seasons also powerfully affect the development and movement of dust storms. Mars has a global dust storm, which at times covers the whole planet and may last for weeks or even months.[11] Such a storm is more likely to occur in the warmer seasons of the year because the atmosphere begins being very active, bringing up dust particles from the ground due to extreme convection currents, triggered by the heating of the planet by the sun. This thin atmosphere on Mars permits the movement of these dust storms for a long distance and to really large sizes. Other than altering the face of the Martian surface by spreading huge areas with dust, these storms also contribute to the seasonal changes in the albedo, or reflectivity, of the planet, a factor that impacts temperature. In addition, dust storms can obscure important features on the surface like craters and valleys as well as regions entirely, making the research into the geology of this planet way more complicated.

Another feature formed through Martian seasons is that of the dunes movement and soil. Mars' equatorial regions have fields of dunes extending mile after mile. They are continuously shifting by the wind's actions, just like on Earth. The seasonal winds play, however, an especially prominent role in the movement of these dunes on Mars. During the Martian summer, the atmosphere becomes a bit thicker and more turbulent, where winds can reach higher speeds. These winds cause a lot of shifting of the position of the dunes over time. Conversely, during winter months, the atmosphere is cold and less dense. As such, wind speeds are lower, and dune movement slows down. This seasonable cycle of wind-driven migration in dunes contains some clues that tell about the dynamic nature of Martian surface processes and aid research into Martian wind patterns and atmospheric behavior.**[12][13]**

Besides dust and dunes, the impact of Martian seasons on soils has equal significance. With time, surface soils of Mars expand and contract with changing temperatures. During winter, when temperatures lower, soils contract, but during summer, they expand with the rise of temperature. Such temperature fluctuations can result in surface cracks and fissures, which become progressively larger features over time. In addition to the motion of dust and sand, the resulting cracks further contribute toward Martian soil erosion and lead to the development of geological features such as rilles and channels.

One of the major long-term effects of Martian seasons on larger-scale surface features, such as canyons and valley and crater erosion-the cause of which is thought to have been past water activity-is likely to be seasonal melting and sublimation of the polar ice caps, which may have created some of the Martian valleys and outflow channels.**[14]** Although liquid water is not currently present on the surface of Earth, all these evidence points out that indeed, water was abundant on Mars earlier in the planet's lifecycle, mainly in certain stages. With seasonal changes, melted ice from polar caps, along with the groundwater that could have been trapped in the soil, could cause seasonal erosion or material shifting that reshapes these valleys and canyons even more. For example, Valles Marineris is one of the largest canyon systems in the solar system and may have at least in part formed due to past liquid water activity, which could have been modulated by seasonal variability that perturbed the planet's once active hydrologic cycle.

Seasonal frost on the surface also plays a big role in surface alteration. Generally, during the winter of Mars, frost deposits appear on the surface, mostly at higher latitudes. This seasonal deposit of frost is thought to create layers in Martian soil that may be temporary. When the frost sublimates during the warmer months, patterns remain that are not very strong on the Martian surface. These frost-patterned formations provide a clue regarding the seasonal behavior of water and carbon dioxide on Mars and thus enable scientists to study how these processes had evolved over time.

The implications of Martian seasonal changes for past water activity are profound. Probably, the temperature oscillations interplayed with the Martian surface, which may have tended towards the conditions favorable for the flow of liquid water during the more ancient epochs, when Mars could still have had a much thicker atmosphere and warmer climate. All signs of ancient riverbeds, deposits of lakes, and mineral formations occur on its surface and explain the possibility that Mars once was a planet so much wetter. Some seasonal processes such as ice deposition, sublimation, and erosion could have impelled the formation of these ancient water features that somehow ruled the habitability of the planet at one point in time. It can be summarized that there are many dynamic processes that affect surface features in Mars directly due to seasonal cycles. From the expansion and contraction of the polar ice caps to moving dust, dunes, and soil, seasonal changes make up the very core elements that shape the Martian landscape. This constant interaction of seasonal processes with the geology of the planet offers some precious insights into the history of water on Mars and whether the conditions on the planet could support life in the past. But to do that, scientists must first understand how Martian seasons affect what happens on the planet's surface.

5. Climate and Weather Changes Due to Martian Seasons

Seasonal changes of Mars are very sensitive, exerting their impact all throughout the climate and weather arising from temperature fluctuations, wind speeds and even atmospheric pressure. The general atmospheric level on Earth tends to cushion the Martian, which is relatively less thick; thus, making the latter's weather very extreme and volatile. As a result of Martian seasons, the changes in temperature and pressure bring into existence captivating and unusual kinds of weather wholly different from the earth's. The most obvious consequence of Martian seasons is variations in temperature. Mars orbits in an elliptical pattern, thus the seasonal temperatures on this planet differ much more than on Earth. Summer when Mars is a far from the Sun (aphelion) falls on the northern hemisphere, while winter when it approaches the Sun (perihelion), for that matters. The result of this situation is cooler and longer summers in the northern hemisphere while colder and more intense winters, though warmer and shorter, in the southern one. The axial tilt of Mars (25.19°) is the primary cause for the difference in seasonality intensity, as though the same in magnitude as Earth, it is different because it combines with its eccentric orbit to make seasonal extremes even more pronounced. Temperatures on Mars have been as high as 20°C (68°F) during a day's and summer's heat over the equator and as low as -125°C (-195°F) at the poles during the depths of winter. The great fluctuations also generate extreme variations in weather and, therefore, are quite a big feature of the global climate system.

Mars boasts of strong seasonal winds too, since its wind is fueled by the temperature variations. In warmer months especially during summer seasons in the southern hemisphere, the contrasting temperatures of the surface and the atmosphere force powerful wind currents. These can have speeds of more than 60 miles per hour, or 97 kilometers per hour; they can raise considerable dust off the ground. The winds are thought to drive enormous dust storms that could blanket the whole planet. Such storms tend to occur most often during the summer in the southern hemisphere, where widespread rising temperatures and a lack of stability in the atmosphere promote growth. The storms are enormous, growing so large that they can blanket the entire face of Mars for several weeks before erasing key features and dramatically altering the face of the planet. Their global nature in turn impacts Mars climate, lowering surface temperatures by blocking sunlight and spreading dust around the planet.

Similarly, atmospheric pressure on Mars also changes with the seasons. This occurs mainly because of the freezing and sublimation of the carbon dioxide at the poles. In winter, temperatures are quite low because the CO2 in the atmosphere condenses and freezes onto the polar caps, thus reducing the amount of CO2 remaining in the atmosphere, and hence reducing the atmospheric pressure. In the spring and summer time, the frozen CO2 sublimates and results in higher atmospheric pressure since the gas is returning to the atmosphere. Therefore, it creates a cyclical pressure system of dynamic seasons, high atmospheric pressure during warm seasons, and low in cold seasons. These fluctuating atmospheric pressures can influence wind patterns and even weather conditions around the world, potentially altering how dust and other particles are transported. The other important feature of the Martian climate is interseasonal variations in atmospheric levels of dust, which has played a very important role for forming weather and climate dynamics within this planet. As Mars completes one seasonal cycle, that cycle brings periodic rises and falls in the amount of dust within the atmosphere. During the summer season in the southern hemisphere, dust storms are also most active and within those summers, finer particles of dust are lifted by strong winds, filling the atmosphere. It has several important effects to presence in the atmosphere. Absorbing sun radiation, warmth of the atmosphere with the surface cooling, leads to temperature inversions. Upper atmosphere warming by dust storms can cause significant variations in atmospheric circulation, which can drive further wind activity and redistribute dust to other regions of the planet. Such dust particles stay in the atmosphere for months if it gets extreme, contributing to long climate effects whereby the surface of the planet gets cooled.

The Martian climate dynamics are controlled primarily by the seasonal behavior of dust. At any level of high dust, the climate in general will fluctuate more dramatically than under low conditions-differences between stronger winds and much greater temperature swings. On the other hand, during lower dust levels, the climate stabilizes, and weather extremes are much less likely. Long-term climate histories of seasons on Mars are similarly brought about through these seasonal events in dust activity because scientists believe that dust-driven climate cycles may have influenced the potential habitability of the planet. By studying how dust storms and seasonal winds influence the current Martian climate, scientists gain valuable insights into the changing trends of the planetary atmosphere over the ages. Studies from NASA observations between January and September 2001, captured through the Hubble Space Telescope, reveal how a massive global dust storm enveloped the entire planet, significantly altering its visible geography fig.4.

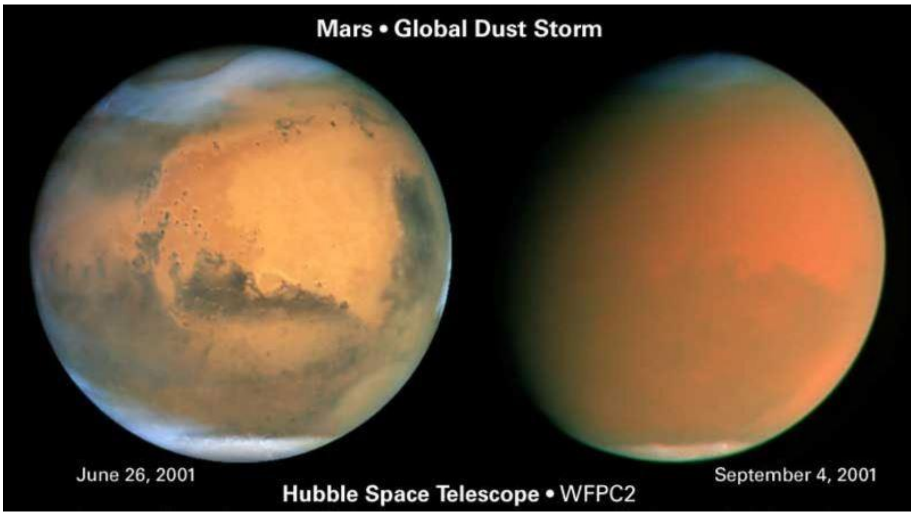

Fig.3 Global Dust Storm on Mars: Hubble Space Telescope Observations (January–September 2001)

[Source: NASA] [16]

6. Atmospheric Behavior During Martian Seasons

The seasons on Mars play a very significant role in shaping its atmospheric conditions, from gas composition to variations in temperatures and pressure. Unlike Earth, it is not characterized by steady atmospheric conditions throughout the year but rather by extreme seasonal changes emanating from orbital peculiarities and axial tilt. The primary reason for the Martian atmosphere is that of seasonal changes in carbon dioxide, which makes up more than 95 percent of this thin atmosphere. Apart from other impacts, CO2 concentrations change as Martian seasons go by responding to shifting polar temperatures. The huge polar ice caps are mainly frozen CO2.

Due to low temperatures, the temperatures at poles during the cold winter months drop to such levels that CO2 becomes condensed into ice and settles onto the surface as polar ice caps. The precipitation process is thus known as CO2 sublimation and deposition. As CO2 freezes out of the atmosphere, its concentration results in a decrease in atmospheric pressure. This pressure drop could indeed be quite huge in winter at the poles and thus makes for a more tenuous and low-density atmosphere. When spring approaches and temperatures begin to increase, the frozen CO2 at the polar caps begins sublimating (turning directly from solid to gas), which in turn means large amounts of CO2 again reenter the atmosphere. This seasonal sublimation increases atmospheric pressure and reestablishes a balance as it redistributes CO2 through the planet's atmosphere. The constantly repeated freezing and thawing of this process is due to a recurring pattern of atmospheric expansion and contraction that can be intense or mild according to the hemisphere and season.

Sublimation processes are directly related to seasonal variations of atmospheric pressure and temperature, making it a factor in the cycles of Martian weather. When CO2 sublimates from the polar ice caps during warm months, the increased atmospheric pressure creates the wind scouring over the surface of the planet, redistributing gases and facilitating dust storms. The winds also affect the transport of materials at the surface, including dust and sand, which are important to the study of Mars' surface development processes. The pressure changes also influence the atmospheric temperature gradients. For example, during the spring and summer months, as CO2 sublimates, the entry of gas heats the atmosphere and during the winter months the condensation of CO2 cools the atmosphere to a considerable degree, resulting in an intensified and quiet climate.**[12][14]**

Aspects of seasonal sublimation play a vital role in Martian atmospheric behavior. The ice caps of Mars are majorly composed of water ice as well as CO2 ice, and its seasonal variations impact Mars' weather. When the atmospheric CO2 freezes onto the polar ice caps in wintertime, the size of the ice caps increases, and atmospheric pressure begins to decrease. As spring and summer set in, the melting brings warmth, and these ice caps shrink as CO2 sublimates back into the atmosphere. This not only drives the wind patterns but also the dust and surface particles when redistributed over Mars. This communication of gases between the atmosphere and polar regions has repercussions across the entire Martian atmosphere - causing seasonal cycles of thinning and thickening. On the other hand, seasonal sublimation of polar caps bears on understanding long-term climate evolutions on Mars. The axial tilt and orbit of Mars have changed their intensity and duration of seasons, respectively, over millions of years, which are linked with the size and behavior of the polar ice caps. Consequently, by understanding current seasonal dynamics, it is possible for scientists to make inferences on the evolution of Mars' atmosphere and climate over geologic time scales by focusing on how water ice and possible liquid deposits on the surface might have changed over time **[15].**

7. Conclusion

This review has focused on the major role that Martian seasons play in determining the planet's atmosphere and climate and surface features. Thus, one of the main aspects is that seasonal sublimation and deposition of carbon dioxide at the poles drive critical changes in atmospheric behavior, indicating influences over temperature, pressure, as well as weather patterns. These shifts also lead to dramatic seasonal dust storms and wind movements that shape the climate. The impact of seasons on surface features is also important because it drives the movement of dust, soil, and polar ice and contributes to the formation and evolution of dunes, valleys, and canyons. It provides the basis for understanding the present landscape as well as any signal of past water activity on Mars. Comparing seasons on Mars and Earth, the longer year and more extreme shifts due to an elliptical orbit make the climate and surface activity much more volatile than that of Earth. These differences are important for future exploration, because mission planning and operation will be influenced by seasonal conditions.

8. Biography of the Author

Jobanpreet Singh, a B. Tech Aerospace Engineering student at Lovely Professional University, Jalandhar, Punjab, India, is deeply passionate about exploring the wonders of the cosmos. With seven years of continuous experience in space observation, Jobanpreet uses advanced telescopes, such as the Celestron Astromaster 130EQ, to conduct detailed studies of celestial bodies. His research spans across various domains, including planetary science and atmospheric research. Since 2019, Jobanpreet has also dedicated himself to the development and testing of solid propellant rockets. He has successfully worked on over 80 rocket models, focusing on fuel configurations and launch tests. His interdisciplinary skills extend beyond rocketry, as he actively participates in conferences, where he has won four "Best Presentation" awards for his insightful research.

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11. Conflict of Interest

The author declares no competing conflict of interest.

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