Analysing the Weather on Mars

[27]

Group 5B

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Contents

1 Abstract

The focus of our report is to analyse NASA's InSight weather data to find daily and seasonal trends in weather variation and compare this to the weather on Earth. The main factors we analyse are temperature, pressure, wind speed and wind direction. We will attempt to find links between each of these factors to understand how the physical systems interact in order to develop a clear understanding of the climate on Mars.

We will use R studio to visualise and interpret the data in order to identify trends that could be of significance to our objective. We found some interesting trends and comparisons to Earth, for example the varying distance of Mars from the Sun due to the elliptical orbit and the axial tilt are responsible for most of the weather variations on Mars. We found that there is greater seasonal variation in weather on Mars compared to Earth. Due to the large CO_2 concentration in Mars' atmosphere, the air pressure in Mars is much thinner to Earth's resulting in much faster winds.

We can validate our findings by comparing it to existing literature and simulated global climate models of the Martian atmosphere to see if our analysis is consistent with these. This project is important as it contributes to our continually expanding understanding of other planets, we produced a seasonal wind rose plot and a lag correlation for consecutive sols, which was not present in any of the literature we came across when conducting our research.

2 Introduction

For our group project, we are analysing the weather on Mars. Our objective for this project is to investigate how the climate of Mars and Earth differ from each other, and how physical processes affect them. In this paper, we will look at factors impacting the weather of Mars including temperature, pressure, wind direction and wind speed supported by data analysis using NASA's weather data from the InSight lander [19]. We will compare our findings to existing literature to determine the accuracy of our results, as well as the observed variation in our findings due to different observational points.

Before showcasing our findings, we must first explain all the underlying physical phenomena and factors which affect the atmosphere of Mars, as well is give a brief overview of the InSight mission.

2.1 What is InSight?

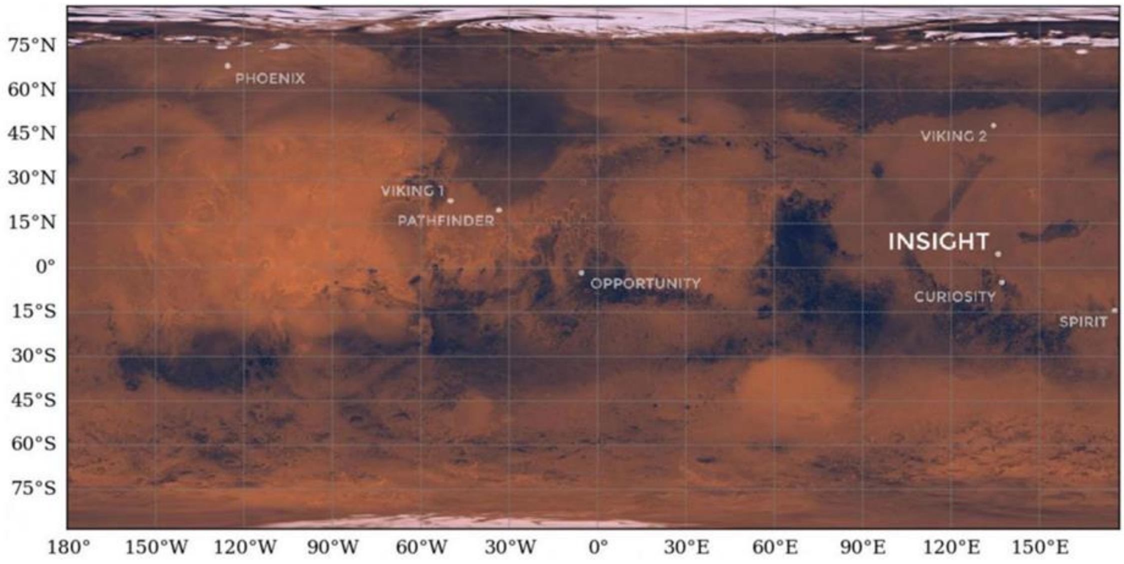


Figure 1: *Location of Insight and other space probes on Mars.* [3]

The NASA InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport) mission [1] occurred as a collaboration between scientists and engineers from multiple countries and organizations worldwide. It was launched on May 5th 2018, traveling a distance of 301 million miles (485 million kilometres) to reach Mars from Earth, and eventually landing on November 26th 2018 [19]. The landing site of the InSight lander is located in the Western Elysium Planitia at 4.5°N 135.9°E, just above the equator of Mars, as shown in see figure 1.

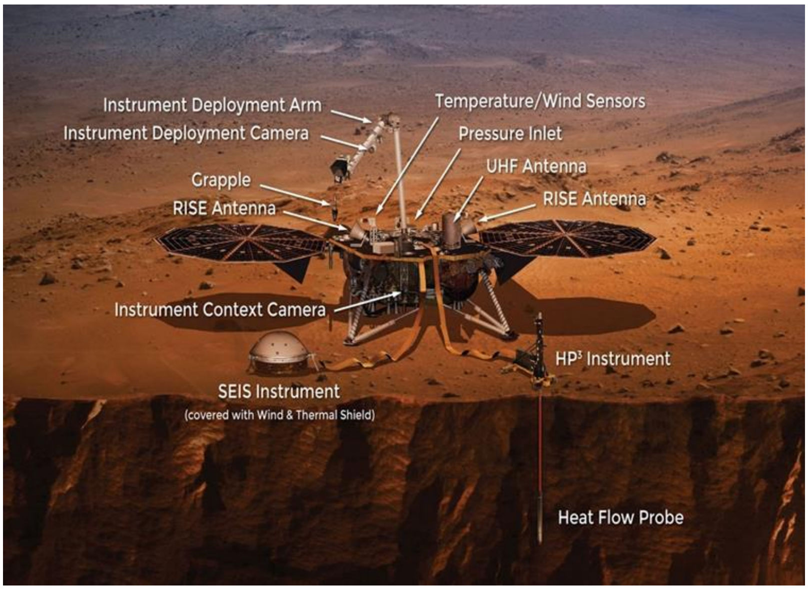


Figure 2: *Illustration of InSight and its various instruments* [1]

The InSight lander is composed of many different instruments, as shown in figure 2, all collecting vital measurements of the planet in order to study the deep interior of Mars. The 3 main measurement instruments include: a Heat Flow Probe (HP3) which measures the heat flowing out of the planet's core, a RISE antenna which measures planetary rotation and a SEIS instrument which measures seismic activity caused by Mars-quakes, and surface vibrations as a result of weather phenomena [33]. There are also other supporting instruments such as a Temperature and Wind Sensor (TWINS) and Pressure sensor which provide additional environmental data of the surface of Mars [6]. All the data collected by the lander contributes to NASA's mission goal of understanding how a rocky body forms and evolves to become a planet by investigating the interior structure and composition of Mars [37].

We acknowledge that the goals they have set out are not completely aligned with ours, however the climate data collected by the TWINS and pressure sensor will be useful in achieving our goal of analysing the weather on Mars and comparing our findings with Earth.

Due to the availability of the data and time frame we have for this project, we've decided to only focus on the measurements taken by TWINS and the pressure sensor which include temperature, pressure, wind speed and wind direction measurements.

2.2 Timekeeping on Mars

A day on Mars is called a sol and is similar in length to a day on Earth at approximately 24 hours and 37 minutes [29]. We have used the "Local Mean Solar Time" or LMST as a measure of time of day on Mars throughout this project. This measure is based around 12 noon being at the point where the Sun is highest in the sky. The data for each sol has been assigned a number by NASA based on time elapsed since InSight initially began collecting data, for example the first day is called Sol 1.

The time of year on Mars is measured using solar longitude (Ls). This is the angle of Mars around the Sun, where 0° is the first day of Spring, known as the Spring equinox, 90° is the Summer solstice, 180° is the Autumn equinox and 270° is the Winter solstice. These refer to the seasons of the Northern hemisphere, as this is where InSight is located. The point where Mars is closest to the sun is called the perihelion, which occurs at Ls 251°, and the closest point called the aphelion occurs at Ls 71°. A complete 360° orbit of the Sun takes 667 sols to complete, which is approximately 1.9 Earth years [34].

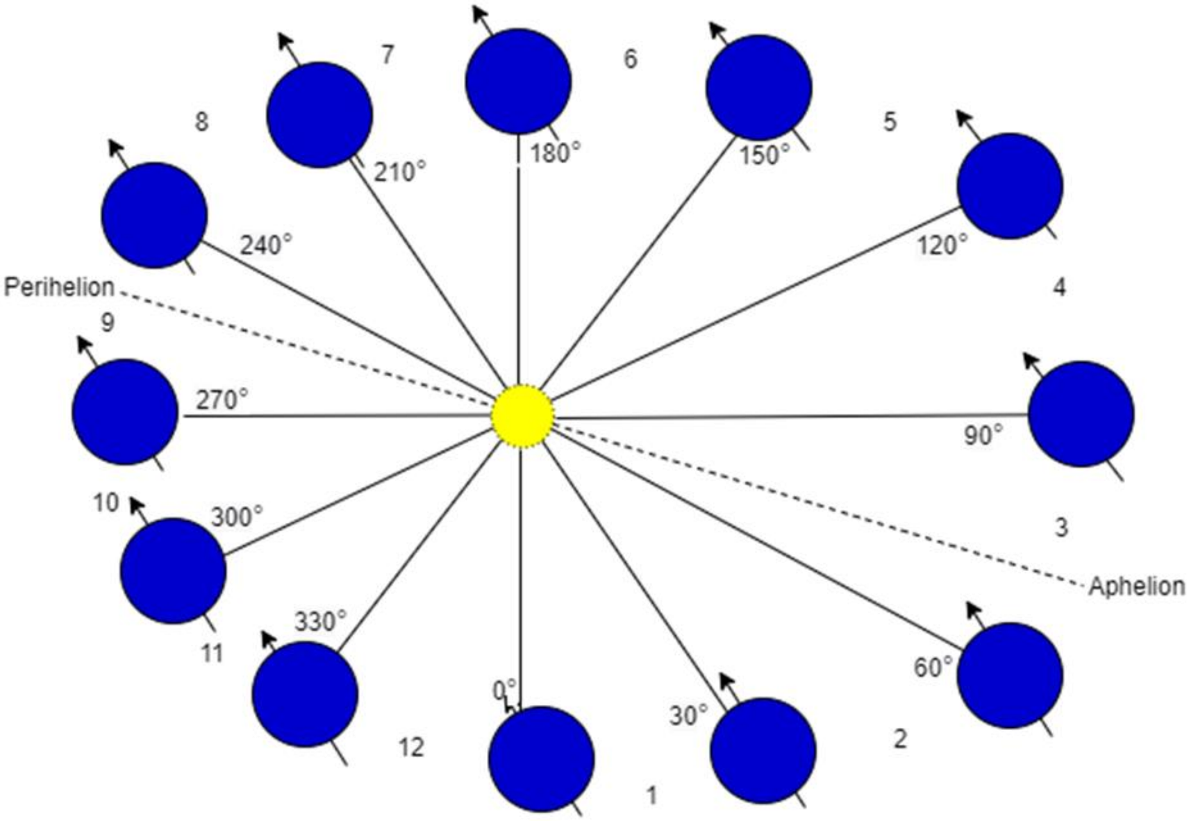


Figure 3: *Diagram of the position of Mars in relation to the Sun at varying solar longitudes.*

Solar longitude	Insight Sol	Event	Solar Longitude	Insight Sol	Season
0	113	Spring equinox	0-90	113-307	Spring
45	207	Mid-Spring			
71	265	Aphelion (furthest from Sun)			
90	307	Summer solstice	90-180	307-485	Summer
135	403	Mid-Summer			
156	442	Mean distance from Sun			
180	485	Autumn equinox	180-270	485-628	Autumn
225	559	Mid-Autumn			
251	599	Perihelion (nearest to Sun)			
270	628	Winter Solstice	270-360	628-782	Winter
315	700	Mid-Winter			
346	755	Mean distance from Sun			
360	782	Spring Equinox			

Figure 4: *Table identifying key sols from the InSight data that are utilised throughout our analysis.*

The orbit of Mars around the Sun has a high eccentricity of 0.0935 and is therefore much more elliptical than the orbit of Earth, which has an eccentricity of 0.016 [7]. This results in seasons of varying length, as although each season consists of 90° of the orbit, the distance travelled around the Sun is much greater in Spring and Summer compared to Autumn and Winter.

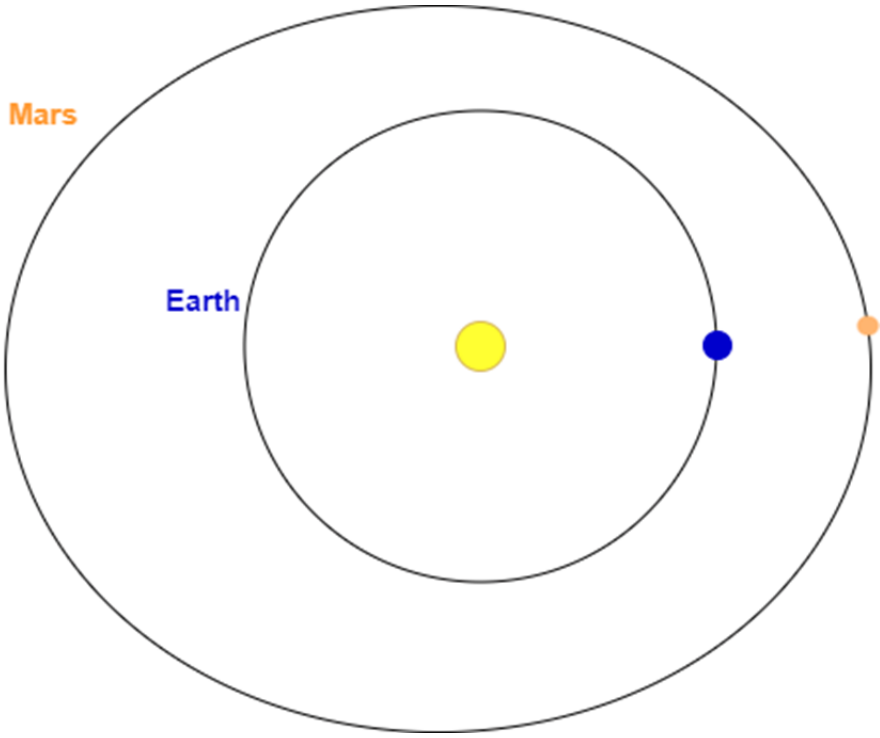


***Figure 5**: Diagram demonstrating the difference in eccentricity of Mars and Earth's orbit around the Sun.*

Mars has an axial tilt of around 25.2°, which is similar to the 23° tilt of Earth [30]. Axial tilt on Earth dictates the seasons, as in Summer the angle to the Sun is more direct so there is more sunlight throughout the day, and in Winter less sunlight reaches the surface, so the temperature is colder. The tilt also means that the season in the Northern Hemisphere is opposite to the season in the Southern Hemisphere for example when it is Summer in the UK it is Winter in Australia [26]. The same is true for Mars, as when the Northern hemisphere is tilted towards the Sun the Southern hemisphere is tilted away. In this project, the seasons refer to the Northern hemisphere seasons, as this is where InSight is situated. Unlike Earth, however, the varying distance of Mars from the Sun due to its elliptical orbit means that Summer is not necessarily the warmest season or that Winter is the coldest. The specific effects that the elliptical orbit has on the weather on Mars will be explored later in the findings section.

2.3 Atmospheric Composition and Planetary Features of Mars and Earth

2.3.1 Atmospheric Composition

The atmospheric composition of Earth and Mars are very different. The atmosphere of Earth is made up of 78% nitrogen, 21% oxygen, 1% argon, 0.04% carbon dioxide and traces of other gases, including water vapour. Whereas the atmosphere of Mars is mainly composed of carbon dioxide which makes up 95% of the atmosphere, 3% nitrogen, 1.6% argon and traces of oxygen, water and significant amounts of dust [10]. Due to the large amount of carbon dioxide present, the atmosphere of Mars is 100 times thinner than that of Earth. The greenhouse effect is also different on both planets, because of the atmosphere of Mars being very thin it means that the greenhouse effect is reduced and so it is generally colder; but there is still a greenhouse effect due to the amount of CO_2 present. The greenhouse effect on Earth is far greater because Earth's atmosphere is thicker and has greenhouse gases such as carbon dioxide and water vapour which cause radiation transmitted from the surface to be reflected into the atmosphere resulting in an overall warming effect.

2.3.2 Size of the Planets and Gravity

Mars has a mean radius of approximately 3,396km, and Earth has a radius of 6,371km, so this means that Mars is around half the size of Earth [30]. Mars also has a much smaller relative mass, with Earth having a Mass 5.97×10^{24} kg, whereas Mars has a Mass of 6.4185×10^{23} kg, which is only around 11% of the Mass of Earth. Due to the smaller relative mass, the gravity on Mars is much weaker than on Earth with a gravitational force of $3.711 ms^{-2}$, compared to Earth gravitational force of $9.807 ms^{-2}$. Surface gravity is therefore only 37.84% of Earth's, meaning that if a person were to stand on a scale on the surface of Mars, they would appear to only weigh 37.84% of their weight on Earth. The low gravity most significantly affects rocks and dust on the surface of Mars, as due to their incredibly low weight it is easier for them to be moved by surface winds [6]. On Earth, it would require a much stronger wind to move dust and rock particles across the surface, but on Mars it only requires a relatively gentle wind. The low gravity also means that Mars has a weaker hold on the atmosphere, so gas molecules are not compressed close together resulting in lower air pressure.

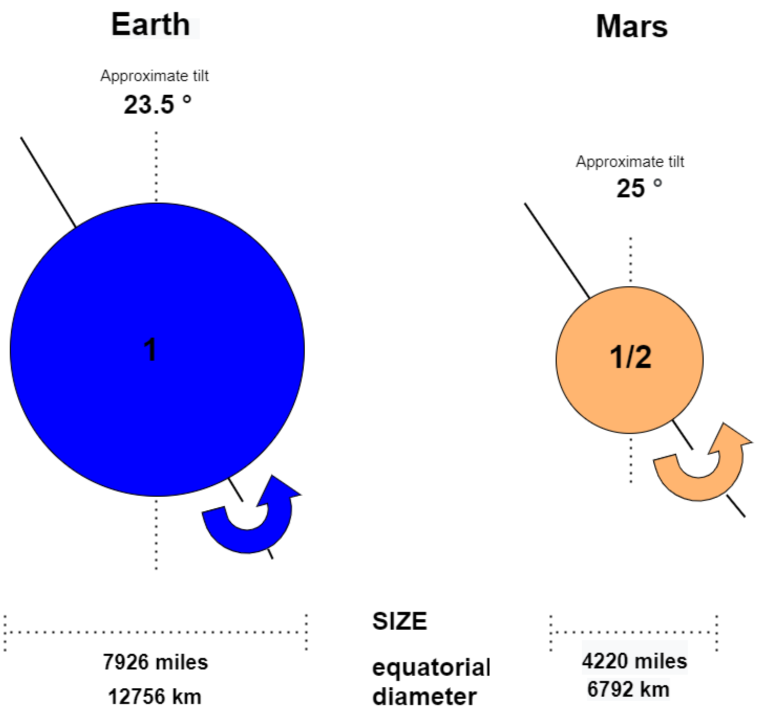


Figure 6*: Sketch comparing the sizes and axial tilts of Earth and Mars*

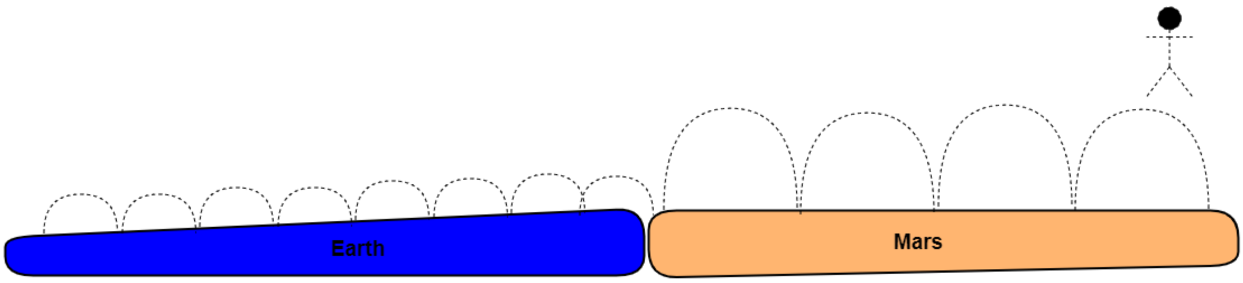


Figure 7*: Sketch demonstrating how you would roughly feel 37.84% of the gravity of Earth on Mars.*

2.3.3 Hadley Cell

One similarity with the weather on Earth and Mars is the presence of Hadley cells in the atmosphere. A Hadley cell is a current of air where the warm air rises by the equator and sinks when it cools at the poles of the planet. On Mars the Hadley cells are much stronger and have a more active effect on the climate system. The atmosphere on Mars is far less dense than the atmosphere on Earth. The Earth has two polar cells and two Hadley Cells, with an additional two Ferrell cells in between them, whereas Mars only has two polar cells and one Hadley Cell. The strengths of the Hadley Cells change throughout the seasons, which will be analysed in detail throughout the wind section of our findings.

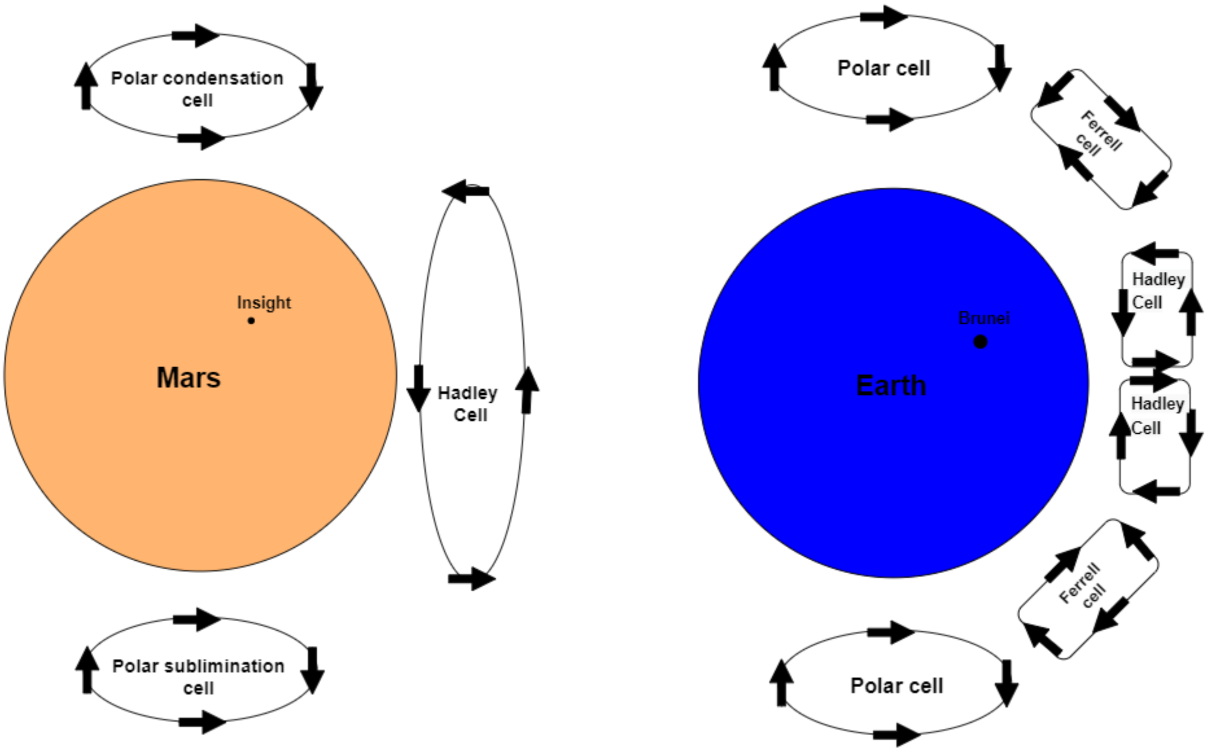


Figure 8*: Diagram demonstrating the difference between Mars and Earth's Hadley cells.*

2.3.4 Dust storms

A key difference between the weather of the Earth and Mars are the dust storms which occur every Northern Hemisphere Autumn on Mars [12]. These dust storms can potentially cause planet-encircling dust storms which happen around every 4 years. Sometimes these dust storms are so extreme that they can be seen through telescopes from Earth. Dust storms are very volatile and unpredictable but are normally greater on the southern hemisphere of the planet. Since the atmosphere on Mars is thin and water is scarce, dust plays an important role in the weather on Mars. When Mars orbits closest to the Sun, the atmosphere is warmer resulting in a feedback loop that causes dust to rise and be transported around the planet, and hence dust storms are formed. The sunlight heats the surface of Mars and the air higher up in the atmosphere stays cooler; it is the imbalance of air temperature that causes the dust storms as the warmer air rises [29]. This is comparable to thunderstorms on Earth. An increase in dust also results in an increase in temperature and an increase in the range of daily surface pressure.

2.3.5 CO_2 Cycle

95% of the atmosphere on Mars is made up of carbon dioxide. The atmosphere composition is very different to Earth and on Mars there are extreme weather differences in each season. This is because firstly of the elliptical orbit of Mars and because of an annual CO_2 cycle on Mars which explains the pressure differences in the colder seasons. In winter, the atmosphere is cool enough for CO_2 to condense into ice at the poles of the planet, this results in a dramatic pressure increase. So, in Autumn and Winter, the air pressure on Mars can increase by a significant amount, up to 25%. Temperature is also affected by the CO_2 cycle, as it decreases throughout Winter as CO_2 condenses into ice and then increases again in summer with carbon dioxide sublimating off the ice caps and returning to the atmosphere [14].

2.3.6 Water cycle

Another similarity of Earth and Mars is the presence of a water cycle. The main source of water on Mars is the Northern residual water ice cap [15]. The ice cap is on display when the carbon dioxide ice has sublimated, producing high levels of water vapor at high latitudes during summer. This water is carried around the atmosphere, between the Northern and Southern polar ice caps, before returning to the surface as either snow or frost. On Mars, the polar caps are covered with a mixture of both carbon dioxide ice and water, whereas on Earth, the ice caps are permanently covered with ice. The water cycle differs hugely from Earth. There are no oceans on Mars and the overall water content is a lot less than Earth.

2.4 Comparison to Earth

Since we have so much more information and resources on Earth, collecting weather information is easier and more accessible. We have found that the weather on Earth is far more predictable due to the relative similarity in the seasons. On Mars the seasons are far more extreme, and the presence of unpredictable dust storms makes predicting the weather more difficult. Although we have a huge amount of information on the topic available to us through NASA, it does not compare to the countless weather reports and predictions made daily.

Figure 9: *Location of Insight's coordinates on Earth (4.5°N 135.9°E [3]) from Google Earth [38]*

Throughout our project we will compare our data collected by InSight with weather reports in Brunei, as it has similar coordinates on Earth as InSight has on Mars. Unfortunately, we cannot use the exact same coordinates as this is located in the North Pacific ocean, however there are some countries close by such as Indonesia, Brunei, the Philippines and Papua New Guinea. We are using Brunei as it shares the exact same latitude as InSight and so is the same relative distance from the equator, meaning it should be a useful tool for comparisons with weather at InSight.

3 Methodology

In order for us to be able to effectively analyse the weather and climate on Mars, it is important for us to understand the topic thoroughly through extensive research. Therefore, throughout our project, we have continuously engaged with literature from reputable scientific reports, including 'The atmosphere of Mars as observed by InSight' by Don Banfield et al. and 'Atmospheric Science with InSight' by Aymeric Spiga et al. which we found to be the most relevant to our objective [2] [3]. The Spiga paper proved to be useful as they had created numerical models predicting Mars' atmosphere before the Insight mission occurred which meant we were able to compare our actual observations using Insight's data against those predicted by the global climate models in the paper. The Banfield paper had analysed data from the Insight lander for over 200 sols, which allowed us to see if our findings coincided with theirs. InSight has now collected data for over 900 sols, so we were able to expand on their findings and analyse an entire Martian year of weather data, which has not yet been achieved using the data from InSight.

To optimize time, we decided to allocate sub-topics and different tasks between colleagues based on everyone's strengths. Working to each person's strengths based on their experience proved to be effective and allowed us to do things simultaneously and at higher quality as a broader and wider range of information was researched. A quick, reliable and accessible line of communication was also quintessential in the success of our project.

People with experience in data science and coding started downloading and interpreting the data obtained by InSight. Some people have a background in climate science, hence they wanted to look at more complex topics such as solar radiation and Hadley cells. A few of us had a background in physics and were better suited at looking at topics such as ellipticity, axial tilt and angular momentum velocity of Mars. Others looked at basic background information about Mars such as Timekeeping on Mars and atmospheric composition. Lastly, presentation roles, referencing, and diagram sketching were carried out by all members.

Post research, we all compiled all our ideas into a shared document in order to achieve consistency throughout the team. This document was presented and explained to the people who had the most coding experience so they can understand what to look for in our data at hand and which topics were most realistic to be shown through data analysis.

3.1 Data Collection

Furthermore, we were able to see clear patterns in key concepts and factors which affect the weather of Mars as well as comparing it to Earth and dissecting the similarities and differences. Throughout the research we were able to identify recurring patterns, ideas, and equations which are useful as we can compare, contrast and critique other models and theories with our own data analysis of the high frequency sample data from the Insight Lander. The lander is equipped with one of the latest high-tech sensors and equipment which can be useful to remove anomalies and uncertainty in current and future models.

Our sources of data were the publicly available TWINS and PS data archives on NASA's InSight weather station page. [19], which contain high frequency sample readings of temperature, pressure, wind speed and direction.

The raw, unedited data is available, however NASA have calibrated this raw data and compiled it into more concise data sets that are easier to use for analysis. There is a TWINS and a PS data set for each sol since InSight landed on Mars, although some sols do not have a complete set of data for the entire duration of the sol. This made data collection a tedious process as we had to find which sols had more complete data to obtain consistent comparable sets of data.

3.2 Coding Process

R is ideal for data analysis as it provides objects, functions and operators combined with a powerful communication library. In our instance the package **"Tidy verse"** which loads the core packages: "**ggplot2**" used for data visualization, "**dplyr**" which is used for data manipulation and lastly "**tidyr**" which is used for data tidying. ggplot2 was used for all the plots, including different mappings, examples include "**geom_line**", "**geom_point**", "**geom_smooth**", "**windrose**". Another two packages "**openair**" and **"mlmetrics"** were used throughout. The various aesthetic tools that allow alterations to colour and size of the particular data, as well as manipulation of axes scales, made R a perfect tool for data visualisation.

The Insight data had a lot of irrelevant or extra information we did not want or need, hence a bulk of the coding actually involved filtering the data and making it as neat and concise as possible to use, especially when certain graphs required a large amount of sols to be plotted. For example, the data for each sol has several columns for time reference, but we used LMST as this uses a 24-hour clock based on the position of the Sun, so it is similar to timekeeping on Earth and is therefore the most useful measure for drawing comparisons with Earth.

3.3 Limitations

When collecting and processing the data, there was always the potential for human error. In order to reduce this possibility, we compared our findings and graphs with existing research to see if it was consistent, for example by plotting the same temperature graph for the same sols to see if our code was correct. Once we had verified that our code was correct, we then plotted our own graphs using sols that we had chosen ourselves. Creating plots to visualize the data required downloading incredibly large spreadsheets of data, for example InSight's pressure sensor takes measurements with a frequency of 10 per second, meaning that each sol had over 887,000 pressure measurements. Downloading such large sets of data takes a very long time and running the code in R Studio for plots containing this many data points is also a lengthy process. This meant we had to take particular care in choosing which data to use as it would have been time consuming to download and create plots using irrelevant data that we would not eventually use in our findings.

Due to time strain and limitation of data from our Insight Lander, we decided which ideas and factors were most relevant to our aims and objective of this paper, given the data at hand. Our findings heavily rely on data analysis, where we chose to visualise concepts and mathematical formulas using R Studio alongside diagram sketches. This observational method takes the impressively high frequency sample data and displays it to show the variation in different observational points. There are also a couple mathematical formulas which are combined with graphs or sketches.

This method has some limitations, for example, just like other academic literature, we are simply analysing existing data instead of contributing to new findings. However, there is very little research on the weather and climatology of Mars, so our research may yield new perspectives which other academic literature may not have necessarily covered. Another possible limitation with data analysis is that we may identify correlations between two completely unrelated trends, and falsely assume that the two are linked.

There are sols that have no recorded data as InSight uses solar power, as a result during dust storms the solar cells are covered by dust and InSight will power down and stop taking readings, resulting in gaps in our findings for certain periods of the year.

There are many alternative approaches which could have been conducted to answer what affects the weather on Mars, including statistical analysis which focuses mainly on the predictability of the weather on Mars. We decided that given our data it was best to show patterns and trends, rather than attempt to predict future weather, as there is not much memory retention in a lot of factors which affect the weather, as we will discuss in our findings. The gaps in data due to dust interfering with the solar panels also cause uncertainty when it comes to predictability, and the nature of the dust storms is incredibly unpredictable so forecasting the weather during these periods is difficult.

Another possible approach could have been analysing wind speed and pressure to calculate a turbulent energy spectrum using a Fourier transformation analysis. This approach would investigate the Kolmogorov theory and how energy is transferred from large scales to small scales. We wanted to make it an expansive project, focusing on multiple factors rather than fixating on just one factor. Hence why we opted for our data analysis approach.

4 Findings

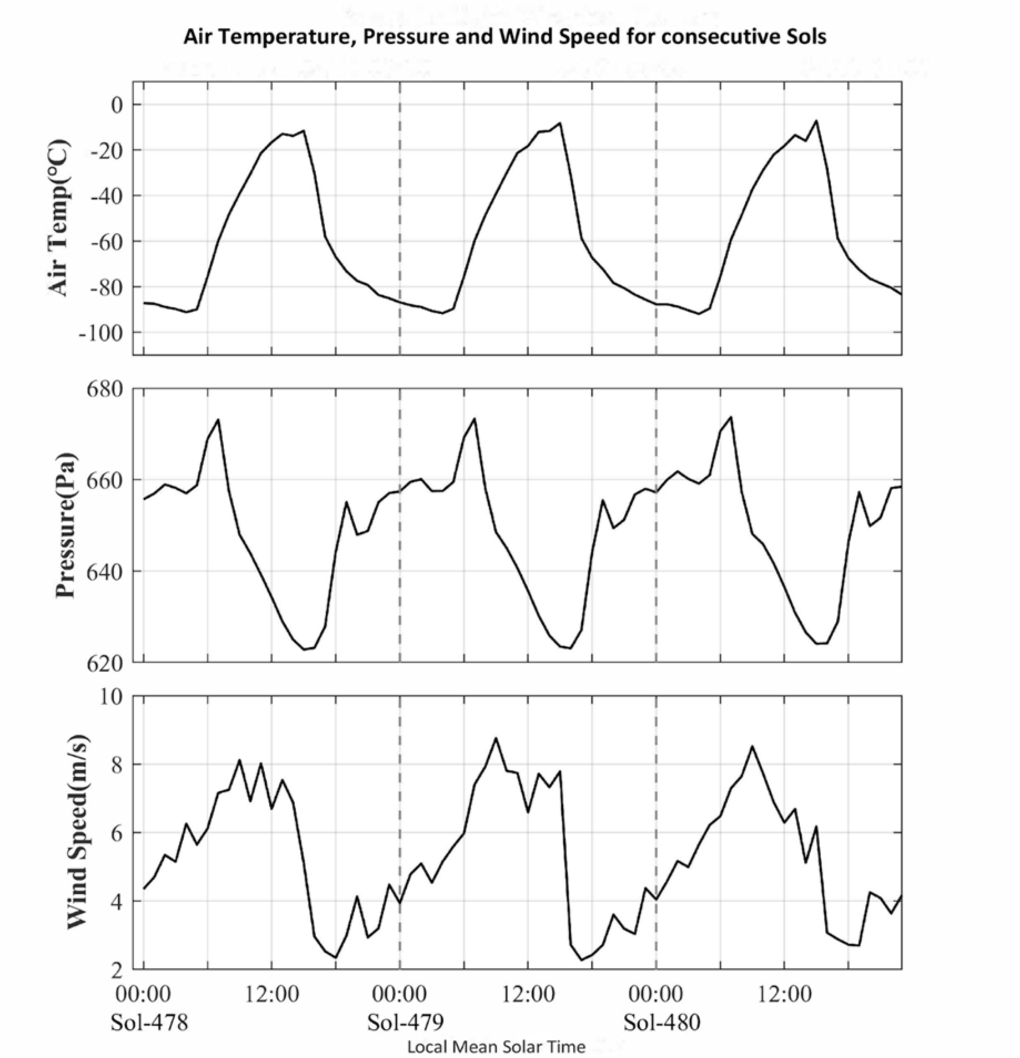
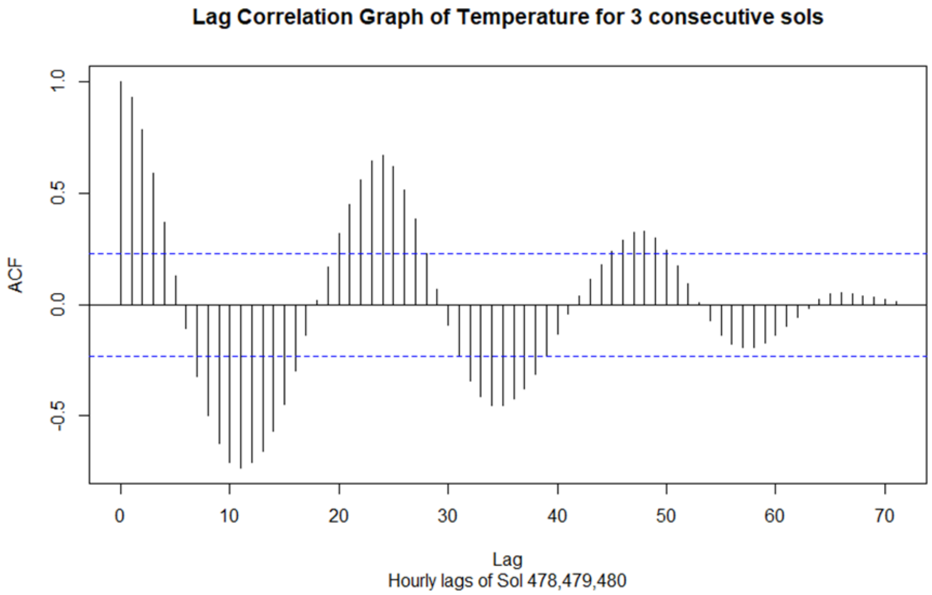


Figure 10*: Graph showing the temperature, pressure and speed variation across three consecutive sols*

This was the first preliminary plot which we decided to create, in order to see if there is memory between consecutive sols. This was done in order to show that there is not much variability from day to day, which is relevant for the rest of the findings. Throughout the rest of this section, we decided that instead of doing seven-day averages or monthly averages or yearly averages, to save time we would show diurnal cycle variations during the seasons using either a lot of sols, or just days at the beginning of each season. As you will see further on, this does not affect the shape of our plots significantly, especially when comparing to other literature and their predicted models, such as in the Spiga and Banfield papers [2] [3] Throughout the rest of this section 4, we look at each factor in further detail and variability.

To further support the preliminary plot, we have produced lag cross correlation graphs, shown in figures 11a and 11b below, which help support the idea that there is memory in both Temperature and Pressure in between consecutive days. This is observed in the graphs as we see during the first 48 hours in the temperature lag graph, the majority of the correlation values fall within the statistically significant region as represented by the blue dashed lines. After 48 hours there appears to be a lack of memory as the values lie within the significance bounds. Both graphs follow a periodic daily cycle which is relevant as it proves that our explanation above that single sols or a combination of sols can be chosen to represent a season.

a)



b)

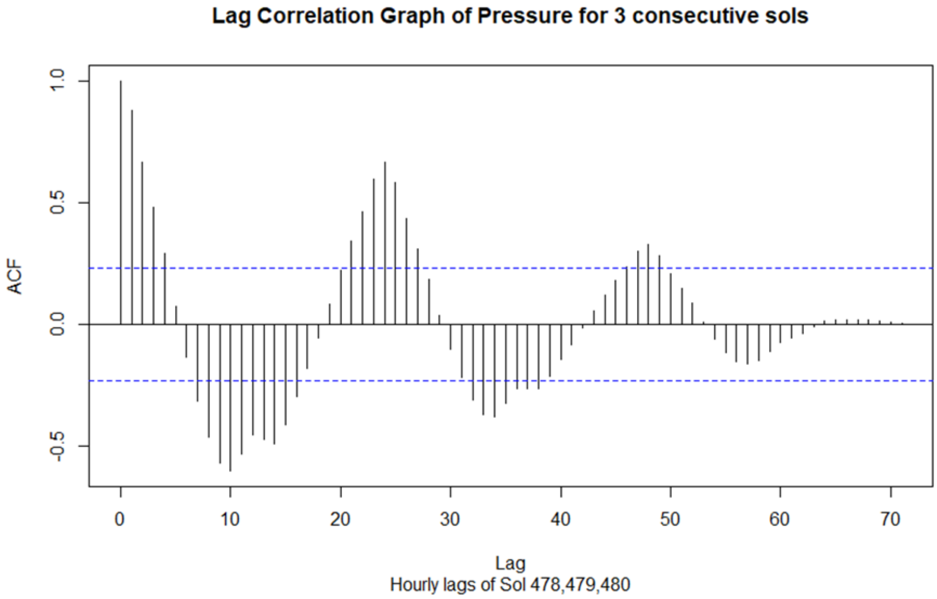


Figure 11: a) *Graph showing the lag correlation for temperature across three consecutive sols*

b) *Graph showing the lag correlation for pressure across three consecutive sols*

4.1 Temperature

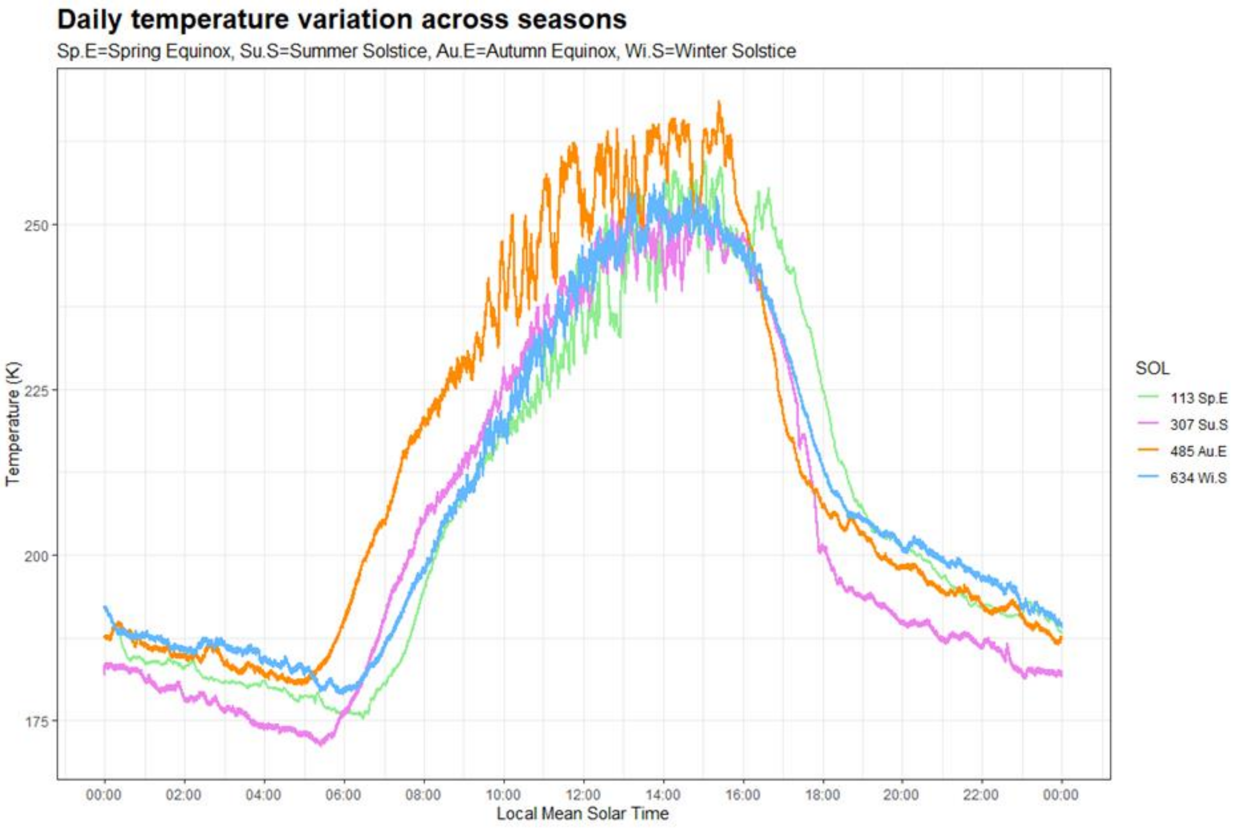


Figure 12*: Graph showing the daily temperature variation of a sol at the start of each season*

Figure 10 compares daily temperature variations of the four sols at the start of each season. Each sol follows a similar daily pattern, with an initial decrease from midnight to 6:00, followed by a sharp increase from around 6:00 until 14:00, and finishes with a sharp decrease from 16:00 to midnight. The temperature begins increasing at slightly different times in the morning as the time the Sun rises varies throughout the year, with sunrise occurring earliest in Autumn and latest in Spring. The temperature decreases drastically after 16:00 pm since Mars has a thin atmosphere and as a result does not retain heat after the Sun has set, this is further offset by the fact that Mars planetary composition has no oceans unlike Earth, as a result heat retention is further stunted [31].

Autumn has the highest temperature peaks; this is due to the position of the planet during Autumn. Mars is closest to the sun during the Autumn at the perihelion, hence its heat transfer due to solar radiation is the highest. The temperature trends between seasons are roughly the same as even though the axial tilt would lead to higher temperatures in the Summer, Mars is further from the Sun during this Season, and opposite is true for Winter, so the temperatures are very similar.

Temperature varies most between 10:00 and 16:00 each day, with variations ranging from 5 to 12 Kelvins. These rapid variations could be attributed to the fact that wind speeds are generally higher during the middle of the day, causing more dust to be airborne and interfering with incoming solar radiation.

This graph is comparable to figure 2c from the Banfield paper [3], which shows the temperature trends on two sols in Winter and one in Spring. Our graph exhibits similar trends for these Sols, but we have expanded this further to include Summer and Autumn sols

Looking at the weather report of Brunei [39], where the temperatures across a single day range from 298K-303K (25-30°C), Mars has much larger daily variations in temperature ranging from 175K-265K. This means that the daily temperature variations on Mars are much greater than on Earth. This can be explained by a number of factors, including the presence of the ocean which has a high heat capacity, meaning that water vapour, which makes up 0.4% of Earth's atmosphere [40] evaporates into the higher latitudes to form clouds, acting as a greenhouse warming effect, trapping in the energy given from sun rays. Mars has no oceans or water sources, hence only 0.03% [41] of Mars atmosphere is composed of water vapour, a significant difference.

4.2 Solar Radiation

Solar radiation is the electromagnetic energy emitted by the Sun, and its intensity, S, is measured in Wm^{-2}. Solar radiation striking a planet of radius R is $S\pi R^2$, but a fraction of the solar radiation, A, known as the albedo is reflected back into space so that absorbed radiation is $S\pi R^2(1-A)$. Mars has a radius $R = 3{,}389.5\ km$, and an albedo $A = 0.17$ [20]

It is useful to assume that Mars behaves as a blackbody, meaning that it is a perfect absorber and emitter of radiation, as we can utilise energy balance equations to find an estimate for the temperature of a planet based on the intensity of the solar radiation. Emitted blackbody radiation from a planet of radius R is $4\pi R^2\sigma T^4$, where T is the surface temperature of the planet and σ is the Stefan-Boltzmann constant (5.67x$10^{-8}\ Wm^{-2}K^{-4}$). As we are assuming Mars to behave as a blackbody, radiation emitted is equal to radiation absorbed, so we can estimate the temperature of the planet, using the energy balance equation

$$T^4 = \frac{S(1-A)}{4\sigma}.$$

S varies with distance; a planet closer to the Sun has more solar radiation incident on it than a planet further away. On Earth, the blackbody surface temperature is easily calculated as Earth's orbit around the Sun is circular, with a low eccentricity of 0.016, so its distance from the Sun is constant throughout an Earth year. Therefore, Earth has constant solar radiation, $S_E = 1365\ Wm^{-2}$. From this, solar radiation on Mars can be calculated using $S = \frac{S_E}{d^2}$, where d is the distance of Mars from the Sun in astronomical units, as S is proportional to distance from the Sun. However, due the eccentricity of the orbit of Mars, its distance from the Sun varies throughout the year. The mean Sun-Mars distance is $D = 1.52$ astronomical units [21], so the mean solar radiation on Mars is $\frac{1365}{1.52^2} = 590.8\ Wm^{-2}$. The distance of Mars from the Sun can be expressed as a function of the solar longitude, L_s, in the relation to the perihelion ($L_s = 251°$) [22], and the eccentricity, $e = 0.0935$ [20]. D, the mean Sun-Mars distance, must also be considered, as the function depends on its proportion to the mean Sun-Earth distance, which is 1 astronomical unit. Therefore, distance can be calculated using the following equation:

$$d = \frac{D^2(1 - e^2)}{1 + ecos(L_s - 251)}$$

Combining this equation with $S = \frac{S_E}{d^2}$ yields a final equation to calculate S at any given solar longitude L_s:

$$S = 590.8\left(\frac{1 + ecos(L_s - 251°)}{1 - e^2}\right)^2$$

which is illustrated in the following graph:

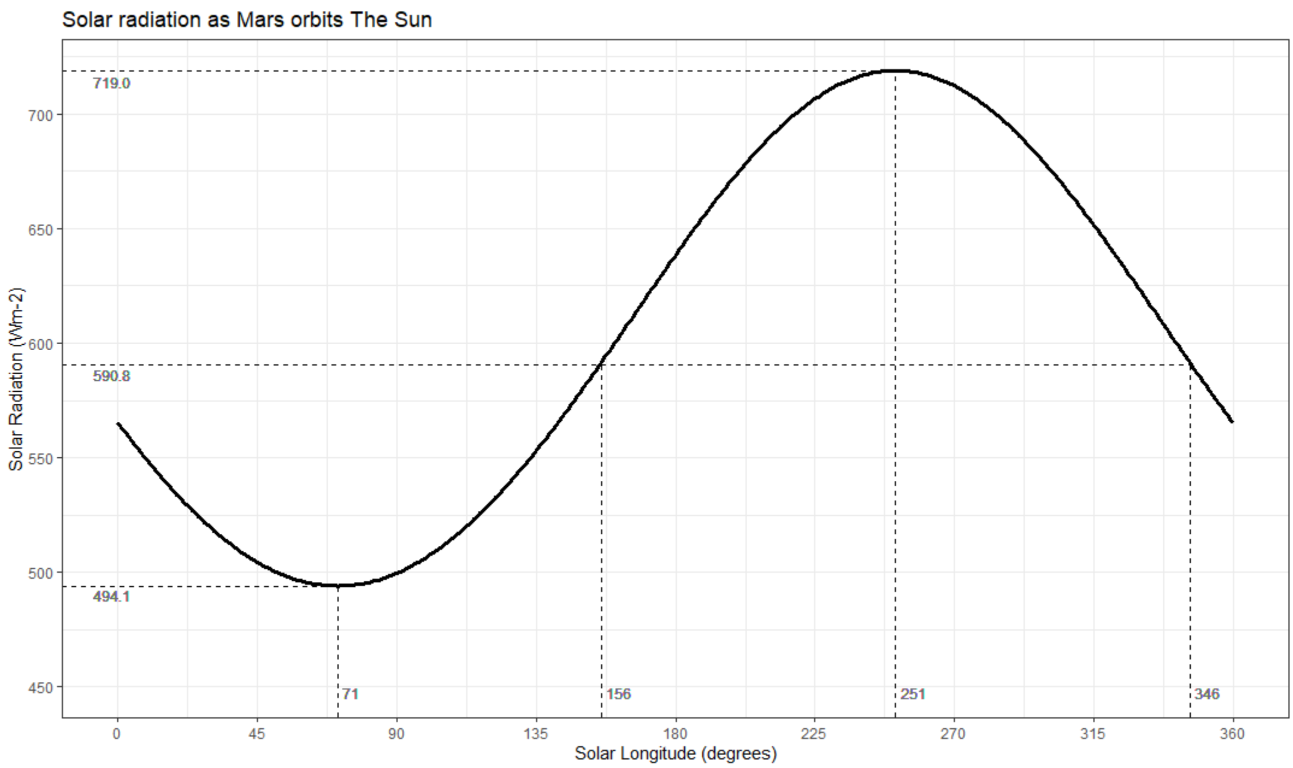


***Figure 13**: Graph showing the solar radiation throughout the Martian year*

When Mars is at aphelion ($L_s = 71°$, during Northern hemisphere Spring) solar radiation is $494.1\ Wm^{-2}$, and at perihelion ($L_s = 251°$, during Northern hemisphere Autumn) solar radiation is $719.0\ Wm^{-2}$. The average solar radiation is $590.8\ Wm^{-2}$, which is also the solar radiation at $L_s = 156°$ and $346°$, which are during Northern hemisphere Summer and Winter respectively. Using these values for S in the equation for blackbody surface temperature an estimate for the expected surface temperature for Mars can be made. This is compared to the actual annual surface temperature as recorded by InSight in the following graph:

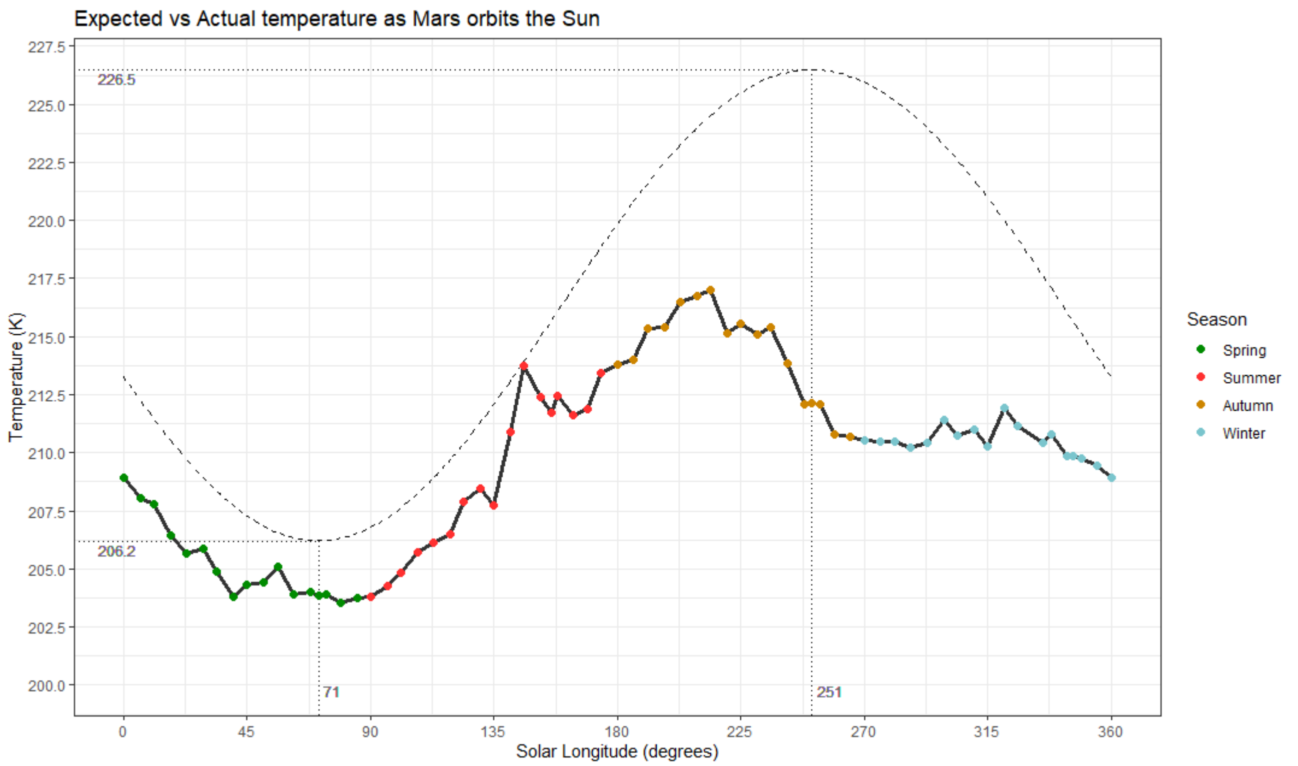


***Figure 14**: Graph showing expected temperature throughout the Martian year (dashed line) compared to the actual temperature as recorded by InSight*

The expected surface temperature begins by following a similar trend to the actual surface temperature: temperature falls during spring, reaching the minimum annual temperature close to the aphelion, then temperatures rise through Summer and into Autumn. The expected temperature peaks at the perihelion, however the actual temperature peaks much earlier than this, and subsequently decreases through Winter but does so at a much slower rate than the expected temperature. The expected surface temperature for Mars has a mean value of 215.6K, a maximum of 226.5K and a minimum of 206.2K, but the actual temperature has a mean value of 209.7K, a maximum of 217.0K and a minimum of 203.5K, so on average the actual temperature is 5.9K less than expected. Because we assumed Mars to behave as a blackbody, this means that the atmosphere of Mars has a significant impact on the surface temperature, as in the absence of an atmosphere the temperature would be the same as the expected temperature.

If the same energy balance equation is calculated for Earth, the expected temperature would be 255K, which is constant throughout the entire year as the Sun-Earth distance does not significantly vary, due to its circular orbit. However, the actual mean surface temperature of Earth is 287K [23], which is due to the Greenhouse effect of Earth's atmosphere.

After observing the annual temperature changes in Brunei [39], it is clear that the annual temperature does not vary much throughout the year, with a small range of 297-304K (24-31°C). This is much higher than the expected temperature for Earth, confirming that the greenhouse effect of Earth's atmosphere significantly increases surface temperatures. The small range is due to the circular orbit of Earth around the Sun, so distance from the Sun does not vary, thus temperature is not as significantly affected throughout the seasons as on Mars.

The greenhouse gases in Earth's atmosphere, which include carbon dioxide and water vapour cause radiation transmitted from the surface to be reflected back into the atmosphere resulting in an overall warming effect. The atmosphere of Mars is 95% carbon dioxide, which would suggest that the greenhouse effect would be very high, however this is clearly not the case. The lack of a greenhouse effect can be explained by a variety of factors, most significantly atmospheric dust and the air pressure on Mars. We will begin by explaining how dust, and in particular the annual dust storms, affect temperature.

4.3 Atmospheric Dust and Dust Storms

The entire planet is covered in red dust, which is why Mars is often referred to as 'the Red Planet'. The lower gravity of Mars, which is around 38% of the gravity on Earth, and the thin atmosphere mean that dust can very easily be picked up and blown across the surface by the wind. As Mars lacks bodies of water, dust and rock particles blown by the wind do not get trapped in water and are free to travel across the surface. As rock particles collide with the surface, they erode more rock and create smaller pieces of rock that range from 3 to 20 micrometres in diameter [24]. By comparison, sand particles on Earth range from 62.5 to 200 micrometres [25], so these rock particles are extremely small and light and can be blown very easily.

During Autumn, Mars experiences dust storms, which can be regional or cover the entire planet. These dust storms result in a high amount of airborne dust. In terms of solar radiation, the airborne dust particles reflect incoming radiation and result in a fall in surface temperature as radiation does not reach the surface as intensely. The red colour of the dust also contributes to this, as red light has the largest wavelength but lowest energy, so radiation that reflects from the dust towards the surface has lower energy than visible light and results in a lower temperature.

The reason these dust storms begin in Autumn is mainly due to the higher temperatures at the start of the season. Warmer air rises, so this means that if dust is blown upwards, it will stay airborne for a longer duration than during a colder season.

When the dust settles on the surface after the storm, the ground becomes covered in dust again, which causes the ground to become brighter and more reflective, essentially increasing the albedo of the surface. This means that less radiation is absorbed by the surface and thus temperature drops after the dust storm ends, which is clearly shown in Figure 12 by the fall in temperature from the middle of Autumn and into Winter.

4.4 Pressure

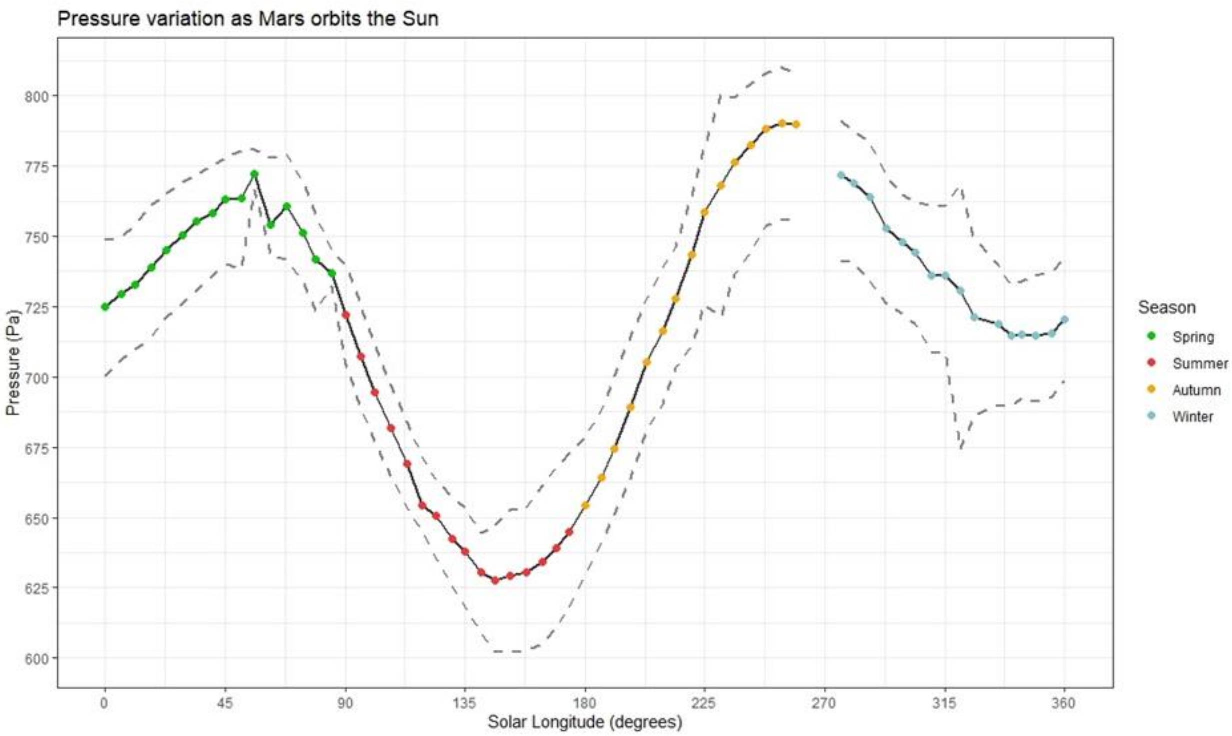


Figure 15*: Graph showing the average pressure variation throughout the Martian year with minimum and maximum pressures (dashed lines)*

The other main contributor to annual temperature variation on Mars is air pressure. This graph shows the variation in air pressure throughout the Martian year. The annual air pressure on Mars at InSight varies between 600 and 812 Pa which is incredibly low compared to Earth's standard sea level air pressure which is 101,300 Pa [26]. The low air pressure means that the atmosphere is so thin that the greenhouse effect does not occur significantly on Mars. This is because the carbon dioxide molecules in the atmosphere do not absorb as much radiation due to being spread far apart, so radiation can escape the atmosphere without interacting with carbon dioxide molecules. This means that radiation reflected from the Martian surface is not reflected down to the surface and trapped in the atmosphere as significantly as on Earth, hence explaining why temperature is much lower than the expected blackbody temperature.

The seasonal air pressure variation has a significant seasonal effect on temperature as it causes the CO_2 concentration to change. Highest pressures occur at the end of the Northern hemisphere Autumn and the lowest occur in Summer. Mars is furthest from the Sun during the Northern hemisphere Summer, so at the South Pole, it is Winter. The combination of distance from the Sun and axial tilt away from the Sun means that the air temperature drops so low that CO_2 gas freezes solid onto the South polar cap. The removal of CO_2 gas from the atmosphere causes an overall drop in pressure, thus explaining the severe drop in pressure in Northern hemisphere Summer. As the temperature increases throughout Autumn, the solid CO_2 on the cap sublimates into gas form, thus increasing the air pressure as shown by the steep incline on the graph at the end of Summer and throughout Autumn. The temperature is higher because Mars is becoming much closer to the Sun, the South polar cap is tilting more towards the Sun.

In Brunei, yearly mean pressure has a range of 100,910-101,040 Pa [39], whereas the range on Mars is 600-812 Pa. Despite the ranges not being too different on the two planets, what is different is the magnitude of pressures. The main reasons are due to the fact that Mars has a thinner atmosphere and a lighter gravitational pull than Earth. Another difference is the number of peaks in pressure across the two planets. The peaks and troughs of the annual pressure cycle on Mars are explained by the CO_2 cycle, but on Earth the pressure peaks seemingly at random. This change in pressure is caused by the variation in temperature gradients, where on Earth they stay constant, hence pressure variation is minimal.

Spiga Fig. 6 [2] shows the predicted seasonal evolution of the mean surface pressure at the Insight Landing site. The basis of this prediction was the sublimation and condensation of CO2 at the polar caps leads to changes in the atmospheric CO2 concentration, thus varying the air pressure. The air pressure in the predicted model ranges from 600 Pa to 800 Pa, This was in line with our findings, as seen above in figure x, where the patterns align, however due to solar power being limited by dust settling on InSight's solar panels following the Autumn dust storm, there is missing data between solar longitudes 259° and 276°. In addition, each sol, the surface pressure is expected to undergo large variation due to the diurnal and semidiurnal thermal tides, as predicted in Spiga Fig. 7 [2]. The dotted lines above and below the pressure curve indicate the maximum and minimum pressure throughout the year, and this large difference is caused by the diurnal pressure variation, which is explored further in Figure 14.

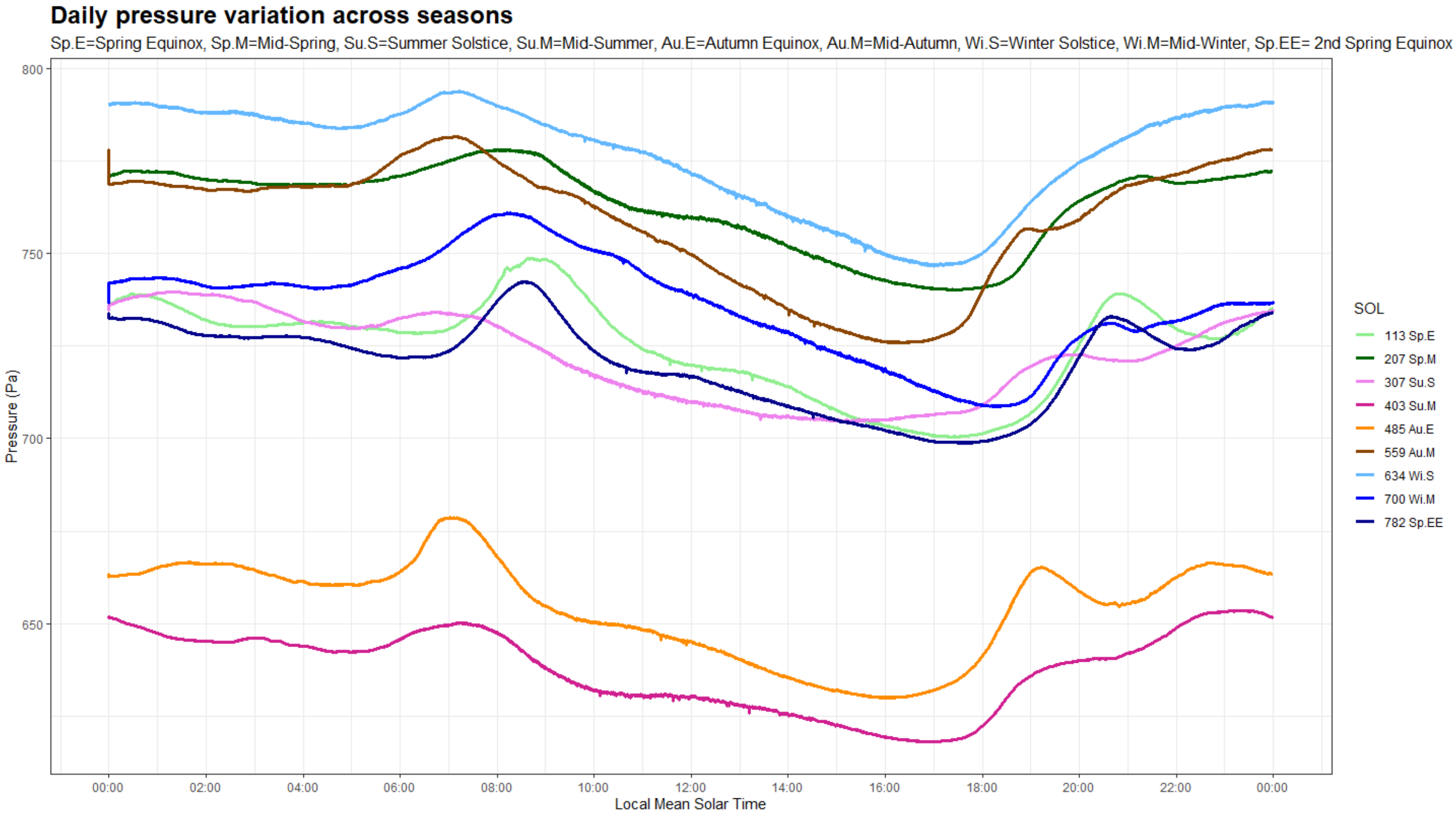


Figure 16*: Graph showing the daily pressure variation of sols in different times in the Martian year*

There is a diurnal cycle of pressure peaks in the morning between 6:00-8:00 and between 19:00-21:00 at night. This daily cycle is due to the thermal tide which is caused by heating in the ground and air. This heating varies due to the tilt and distance of Mars in relation to the Sun. For example, from Mid-Summer to the Autumn equinox, shown by the purple and orange lines and the key, the pressure is significantly lower than the rest of the year as temperature is increasing due to warm air rising, whereas in the Winter and Spring, air is cooling throughout these seasons resulting in less kinetic energy transferred between particles, hence less pressure. The circulation of warm and cold air across the surface and upper atmospheres of Mars will be explained throughout the next section.

4.5 Wind Speed and Direction

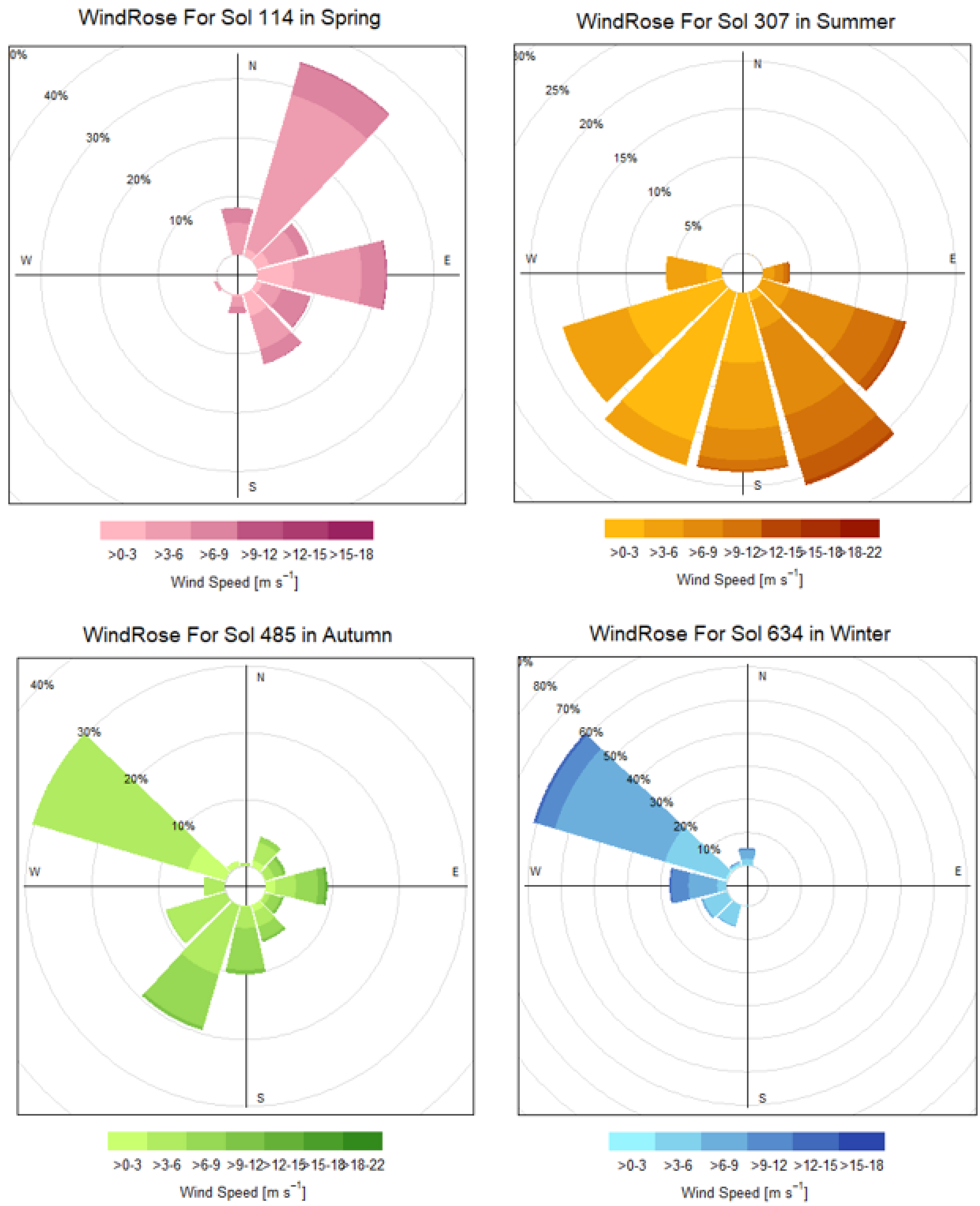


***Figure 17**: Wind rose diagrams showing variability in wind direction for sols from different seasons. (The spoke indicates the direction from which wind is blowing from)*

Many factors influence the direction and speed of the winds on Mars. These include the topography of Mars, the global circulation pattern and the changes in seasonal temperature. From figure 15 above, we can see that there is a North-Westerly wind direction in Northern hemisphere Winter indicated by the 60% spoke and a predominant Southern wind direction in the Summer. Due to the Hadley cell Circulation, we would expect in Northern hemisphere winter for the return branch of the Hadley cell to blow southward whilst in Northern hemisphere summer, the wind would be blowing to the north which is confirmed by the Winter and Summer wind roses.

The Autumn wind rose shows the most variability in wind direction, where there is a concentrated spoke of 30% in the North-west direction. This variability could be due to the rapid temperature rise from Summer to Autumn, due to Mars approaching the perihelion, as the data we used was the starting sol of the Autumnal equinox. During Autumnal equinox we expect the Hadley cell to be symmetric. This is clear from the Autumn wind rose as there is no clear dominating wind direction.

The conservation of Angular Momentum in a Hadley cell can furthermore explain the large north-west spoke observed in the Autumn wind rose resulting in winds blowing towards the south-east. As an air particle moves towards the poles, its radius of rotation about the axis is reduced, resulting in its angular velocity increasing to counter this change. This means for an air particle moving northward, the zonal (east-west) velocity increases in the eastward direction.

Whilst we have produced wind rose diagrams for sols in each season, Spiga Fig. 19 [2] shows an annual wind rose diagram to illustrate the GCM predictions for wind speed and direction of all the seasons. Showing the wind roses for individual seasons gives a much clearer view on the annual variation throughout the year and allows us to easily visualise the changes to the wind in relation to the Hadley cell circulation.

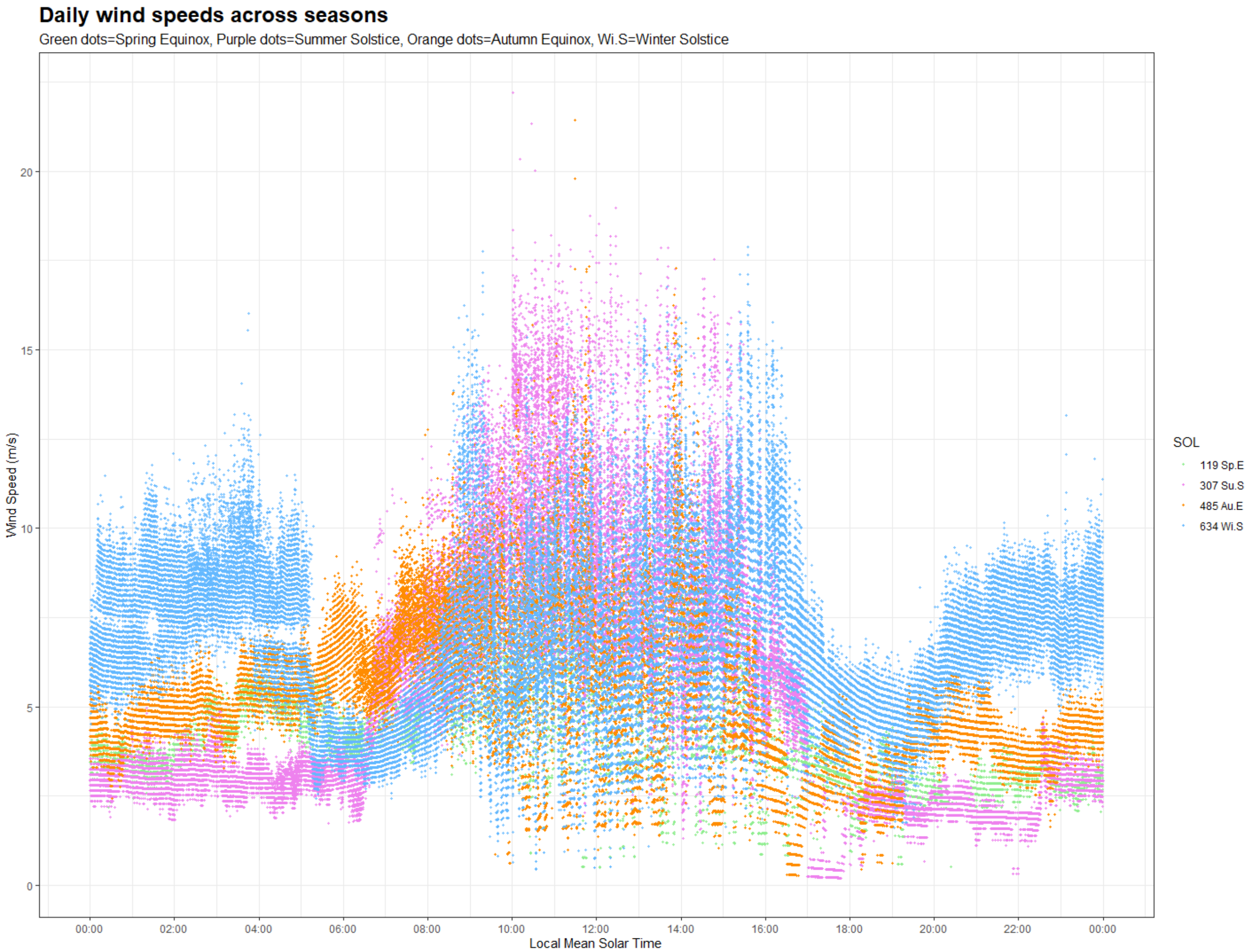


***Figure 18**: Graph to show daily wind speed variation for a sol in each season*

This graph shows the daily wind speed for a sol across seasons. Banfield Fig. 2b [3] shows a similar graph using the data from 3 sols shortly after InSight had landed, which does not show much variation as they all take place at a similar time of the year. We have expanded this to include sols from each season, giving a clearer view of seasonal wind speed variation. Due to the large data set, there are many points which overlap with other sols, making this graph difficult to analyse, despite having some clear patterns. To further see more trends, a statistical smoothing process was applied.

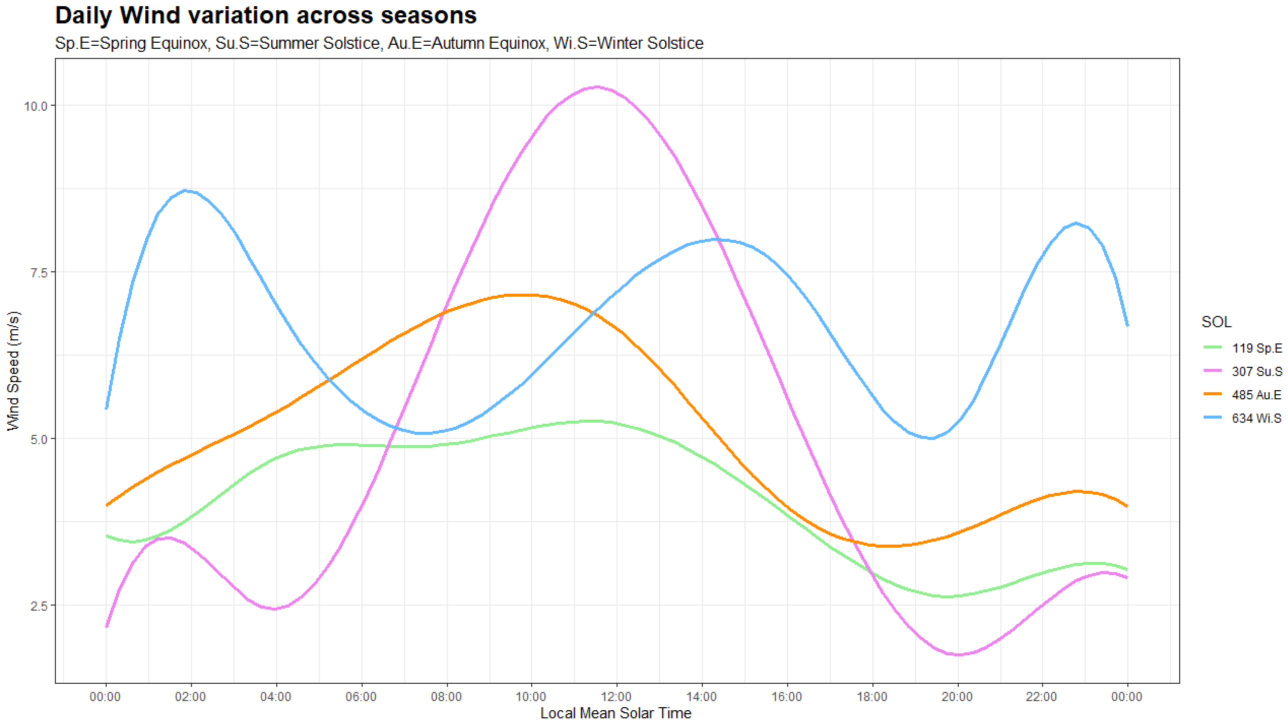


Figure 19: *Smoothed version of figure 18*

The smoothed-out graph shows clearer patterns. During the spring and autumn, wind speeds seem to have a low variation and calmer peaks throughout the day, this could be explained due to pressure during spring and autumn increasing, this keeps the air particles more tightly packed together and more energy is required by the particles to move due to a stronger bond. Whereas Summer and Winter however have a more bipolar trend, with higher peak wind speeds throughout the mid days in the summer and a cyclical variation of wind speeds with 3 peaks throughout the day, as shown earlier in the pressure graphs across a whole year, we can see that pressure drops each an absolute low in the summer and starts drastically decreasing in the winter. This smoothed out graph is consistent with the wind rose diagrams across seasons as shown earlier.

Now compared to Brunei as seen in a weather report on 21st December 2020 [39], we have an hourly wind speed graph for a day corresponding to the beginning of the winter season on Earth. This day translates to sol 735 which is mid-winter on Mars, this difference can be explained by the position of each planet on its respective orbit in relation to the position of the Sun. In Brunei, the variation in wind speeds ranges from 1.0-8.8 m/s, whereas Mars has a range of 5-9 m/s. The difference between the ranges of speeds across the two planets can be attributed to temperature, as seen in figure 12, where the temperature is the lowest throughout the year.

The differences in temperature between air masses causes a pressure variation, which creates wind. Winter brings the highest temperature gradients throughout the Martian year; this is largely due to the shift of the CO2 cycle of carbon where it condensates and sublimates throughout the year in the polar regions. These explain why Mars has higher wind speeds. In contrast to Earth where the atmospheric and planetary differences include the presence of greenhouse gases and a heat capacitor (the Ocean) which keep temperature gradients at a smoother rate of change, as a result lower pressure differences, hence there is a larger variation between calmer and stronger winds.

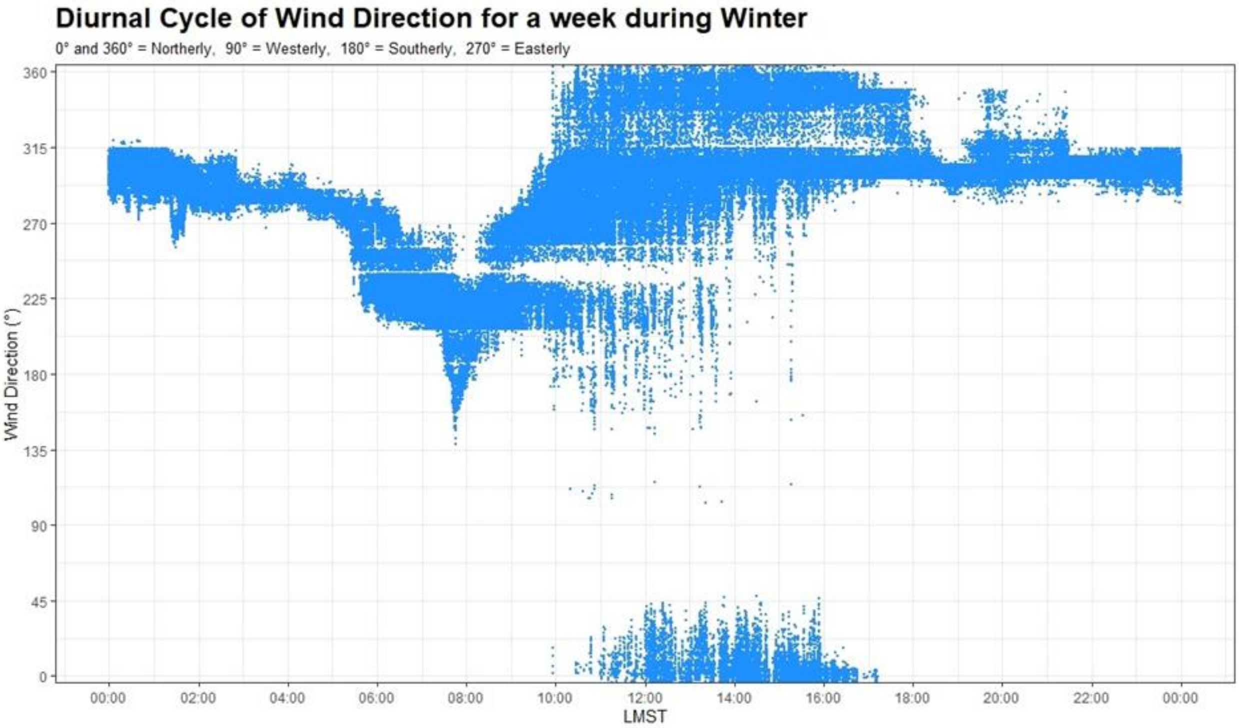
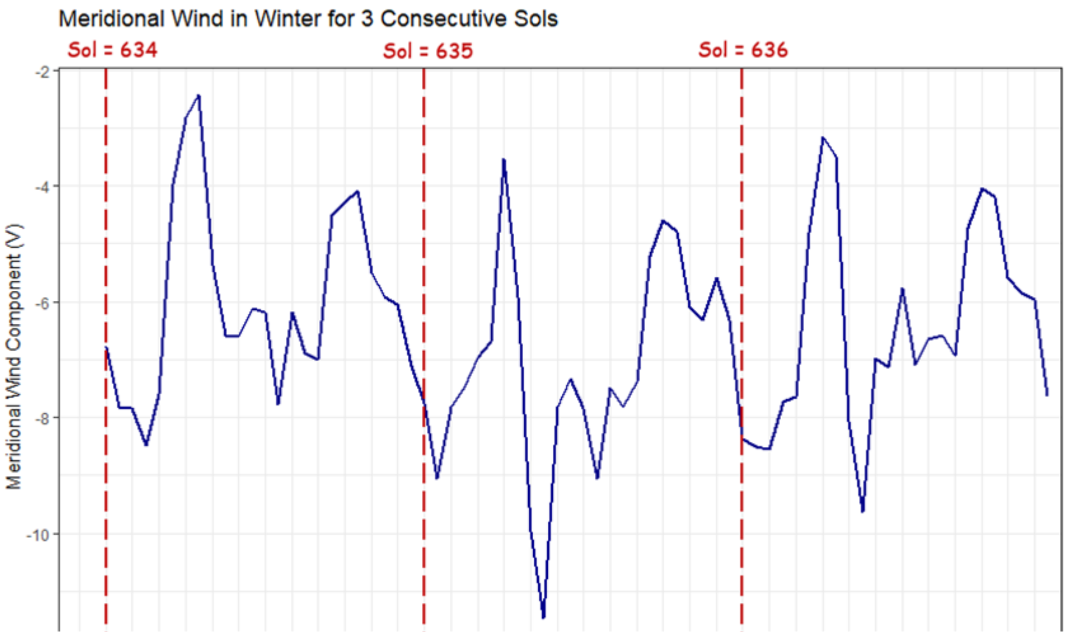


***Figure 20**: Graph to show daily wind speed variation for a sol in each season*

Banfield Fig. 4 [3], is a Global Climate Model prediction of the diurnal cycle of wind direction from sols 15 to 57, which is roughly a Martian month in Winter. We aimed to recreate this graph using the actual wind direction measurements, but due to time restraints we were only able to do this for a week. We used sols 15 - 21 to create the above graph, which confirms the findings of the GCM. The wind direction is mostly North-Westerly, which is the same as our findings in the wind rose for sol 634 which takes place in the next Winter. As InSight has only been on Mars for just over one Martian year, we unfortunately cannot compare how the data from one year correlates with another, except in Winter. As we have found wind direction to be the same during both Winters that InSight has observed, as we have the in the Winter wind rose in figure 15, we can be confident that our theory relating to wind direction is correct.

a)



b)

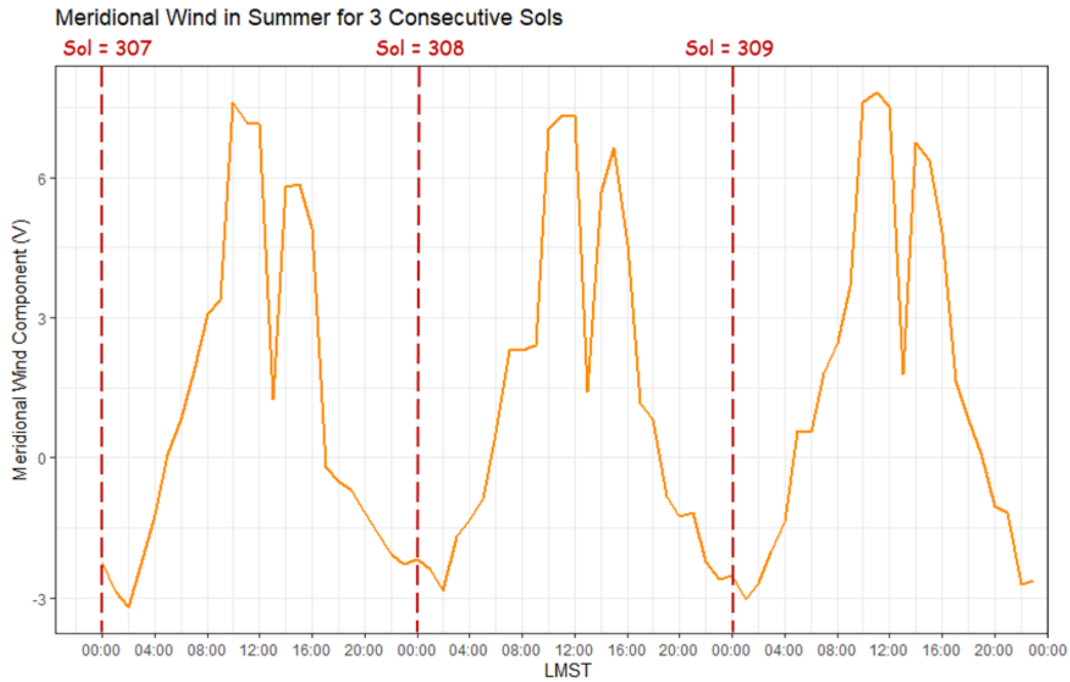


Figure 21: a) *Graph showing the hourly meridional wind component (v) for 3 consecutive sols in Winter* ***b)*** *Summer*

Martian winds in the atmosphere can be classified using their speed and direction. In meteorology, winds are classified using u and v components, where u represents Zonal Winds (East-West) and v represents Meridional Winds (North-South). A positive v component indicates winds blowing from the South to North, while a negative v value indicates the opposite. The meridional graphs for Winter and Summer on Mars have been shown in figure 21.

The Meridional winter graph (figure 21a) supports the findings observed in the Winter wind rose diagram in figure 15, as seen by the negative v value indicating wind blowing from North to South for all 3 consecutive sols. Whilst in the Meridional Summer graph (figure 21b), the majority of wind during the day blows southward coinciding with the summer wind rose diagram. However, towards the start and end of each sol, we see winds blowing from North to South. The daily wind cycle observed could be as a result of other factors including the diurnal day and night cycles, features of the local topography surrounding Insight.

5 Conclusions

5.1 Conclusions from our Findings

In this report we have been using NASA's InSight weather data to compare and contrast the climate of Earth and Mars. We have decided to focus mainly on the temperature, pressure, wind speed and wind direction readings from the Insight lander and Brunei, which is a country at a similar latitude and longitude on Earth as the Insight lander is on Mars. We have found that one of the important differences between Earth and Mars that influences annual temperature variations is the eccentricity of the two orbits. The effect of this on solar radiation means that solar radiation has very little variation throughout an Earth year, but on Mars the variation is very large due to its thin atmosphere, lack of water vapours and heat capacity due to the lack of ocean. Contrasting to Earth, where there is water evaporation above sea level from solar radiance, this water vapor rises due to Earth's Hadley cells and traps in solar radiance, acting as a greenhouse gas. This explains the relatively constant daily variation of Earth's temperature, but axial tilt is the main cause for seasonal temperature variation, as this causes the angle of the Sun to the surface to vary. As Brunei is close to the equator, there is little seasonal variation in temperature as the angle of the surface exposed to the Sun does not change significantly throughout the year.

Mars is mostly 95% carbon dioxide, this does not act as a greenhouse warming effect compared to Earth, this is due to the significantly lower pressure than Earth. This means that the atmosphere is thin and particles are spread far apart, linking with why temperature is not retained by the atmosphere on Mars, unlike on Earth where radiation from the surface is reflected back and trapped in the atmosphere due to the greenhouse gases and higher air pressure. The difference in the extreme pressure differences between the planets is caused by their gravitational pull, due to the fact Mars is smaller in its size and planetary compositions, therefore it has a lighter gravitational pull than Earth. Seasonal variations in air pressure are explained by the CO_2 cycle, which is because of the varying distance from the Sun throughout the year due to the elliptical orbit and axial tilt. In contrast, Earth distance from the Sun does not vary as the orbit is circular and axial tilt is less extreme, so these seasonal pressure variations do not occur.

The general circulation of Mars is similar to that of Earth, as both planets are made up of Hadley cells, however the Martian Hadley cell circulation extends further than that of Earths to above 60km altitude. The seasonal changes of the Hadley circulation on Mars are much greater than on Earth, despite the planets having a similar axial tilt. This relates to the thin atmosphere due to low air pressure, and varying distance from the Sun, as these result in greater seasonal temperature variation than on Earth. In Northern hemisphere Winter on Mars, the air in the Hadley cells rises to higher latitudes, the return branch blows primarily from the North, and in Summer the air rises to lower latitudes, so the return branch comes from the South.

Mars's global average temperature is lower than that of Earth's, due to the planet's inefficient heat retention and its thin atmosphere. The difference in temperatures between the planets, means that Mars experiences higher wind speeds than Earth however Earth has a broader daily range. The seasonal variation in pressure due to the condensation and sublimation that occurs at the polar regions of Mars, causes a higher temperature gradient, thus resulting in stronger winds.

5.2 Limitations

There is much variation between the two planets so conclusions may not be entirely valid. These include that the Earth has oceans, living organisms, and man-made climate change. The Earth has many other weather parameters not present on Mars that can be explored, such as rainfall and thunderstorms.

It is particularly difficult to draw solid conclusions when comparing Mars wind data to Earth. The topography of Mars may alter some of the data, as wind speeds and directions can be significantly affected by mountains and uneven terrain.

We have only compared weather data from one location on Earth and one location on Mars, so our findings are not applicable to the entirety of each planet. The data from locations that are closer to the poles would be different, in particular on Earth as there would be greater seasonal variations in temperature.

In spite of this, our findings confirmed much of our theory, for example the Hadley cell circulation was aligned with the wind direction data, and many of our graphs line up with findings and predictions from other literature, so we can be confident that our findings are valid.

5.3 Future Work

We have contributed to further understanding the weather on Mars by creating plots incorporating recordings from InSight that include data from across an entire Martian year, which has not been achieved by previous research papers. We have been able to extensively compare seasonal weather variations and find links between temperature, pressure, and wind speed and wind directions, through the use of plots that had not yet been created. These include a wind rose for each season, a lag correlation for consecutive sols, a smoothed wind speed graph for sols in different seasons and the comparison of expected temperature based on solar radiation and actual temperature.

If given the possibility to re-conduct our research, we would have also focused on other interesting aspects such as baroclinic instability, gravity waves and the turbulent energy spectrum. Academic literature, such as the Spiga paper [2], investigated the kinetic energy of wind and other fluid dynamics related topics with more depth. Given additional time for our project, investigating this topic would certainly have yielded more interesting information on turbulence, which is particularly interesting for wind and the high-frequency fluctuations of atmospheric pressure. Similarly, with more time we could have investigated statistical aspects with more rigour. We could potentially investigate predictability of weather, comparing the memory of Mars with that of Earth while exploring potential reasons for any differences. If we were to repeat this project again in a few years we would have far more data to analyse, giving us the ability to compare the weather trends of multiple Martian years.

6 Appendix

Press this **link** to access the code used for our data analysis throughout this project uploaded onto **Github**
Alternatively go to link below:
https://github.com/5BWeatheronMars/Analysing-the-weather-on-Mars/commit/8e9e514194b647f32cbb80c15335f36971496a54?fbclid=IwAR1z3Y_bkwOoi12zZOkkn-kkUk4EpfOhxa4iU_gzwdXHcXCA7y5XWgHtf_g

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