Study on Temperature Profiles of Neutral Atmosphere of Venus using Radio Occultation and Models

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Declaration by Student

- I hereby declare that the data presented in this Dissertation report entitled, "Study of Temperature Profiles of Venus Neutral Atmosphere using Radio Occultation and Models" is based on the results of investigations carried out by me in the field of Atmospheric and Space Sciences at Space Physics Laboratory, VSSC, ISRO under the Supervision of Dr.Raj Kumar Choudhary, and the same has not been submitted elsewhere for the award of a degree or diploma by me. Further, I understand that Goa University will not be responsible for the correctness of observations / experimental or other findings given in the dissertation. I hereby authorize the University authorities to upload this dissertation to the dissertation repository or anywhere else as the UGC regulations demand and make it available to anyone as needed.

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Preface

As a student pursuing a Master's degree in Physics, I have always been fascinated by the mysteries of astronomy. When I was offered the opportunity to work at VSSC, where I could get opportunities to explore and understand the complexities of planetary atmospheres, I eagerly seized it. This led me to embark on a comprehensive study of Venus's atmospheric dynamics, seeking to unravel its atmospheric dynamics through the analysis of temperature profiles obtained via Radio Occultation techniques and models such as Venus GRAM and the Venus Climate database.

Drawing upon data gathered from the Venus Express and Akatsuki missions, this study aims to shed light on the underlying mechanisms driving temperature variations within the Venusian atmosphere and to support previous findings. During the project, I carefully analyzed the observed data and also compared it with data computed by models and inferred my findings.

This study not only represents a significant milestone in my academic journey but also contributes to the broader scientific discussion surrounding planetary atmospheres. It is my sincere hope that the findings presented herein will inspire further inquiry and pave the way for future advancements in our understanding of Venus's atmospheric complexities.

Acknowledgment

First and foremost, I express my heartfelt gratitude to the Almighty for providing me with the opportunity to undertake this project at the esteemed Vikram Sarabhai Space Center, ISRO. I am deeply indebted to my parents and sisters, who have consistently been my pillars of support and encouragement, motivating me to strive for excellence.

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Lastly, I express my gratitude to my relatives, friends, and colleagues for their contributions and encouragement throughout this endeavor.

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Acronyms

ESA European Space Agency. 21

IDSN Indian Deep Space Network. 22

LST Local Standard Time. 41

RO Radio Occultation. 23

UDSC Udusa Deesp Space Center. 22

VCD Venus Climate Database. 43, 48

Venus-GRAM Venus- Global Reference Atmospheric Model. 42

VIRA Venus International Reference Atmosphere. 22, 41, 42

1 ABSTRACT

Venus, often referred to as our toxic sister, has captured the interest of researchers since ancient times. However, due to its inherent limitations, the full understanding of this mysterious planet remains elusive. In this study, we focus on a fundamental yet critical parameter of Venus: temperature. Using the Radio Occultation technique, we analyzed temperature profiles of Venus' atmosphere from 2006 to 2022. Our investigation delved into the temperature's dependence on latitude, longitude, and time, determining static stability and exploring its variations with latitude. Additionally, we calculated the tropopause height and examined its relationship with latitude. Furthermore, we compared observed data with model-simulated temperature profiles. Finally, we investigated atmospheric dynamics and their implications based on our findings.

2 INTRODUCTION

2.1 Background

From ancient times, the skies above have been fascinating to all. The enchanting Venus in the night sky particularly attracted the attention of astronomers. Ever since, there has been an urge to study Venus, the so-called "Phosphorus" morning star or "Hesperus" evening star. Venus orbits at a distance of $\approx$ 108 million km with a radius of $\approx$ 6052 km, a mass of 4.9 x $10^2 4$ kg, and a volume of 9.28 x $10^1 1 km^3$. Venus is known as a clone of the Earth in terms of size and distance from the Sun, and both are said to originate from the same nebula, probably with huge amounts of CO_2 in the atmosphere and liquid water in the oceans. The disparities with Earth, however, include intense sulfuric acid clouds, surface pressures of 90 bars, and temperatures of 750 K with no moons and no seasons. These convolute features of Venus led people to dig deeper into this planet.

Venus is known to be an extraordinary terrestrial planet. Beginning with its slow rotation a solar day is 243 Earth days, and an Earth year is 225 days. The surface of Venus possess a barren, dim and rocky landscape with signs of active volcanism. Its spin is retrograde, i.e., to the west rather than to the east like most of the other planets in the solar system. The most popular feature of Venus is the super-rotating atmosphere which is 60 times faster than the surface which is directed westward same as the planet. The maximum speed is $\approx$ 100 m/s at the cloud tops within the altitude range 65-70km. [2]

The warm polar vortex is zonally surrounded by a cold latitude band located at 60^o-80^o latitude, which is a unique feature called 'cold collar' in the Venus atmosphere.

Although these structures and super rotation have been observed in numerous previous observations, the mechanism is still vague. Our understanding of Venus remains unclear, yet with each mission, we steadily advance in unraveling the mysteries shrouding this enigmatic planet. Over numerous missions, various techniques and wide range of spatial and temporal ranges our understanding of Venus atmosphere has developed.

Venusian dense atmosphere traps heat in a runaway model of the greenhouse effect.The thick CO_2 makes it very difficult for the infra-red radiations from the ground to get back to space as it acts like a blanket. The surface in turn heats up and the energy balance could only be restored by the planet radiating as much energy as it receives from the Sun. This could happen only with a lower atmosphere of high temperature. In short, the greenhouse heating could be thought of being responsible for the raise in Venusian surface temperature until this energy balance is achieved. Consequently, this would mean a noticeable increase in the atmospheric carbon dioxide and water vapour, gases that amplify greenhouse effect in Venusian atmosphere. Further release of these gases leads to more heat near Venus' surface; creating the state of runaway greenhouse effect. As and when Venus became hotter, its oceans evaporated destabilizing that safety valve. But in the presence of Sun's ultraviolet light, the water vapour content in the planet's atmosphere does not last forever. The light element hydrogen can getaway from the atmosphere, leaving behind oxygen to combine chemically with surface rock. Hence, water loss turns out to be an irreversible process and can't be restored, once gone. Evidences support the statement that this was what occurred to water once present on Venus. The main cloud layers of the planet extend along the altitude range between 45 and 70km, with hazes upto 90km and down to 30km in addition. Cloud particles comprises of sulfuric acid (H_2SO_4). At high altitudes (80-90km) where solar ultraviolet light undergo photo-dissociation to give SO_2 followed by chemical reactions with compounds like H_2O leads to the production of H_2SO_4, thus forming droplets. When these droplets fall, they grow. At lower altitudes (<45km), the droplets tend to evaporate. The temperature is too high for the droplets to exist below 30km height and hence the atmosphere is clear. [3] [4] [5] [6]

2.2 Aim and Objectives

The aim of the study is to deepen our understanding of atmospheric dynamics on our sister planet Venus by looking into the temperature variation. The general objectives are as follows: (1)To analyze temperature variations in the lower atmosphere of Venus with respect to latitude, longitude, local time, solar zenith angle, and altitude. (2) To identify and characterize prominent atmospheric features such as temperature inversions, cold collars, and warm vortexes. (3)To compare observed temperature data with models (Venus-GRAM and Venus Climate Database) to assess model accuracy and improve our understanding of Venus's atmospheric processes. (4)To examine the influence of latitude on the static stability and tropopause dynamics. (5)To identify gaps and limitations in current understanding and propose areas for future research in Venusian atmospheric science.

2.3 Research question

Since the discovery of Venus by M.Lomonosov in 1761 till date we continue to know more about the planet's extreme climate and weather. However, due to extremities there have been hardly any in-situ measurements of Venus. As a result, most of the apprehension about the planet comes from remote sensing techniques such as telescopic observations, Radar mapping, Infrared Spectrsocopy, Ultraviolet imaging, Thermal emission spectrosocopy, LIDAR and Radio Occultation. But exploration of our sister world is still a long way.To further amplify our investigation of the planet by looking into the spatial and temporal variation in temperature profiles within the lower atmosphere of Venus and its impact in the overall atmospheric dynamics, the most suited research question for this study is: "What are the spatial and temporal variations in temperature profiles within the lower atmosphere of Venus, and how do these variations contribute to our understanding of atmospheric dynamics and climate on the planet?

2.4 Scope

Venus and Earth are very different twin planets. Understanding their difference particularly with regard to climate is crucial in unraveling the divergent evolutionary paths of the two planets. Venus' atmosphere has its limitations, thus there remains numerous unanswered questions regarding its composition, structure and dynamics.

In this study, the focus is in the middle atmospheric region, spanning altitudes 45-85 km, that comprises of the upper troposphere and the lower mesosphere. The sources of the observational data used in the analysis is from Venus Express and JAXA's Akatsuki missions using radio occultation technique. The dataset comprises of only publicly available profiles. Additionally, the Venus Climate database and Venus Global Reference Atmospheric model is used for the comparison study.

The primary variable under investigation is temperature, with analysis inclusive of temperature variations with latitude, solar zenith angle, and altitude. Static Stability derived from temperature profiles is also a focal point. Various atmospheric phenomena such as temperature inversions, cold collars, warm vortexes, tropopause dynamics are of interest in the study.

The Venus-GRAM and Venus Climate Database (VCD) are the two widely used models to comprehend the atmosphere of Venus. Venus-GRAM was developed by NASA based on Pioneer Venus Orbiter and probe data in 2005 and Venus climate database is the latest and open-source model developed by IPSL and based on the general circulation model for Earth. VCD can produce a high resolution 3D view for a given altitude range and latitude range. Though the models can return various parameters, for their comparison with Radio Occultation measurement, with uttermost focus on temperature patterns. Analytical methods employed to study temperature profiles include contour plots, statistical analyses including averaging, standard deviation and comparison techniques such as correlation factor.

Despite analysing the profiles from 2006-2022, the dataset is relatively small with on 275 profiles and limited coverage at higher latitudes and extreme solar zenith angles.

Also, the models have their own limitations one being Venus-GRAM 2005 version 1 developed with a limited data set back in 1988 and Venus Climate database a theoretical model still has many modifications yet to be implemented.

The novelty of this study lies in its long time span i.e. 2006-2022 using highly accurate temperature data using radio occultation technique. By revisiting existing findings and examining variations over time, this study aims to identify areas for improvement in existing models and contribute to our understanding of Venus's atmospheric dynamics.

3 LITERATURE REVIEW

3.1 Introduction to Venus Atmosphere

The thermal structure of the Venus atmosphere, extending more than two hundred km above the surface, is a result of the radiative and convective processes, which are governed by the scattering and absorption of the incident solar radiation and of the infrared emitted radiation from the surface and the atmosphere. In this paper, we focus below about 200 km due to paucity of observations above 130 km. One might anticipate that with a very low obliquity spin axis, circular orbit, ubiquitous cloud cover and no oceans, the Venus atmosphere would be relatively easy to understand with regard to its thermal structure, radiative balance and circulation. The global atmospheric thermal structure is key to the global atmospheric circulation and the structure of the global cloud cover. The global thermal structure of the deep Venus atmosphere, extending nearly two hundred km above the surface, is a result of the radiative and convective processes. Thus understanding the thermal structure requires a knowledge of the absorption of the incident solar radiation and escape to space of the emitted infrared radiation from the surface and the atmosphere itself. Both the absorption and escape of radiation depend on the cloud structure and the chemical composition of the atmosphere. [4]

3.2 Latitude and altitude based temperature dynamics

Venus' neutral atmosphere, plays a crucial role in shaping the planet's overall atmospheric dynamics. Study of the variation of atmospheric temperature specifically provides valuable information about the thermal structure and stability of the planet's atmosphere. Studying temperature profiles within the lower atmosphere of Venus is not only crucial for understanding the atmospheric dynamics of this enigmatic planet but also holds broader implications for planetary science for instance the its long-term climate evolution. Insights gained from studying Venus's atmosphere can provide valuable comparative data for understanding Earth's climate system and inform our understanding of planetary atmospheres beyond our solar system. [2]

Temperature is one key parameter that provides vast information about the atmosphere and is easily understandable to laymen too. The variations in temperature can influence atmospheric circulation patterns, cloud formation, and the distribution of atmospheric gases. By focusing on the specific characteristics of Venus' atmosphere, researchers can shed light on the complex interplay of factors shaping its temperature profiles. To understand the temperature profiles in the lower atmosphere, researchers have investigated variations in temperature with latitude and altitude.

At lower altitudes below the clouds, the temperature decreases with increasing latitudes. A prominent characteristic known as the cold collar, is a severe temperature inversion that occurs at an altitude of 60–70 km in both hemispheres. At still higher altitudes ≈70 km, an intriguing feature contradicting the radiative-convective equilibrium, that the equator will be warmer due to higher solar heating, however temperatures rises from the equator towards the poles forming the warm polar mesosphere. Cold air circling the warm polar vortices of Venus between 60° and 80° is about 20 K colder than at the equator and 15 K colder than at the poles. The average temperature difference between the coldest area of the cold collar and the warmest nucleus of the vortex is ≈30 K.

It is expected that the temperature difference would cause it to dissipate quickly, however it has been a permanent structure since early research implying that it is forced by some unknown mechanism. Although these polar structures have been observed repeatedly, their origin and formation mechanism are still unknown. Some studies concluded that thermal tides or baroclinic waves or meridonial circulation or even barotropic Rossby waves might contribute to the cold collar and warm polar vortex. However, the observed structures could not be fully explained. [7]

[8] highlights that the most distinct feature observed in the range of 49.7 ^{o} to 88.3 ^{o} latitudes, is a prominent inversion at the level of about 100 mbar ($\approx$ 65km). However, when the latitude decreases below about 45 ^{o}, the inversion disappears, and the transition from the troposphere to the stratosphere becomes much more gradual. The decrease in the magnitude of the inversion from the pole to the equator appears to be correlated with the amount of turbulence observed at that level, hinting relation with the dynamics of the Venus atmosphere. [9] suggests that the behavior is co-occurring with the strong zonal winds and the superposition of the zonal retrograde rotation and also the descending branch of the Hadley circulation leading to the strong polar vortex and cold collar structures at higher latitudes.

In summary, the collar region serves as a boundary dividing the atmosphere by latitude and altitude. Moving from equator towards the poles, a temperature decrease is observed with maximum drop occuring at the cold collar typically in the latitude range of 70s and and again increases polewards, but it is not completely uniform along the latitude circles. Whereas in context to altitude variation, below the collar, the atmosphere cools with increasing latitude and above, the temperature gradient is reversed (Figure 10 from kliore 1980). Again the origin and dynamics of this structure remain unknown.

Latitudinal variations plays a dominant role in modeling the structure of the lower and mid atmosphere. These changes are noticeable at 30km altitude.[10] and are pronounced in the cloud layer (45–70 km) and beyond. It is primarily related to the cyclostrophic balance of the high-velocity zonal winds. Cooling of the atmosphere at 60-km altitude is affected by the rotating pair of infrared emission windows found at slightly higher latitudes than the cold collar structures. This, together with radiative absorption at higher levels, could be related to the strong inversion. Also, diabatic heating or dynamically controlled processes could be responsible for the observed structures. At the altitude of the collar and closer to the pole the atmosphere is almost isothermal and also much warmer than the surrounding areas. [7]

3.3 Importance of Cloud Layers

Understanding the temperature profiles within the cloud layers is essential for unraveling the complex interactions between various atmospheric components and for gaining insights into the broader climate dynamics of Venus. Temperature variations within these cloud layers can impact cloud formation processes and atmospheric circulation patterns. Understanding the interactions between temperature profiles and cloud dynamics is crucial for comprehending the overall climate system of Venus. The thermal structure is crucial to comprehend the general circulation of the atmosphere, namely the mean meridional circulation and baroclinic-instability waves that contribute to the super-rotating atmosphere and heat transportation.[11] The cloud layers, consisting mainly of sulphuric acid droplets, have a strong influence on the thermal structure and stability of the Venus atmosphere, even at heights well above and below the clouds. The circulation patterns in the troposphere and mesosphere are believed to be also strongly dependent on the thick cloud layers.[9] However,the dynamics of the Venusian atmosphere remain elusive due to the complete global coverage of thick clouds spanning altitudes from 48 to 70 km.

3.3.1 Static Stability

The static stability S of an atmosphere is defined as the difference between the change in temperature of the atmosphere with altitude dT/dz and its dry adiabatic lapse rate Γ:

$$S = \frac{dT}{dz} - \Gamma \tag{1}$$

The adiabatic lapse rate Γ is given by

$$\Gamma = \frac{g}{Cp} \tag{2}$$

where Cp is the specific heat per unit mass. The value of Cp for CO_2 is dependent on temperature and Γ varies from 10.0^{o}K/km at 300K to 8.1^{o}K/km at 600K.[12] . Exploring the static stability within the lower and middle layers of Venus' atmosphere is crucial to gain insights of Venus' atmospheric dynamics.

Positive values of S indicate atmospheric stability, while negative values suggest instability against convective overturning. Generally, the atmosphere exhibits stability at all altitudes above 45 km, but abrupt changes have been noted at the upper boundary of the clouds. The lapse rate closely approaches adiabatic conditions within the middle cloud layer, spanning approximately from 49 to 59 km, and exhibits latitude-dependent characteristics. Convective regions ($S < 0$) are confined to very shallow layers within this middle cloud deck. Examples between 52 and 54 km illustrate typical instances where S $\approx$-1. This result is in good agreement with previous observations indicating a stable, stratified atmosphere with shallow convection in the middle cloud regions. [9]

A stable region in the troposphere, beginning just below the middle cloud deck near 50 km, extends well below the clouds. Results from in situ measurements have shown that the stability is maximum at about 45 km.[13] Previous in-situ meaurements show that the atmosphere can be categorised into 3 regions:

(1) Low stability (0-1 K/km)

(2) Moderate stability (1-4 K/km)

(3) Highly stratified (> 4 K/km).

The static stability of an atmosphere is closely associated with the behavior of the tropopause [9]. [11] showed that the overall structure is more or less hemispherically symmetric. The low stability layer in the lower and middle cloud region (50-58km) and is the latitude dependent broadening polewards to $\approx 70\ ^{o}$ latitude and abruptly expands down to an altitude of 42km beyond cold collar latitudes. Moderately stratified layer has been observed below 50km and highly stratified layer is located above 58km with exceptional stability at higher latitudes. Modelling studies in the past have indicated that movement of air between altitudes of 50- 60 km may be forced by infrared heating at the cloud bottoms. This phenomenon is more pronounced in polar areas because the upper clouds experience more efficient infrared cooling, particularly at higher latitudes. As a result, the convective motion could creep through the stable layer of air below, potentially causing it to become thicker in regions closer to the poles.Another theory suggests that the temperature below 60 km altitude could be affected by the meridional circulation and wave movements. The circulation pattern within and beneath the cloud layer is complex. A powerful downward flow linked to this circulation beneath the polar clouds may warm the atmosphere and reduce its stability, even though the specific circulation pattern remains uncertain.

3.4 Tropopause

Venus atmosphere is divided only into 2 distinct regions based on the thermal structure, the troposphere and the mesosphere. The troposphere extends from the surface to the point of maximum temperature inversion observed at the upper boundary of the clouds ≈ 60km. The altitude at which the troposphere terminates is called the tropopause. The mesosphere also called the transition region extends from the tropopause to about 100km. The tropopause temperature ranges from 210-280K with a maximum value in the equatorial latitudes near ±15 to a minimum near ±70 latitude at the cold collar region and increases again as the poles are neared. In studying the Venus atmosphere using Pioneer Venus Radio occultation data, [8] found the tropopause at an altitude of 56 km in the low latitudes where the transition from troposphere to mesosphere is gradual. At higher latitudes the tropopause altitude gradually increases till it reaches a maximum altitude of 62km in the cold collar region, where the temperature inversion is of magnitude ≈ 30K. At the polar region 80 -90 degrees latitudes the tropopause height drop down to nearly 50km. No specific mention has been made of the reason for setting the tropopause threshold as $dT/dz > -8$. The tropopause height is real and is dependent on the dynamical changes in the atmosphere. From the plots of [8] it can be observed that there is a significant change in the tropospheric temperatures at like latitudes. This concludes that the dynamical processes that are responsible for the height of the tropopause and structure of mesosphere change with time or hemispheric location. In [9] it is noted that the average lapse rate is approximately 10K/km below the tropopause. The atmospheric lapse rate in the middle atmosphere is almost isothermal upto ≈ 75km. Small scale fluctuation have been observed specifically in the middle atmosphere.

3.5 Review of Models used in atmospheric studies of Venus

Venus is a fascinating planet with numerous mysteries, especially when it comes to its atmosphere. Even though it's challenging to explore Venus firsthand, models are essential for scientists to grasp its atmospheric dynamics and predict changes in different locations. Scientists can use computational models and scientific principles to simulate atmospheric events on Venus. These models provide valuable insights of Venus atmosphere, like its composition, temperature variation, cloud formations and circulation patterns. By utilizing models, scientists can investigate mysteries about Venus atmosphere, such as the cause super-rotation, intense greenhouse effect leading to high temperatures, the formation and movement of its sulfuric acid clouds, and whether there could be a possibility for existence of life in the atmosphere. These models help predict the cause for the observed characteristics of Venus atmosphere and pave a path guiding future missions. As modeling techniques get better and we continue to gather data from profound missions to Venus like Venus Express and Akatsuki we will learn even more about Venus's atmosphere and its importance in planetary science.

Modelling of the atmosphere can be of different types : (a) Empirical Models that are based on observed data and statistical techniques. (b)Theoretical models explain the atmospheric phenomenons based on fundamental physical principles and mathematical equations describing the behaviour of fluids and gases in the atmosphere. (c) Numerical Weather prediction models, use numerical methods as the name suggests and simulate the evolution of atmospheric parameters over time, mainly to predict short term weather forecasting. (d) Climate models forecast the long term behavior of the atmosphere by including the solar impact, emission of gases and even oceanic behavior. (e)Chemical transport Models mainly focus on incorporating chemical reactions, emission rates of pollutants and atmospheric variation. (f) Regional and local- scale models emphasize on simulating atmospheric processes over small geographic areas like cities, regions, or specific ecosystems.

Venus has been explored since 1960s and its peculiar characteristics have been revealed by numerous missions providing invaluable data. However, limited empirical models have been developed but several theoretical models, attempting to explain the atmospheric dynamics.

The pioneering 3-D general circulation model developed 30 years ago led the path to simulate and interpret the Venus atmosphere employing Theoretical atmospheric models. [14] Theoretical models based on fundamental physical principles and mathematical equation simulate atmospheric parameters to describe their behaviour in the planetary atmosphere. In this study we have focused on the latest models available i.e., Venus Climate Database 2.3 based on General Circulation MOdel and Venus General Reference Atmospheric Model based on Pioneer Venus Orbiter and probe data.

4 METHODOLOGY

4.1 Data collection sources

Due to Venus' thick layer of clouds and intense greenhouse effect it is difficult to directly measure temperature profiles in the lower atmosphere. Traditional detection techniques used on Earth and other planets may not be applicable in this unique environment. Scientists have developed instruments and techniques most suited of Venus, that can penetrate its thick cloud cover and provide valuable data about temperature profiles in its lower atmosphere. The eagerness to explore has led to a notable number of Venus missions since 1961. Because of the extreme conditions on Venus, only flybys, orbiters, balloons, probes, short-lived landers and earth-based observations have been used to explore Venus. However, not all missions were fruitful as expected but some have contributed exceptionally, that has sculpted our understanding of Venus. Kicking off with success in flyby Mariner 2 being the first successful planetary mission in the history of solar system exploration. Following, Venera 2, and moving towards atmospheric probes Venera 4,5,6. Venera 7 was the first spacecraft to safely reach the surface in 1972. The peak point of Venus exploration was in 1978 with Venera 11, 12, Pioneer Venus Orbiter and four descent probes visiting the planet. The landers did not last more than a few hours but the zeal to explore this puzzling world led to persistent interest in it. Venus Express by the European Space Agency has already changed our understanding of Venus by providing invaluable data. And Japan's Exploratory Space Agency's Akatsuki is still doing a commendable job and facilitating with additional critical data insights. The realm of Venus exploration is increasing with several Venus discovery proposals knocking at the doors of NASA like DAVINCI, VERITAS, EnVISION. [**?**]

Different payloads facilitate study of different component of the atmosphere. To study the temperature profiles, VeRa payload on VeX and USO (Ultra stable Oscillator) on Akatsuki are used. Radio Occultation is the most prefered technique with a resolution of $\approx$ 1K.

4.2 Processing Radio Occultation data

Occultation is an event when an object gets hidden by another object which passes between it and the observer. Astronomers utilized stellar occultation events to study surrounding ambiance

of a target planet. However, due to scarcity of such natural events, highly stable radio sources are needed to describe the properties of the target planetary atmosphere, which can not be done with stellar occultation events. These requirements could get fulfilled only by employing active radio transmitters. The stability of the radio source defines the reliability of the observation. The use of active radio sounding to study the planetary atmosphere was initiated by Kliore who first attempted radio science experiments to study Mars. Eshleman, along with his students Gunnar Fjeldbo and Len Tyler worked on the retrieval theory, to determine the refractive index profile of the probed medium using the phase changes in the radio signals and they successfully refined the RO retrieval technique.[**?**]
The very first atmospheric profiles of the Venusian atmosphere were observed by Mariner-5. After a few grand successes, the Radio Occultation experiments became an integral part of all planetary missions and proved its utility to study the atmosphere/ionosphere for several planetary bodies including, Mercury, Jupiter, Saturn, Uranus, Neptune, Pluto, Titan, Europa and Moon. The advantages of this technique over other remote sensing techniques are its high vertical resolution (typically ¡ 1 km) and high temperature resolution (typically ¡ 1 K). However, the quality of the measurement declines below 40 km and no information is obtained below 32 km since the curvature of the ray path exceeds that of the planetary surface and due to defocusing loss which is a cause of the dense Venus atmosphere and absorption loss because of the presence of different species in the Venusian clouds at three different altitudes.[15]

Radio occultation has played a crucial role in determining the structures of the planetary atmospheres. In a radio occultation experiment the spacecraft has to be equipped with a stable frequency source called Ultra Stable Oscillator, that continuously transmits radio waves toward the Earth. While it goes behind the planet and reemerges as seen from the Earth, the radio signal is attenuated. After analysing the received signal, can be used to retrieve parametric profiles of the planetary medium.

The basic geometrical arrangement of an RO experiment requires two radio elements, namely a transmitter onboard the orbiting spacecraft, and a receiver at the ground.

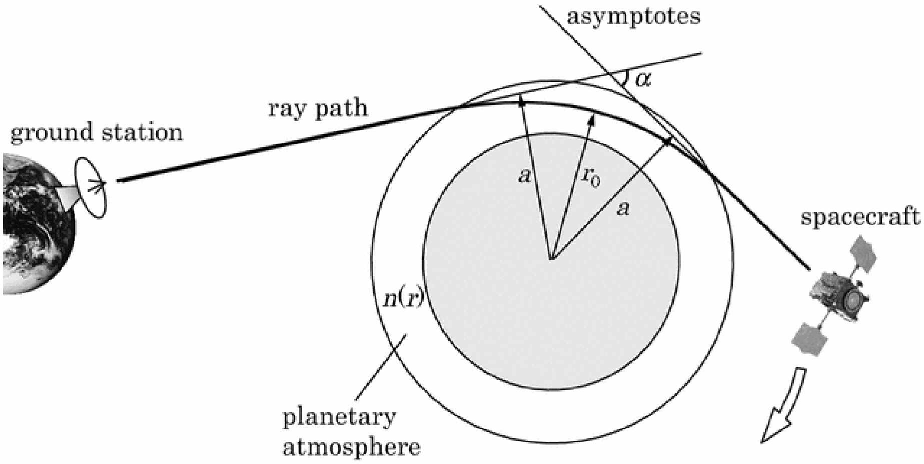


Figure 4.1: Schematic of Radio Occultation Experiment [1]

Based on modes of radio communication, RO experiments are classified into the following categories.
(1)If radio signals of a single frequency are transmitted from spacecraft and received at ground stations or low earth orbit (LEO) satellites, it is known as one-way downlink single frequency RO experiments [1].
(2) If, on the other hand, the radio signals of two coherent frequencies are transmitted simultaneously then the arrangement is known as a one-way downlink dual-frequency RO experiment.[9]
(3)Single / dual-frequency radio signals can be transmitted from the ground station to the spacecraft, which after getting phase-locked with an onboard oscillator are transmitted back to the ground station. This arrangement is known as two-way single/double frequency RO experiments. In this two-way mode, both the transmitting and receiving antenna at the ground station remains the same. [16]
(4)A "three way" RO experiment is also possible when the signals are sent from one ground station, and received at another ground station after being sent back from the satellite.
In this study, data is retrieved from Venus Express and Aksatuski missions that employ one-way downlink single/dual frequency in the Radio science experiment in bistatic mode.
The essential requirement as mentioned above for a RO experiment are USOs, for generating a stable radio signal and another to receive the same at the receiver end with high accuracy The transmitted

radio signals, after being received at the ground station antenna, pass through the Low Noise Amplifier (LNA) and are then down-converted and sent to the Signal Processing Center (SPC). Here the intermediate frequency is converted to digital converter (IDC) to get the final analog frequency (approximately 70 MHz) and then performs analog-to-digital conversion (ADC).

The basic theory for the retrieving atmospheric parameters, namely electron density profile of the ionosphere, and temperature, pressure and neutral density profile of the lower atmosphere was developed in 1960s. The bending angles of the radio signal due to the target medium were estimated using the phase change in the radio signal, geometrical details of the involved bodies, Newtonian mechanics, and geometrical optics approximation [17].

The utilization of Radio Occultation (RO) method for exploring the ionosphere and neutral atmosphere originated from the Mariner-4 occultation experiment on Mars. This significant experiment confirmed that Mars had a surface pressure of approximately 4 hPa and a CO2-dominated atmosphere. This discovery opened up opportunities for RO experiments to become vital elements of future planetary missions. RO methods have been instrumental in progressing our knowledge of the vertical composition of the atmosphere and ionosphere of different celestial entities in the solar system, particularly Venus[15]. The first radio occultation investigation of Venus was conducted during the flyby of Mariner 5 in 1967.This was followed by Mariner-10, Venera-9 and -10 , Venera-15 and -16 and Magellan. The most extensive campaign of radio occultation experiments at Venus was carried out with PVO.
During a radio experiment with the spacecraft orbiting Venus, it sends radio waves to Earth's tracking station. When the spacecraft goes behind Venus's atmosphere (ingress) and comes back out on the other side (egress) from the tracking station's viewpoint, the transmitted signal is affected. This effect happens due the gases of varying refractive indices in the atmosphere that change the direction of propagation, causing the signal to follow a curved path and resulting in perturbed frequency. The tracking station captures the signal and later analyzes the frequency data. To separate out the atmospheric interference, the Doppler shift caused by the movement of the spacecraft and the ground receiver is eliminated. Assuming that the rays are bent locally in a symmetrical manner, the closest approach point and impact distance are determined using geometric optics. The refractive

index is then calculated from the bending angle using an Abel transform,

$$lnn(r) = -\frac{1}{\pi}\int_{a_1}^{\infty} ln\{\frac{a}{a_1} + [(\frac{a}{a_1})^2, -1]^{\frac{1}{2}}\}, \frac{d\alpha}{da}da \tag{3}$$

where a_1 is the impact parameter for a ray whose radius of closest approach is r, and a_1 and r are related with each other through Bouguer's rule, n(r) r = a_1. The refractive profile $\mu(h)$ is then determined by the state of the neutral atmosphere and electron density $N_e(h)$

$$\mu(h) = -C_3.\frac{N_e(h)}{f_o^2} + C_1.n(h).k \tag{4}$$

where k is the Boltzmann constant, n(h) is the vertical distribution of neutral number density, C_3 = 40.31 m^3/s^2, $C_1 \approx$ 1312 10^6 Km s^2/kg and f_o is the frequency of the radio signal. It is then used to create a density profile based on the assumed composition of the atmosphere. Finally, the concepts of hydrostatic equilibrium and the equation of state are used to determine the temperature and pressure profiles.[9] [17]

$$T(h) = \frac{\mu_{up}}{\mu(h)}.T_{up} + \frac{\bar{m}}{k.n(h)}\int_{h}^{h_{up}} n(h').g(h')dh' \tag{5}$$

4.2.1 Venus Express

Venus went unnoticed for over a decade and mysteries about the planet still remained unanswered. However, the importance of Venus in understanding the general evolution of terrestrial planets was not forgotten. The European Space Agency (ESA) launched Venus Express to open up opportunities for new investigations with a combination of instruments employing completely new techniques and improved versions of conventional instruments.[18] The Venus Express Radio Science Experiment (VeRa) uses radio signals at wavelengths of 3.6 and 13 cm ("X"- and "S"-band, respectively) to investigate the Venus surface, neutral atmosphere, ionosphere, and gravity field, as well as the interplanetary medium. An ultrastable oscillator (USO) provides a high quality onboard reference frequency source; instrumentation on Earth is used to record amplitude, phase, propagation time, and polarization of the received signals. [19] Radio signals for VeRa observations were tracked at two ground stations, namely ESA's New Norcia and NASA's DSN station DSS-63. The data was recorded in the open loop mode. The data collected from Venus Express is available as level 1, raw data. [20]

4.2.2 Akatsuki

Orbiter Akatsuki also known as Planet-C, by the Japan Aerospace Exploration Agency began its journey in its second attempt in December 2015 with observations using radio occultation technique starting in 2016. The response to the initial results and findings has been very enthusiastic, generating renewed interest both in the scientific community and in the major space agencies.
One-way downlink at X-band (8410.932 MHz) is used in the experiment. The experiment relies on the frequency stability of both the onboard radio wave source and the recording system at the ground station. Akatsuki Radio Science employs an ultra-stable oscillator (USO) as the onboard frequency source. Radio signals for Akatsuki observations were tracked at two ground stations, namely Usuda Deep Space Center and Indian Deep Space Network. [1],[21]
The data recieved at UDSCandIDSNhas been processed and Level 3 data, that includes the temperature with varying altitude, pressure, neutral density, latitude, longitude, solar zenith angle and time is available on Jaxa website. [22]

4.3 Venus Climate Database

The Venus Climate Database (VCD) stands as a comprehensive Venusian climatology, derived from The Venus Planetary Climate Model and validated using available observational data. Accessible through both software and a web interface at `http://www-venus.lmd.jussieu.fr/vcd_python/`, VCD incorporates a full radiative transfer model and factors in atmospheric composition and cloud formation. It encompasses circulation computations from the surface up to 100 kilometers, with potential extension into the thermosphere up to approximately 250 kilometers [14], [7], [23].

VCD boasts the capability to generate up to four parameters based on specified Solar flux (sfu), latitude, longitude, Earth date, and altitude range. The parameters span a wide range, encompassing temperature, pressure, horizontal and vertical wind speeds, as well as W-E and N-S wind speeds, among others. Additionally, this web interface provides access to VIRA-computed temperature and pressure data.

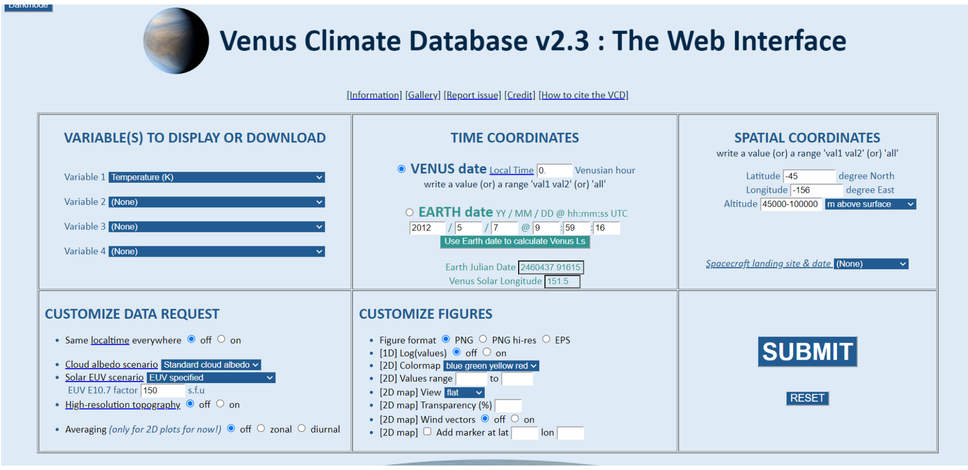


Figure 4.2: Screen capture on the Venus Climate Database web interface 2.3

In this study, the model was executed for days corresponding to the availability of Radio Occultation (RO) data from either Akatsuki or Venus Express missions. Subsequently, the data was meticulously sorted based on the year, month, and date to facilitate thorough analysis.

4.4 Venus General Reference Atmospheric Model

Venus-GRAM is derived from with significant modifications. This model operates using Fortran. It contains three essential files - INPUT, LIST and OUTPUT- along with set of codes. The specific parameter should be fed in the input file as show in the figure 4.3 and then executing the Fortran program file via the terminal using the command "$f77 - ovenusgrm_V 05.exe$" followed by the input file name. The list file and the output file is automatically created. This meticulous process ensures efficient handling and analysis of data, contributing to the model's robust functionality in simulating Venus's atmospheric dynamics.

4.5 Data Analysis

Data sorting serves as a crucial initial step in data analysis, laying the foundation for further investigation. In this study, the data underwent merging and interpolation processes to establish complete temperature profiles from both Radio Occultation ROdata and model-generated data.

```
$INPUT
 LSTFL     = 'LIST01012012.txt'
 OUTFL     = 'OUTPUT01012012.txt'
 TRAJFL    = 'TRAJDATA.txt'
 profile   = 'null'
 DATADIR   = '/home/Ophra/venusgram/Venus-GRAMMar05/UnxFiles/'
 IERT      = 1
 IUTC      = 1
 Month     = 01
 Mday      = 01
 Myear     = 12
 Ihr       = 9
 Imin      = 01
 Sec       = 06.0
 NPOS      = 251
 LonEast   = 1
 NR1       = 1234
 NVARX     = 1
 NVARY     = 0
 LOGSCALE  = 0
 FLAT      = -10
 FLON      = 74.0
 FHGT      = 0.0
 DELHGT    = 0.5
 DELLAT    = 0.0
 DELLON    = 0.0
 DELTIME   = 0.0
 profnear  = 0.0
 proffar   = 0.0
 rpscale   = 1.0
 NMONTE    = 1
 iup       = 13
 corlmin   = 0.0
$END
```

Figure 4.3: Screen capture of the input file for Venus-GRAM

Python programming was employed, leveraging functions such as concat and append, along with the SciPy model for interpolation purposes. Subsequently, plots depicting the temperature profiles were generated, providing detailed insights into the data.

Following the analysis of individual profiles, contour plots were generated to explore temperature variations across latitude, longitude, solar zenith angle, and time. This involved combining all available data using the os walk model in Python, followed by concatenation for comprehensive analysis. Statistical analysis techniques, including linear regression, correlation analysis, and fitting on distribution curves, were employed to scientifically analyze the data, uncovering underlying patterns and relationships.

Furthermore, to investigate the influence of gravity waves on temperature profiles above 60 kilometers, Butterworth filtering was implemented, providing additional insights into atmospheric dynamics, however that has not been included in the project.

5 RESULTS

5.1 Data Set

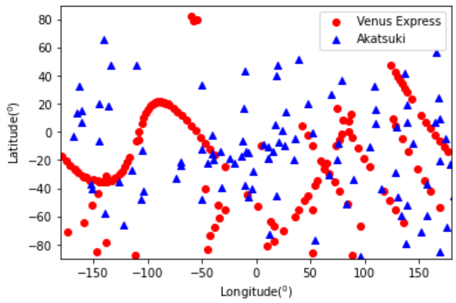


Figure 5.1: Spatial distribution of occultation profiles as a function of longitude and latitude

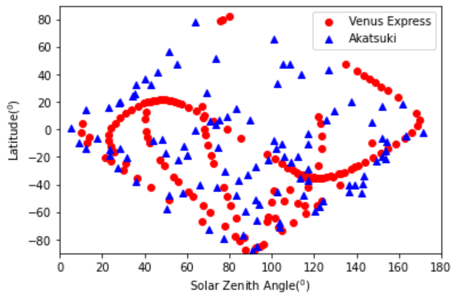


Figure 5.2: Distribution of occultation profiles over solar zenith angle and latitude

Figure 5.1 illustrates the spatial distribution of occultation measurements utilized in this study, drawing upon atmospheric profiles retrieved from the most recent missions, Venus Express by the European Space Agency and Akatsuki by the Japan Aerospace Exploration Agency. The dataset comprises publicly available observations, encompassing 177 profiles from Venus Express (VEX) and 105 profiles from Akatsuki.

Notably, each occultation event yields two retrieved atmospheric profiles, ingress, and egress, although only one was accessible for VEX. The dataset exhibits comprehensive spatial coverage across the equatorial and southern hemisphere regions. However, there exists a notable gap in coverage as we progress to higher latitudes in the northern hemisphere. Akatsuki, operating on an inclined orbit, contributes to a well-distributed data point distribution. In contrast, Venus Express, traversing an equatorial orbit, results in clustered data points at the poles.

In Figure 5.2, depicting the distribution of latitude-solar zenith angle, observations demonstrate nearly equal distribution for solar zenith angles (SZA) both less than and greater than 90 degrees. The most significant concentration of data points is observed around noon, commonly referred to as the terminator region (at 90 degrees), with a gradual decrease in profiles as we move towards the extremes.

5.2 Temperature Variation Analysis

5.2.1 Latitudinal influence on temperature

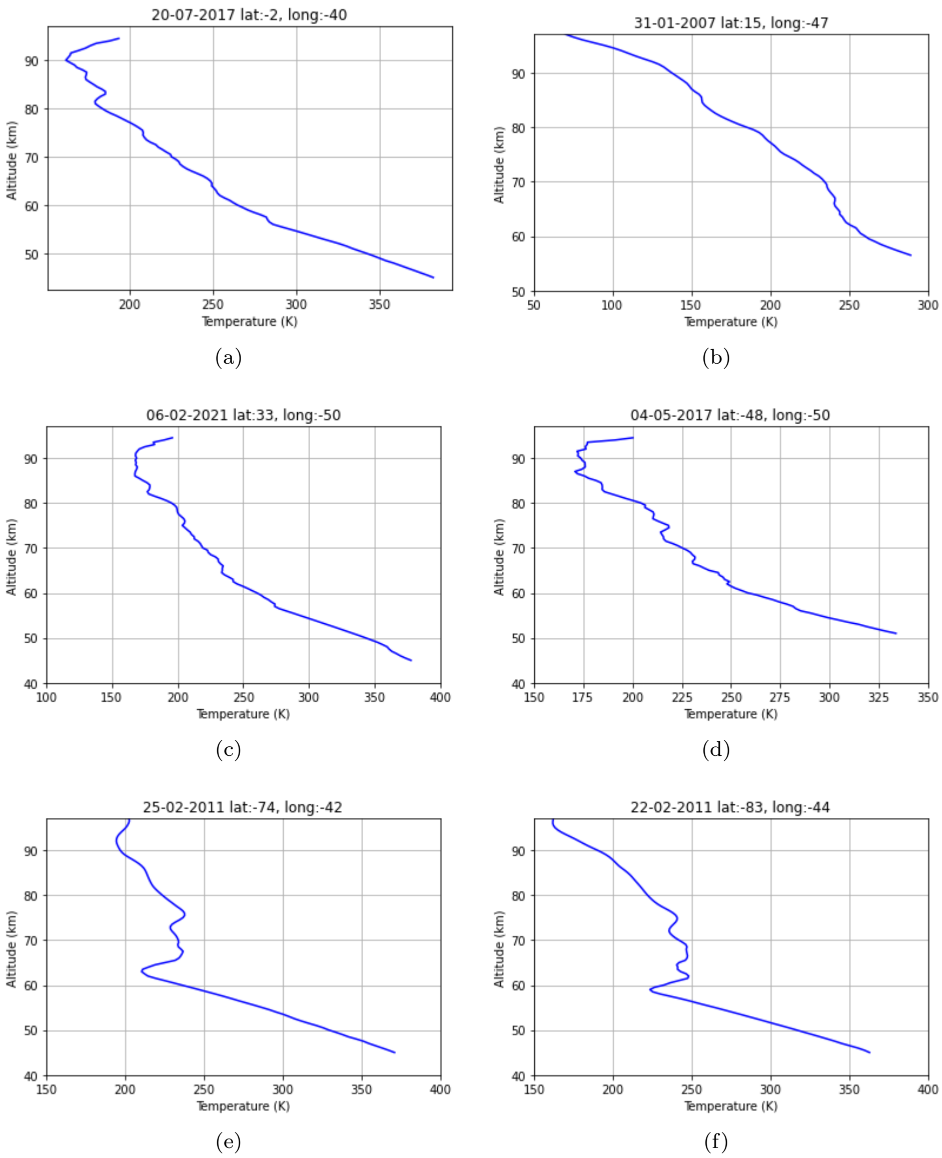


Figure 5.3: Individual Temperature profiles at varying latitudes keeping longitude in the range 40^o-50^o

In figure 5.3, typical temperature profiles of the Venus atmosphere between 45 to 95 km at varying latitudes are depicted. The first two plots (a) and (b) represent lower latitudes (0-30 degrees), (c) and (d) depict mid latitudes (30-60 degrees), and (e) and (f) illustrate high latitudes (60-90 degrees). The altitude range is chosen such, because of defocusing losses, make the lower altitudes inaccessible to occultation measurements. The temperature profiles are selectively studied using radio occultation technique as the uncertainty in the temperature retrieved as a function of altitude is said to be of the order of 1K. [9]

As illustrated in the figures, at lower latitudes, the temperature decreases linearly with altitude. At mid-latitudes, it is observed that the temperature profiles slightly curve inwards, showing a dip in temperature between altitudes 60-70 km. At polar latitudes, in profile figure 5.3 (e) at latitude -74 degrees, a deep temperature inversion is seen between 60-70 km, and the temperature rises again above 70 km. At a still higher latitude value of -83 degrees, the temperature inversion is still visible but has slightly shifted to a lower altitude, just below 60 km. It exhibits a similar characteristic to figure (e); however, between 60-80 km, the temperature change is nearly adiabatic, and beyond 80 km, the temperature again begins to decrease linearly. In figure (e), too, temperature is approximately constant with respect to altitude but for a shorter height range than figure (f).

Due to this temperature inversion and adiabatic behavior for a limited altitude range, the Venus atmosphere was divided into two distinct regions with respect to temperature variation, analogous to Earth's atmosphere, i.e., (1) Troposphere and (2) Mesosphere. In the Venus atmosphere, the stratosphere is missing as there is no increase in temperature; rather, both layers only show varied decreases in temperature. Beyond 100 km lies the thermosphere, but it's not of concern in this study. From the individual profiles, it is clear that latitude indeed plays a significant role in the thermal structure of the Venus atmosphere. For all the profiles, the longitude range is set between 40-50 degrees to exclude the impact of longitudinal variation.

In figure 5.4the previously discussed profiles are combined onto a single plot to provide a clearer understanding of temperature variability with altitude. Here, the two lower latitude profiles are represented by solid lines, the mid-latitudes by dash-dot lines, and the high latitudes by dashed

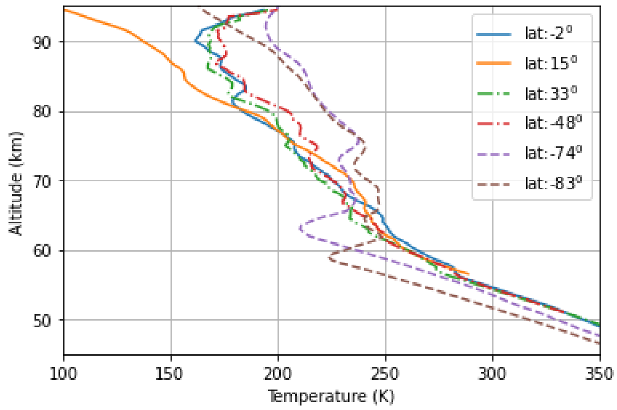


Figure 5.4: Combined plot of Temperature profiles at low, mid and high latitudes

lines. Comparing with the lower or equatorial latitudes, the higher latitudes exhibit a decrease in temperature below 70 km and a rise in temperature above 70 km with increasing latitude values. However, these individual profiles cannot provide a clear view of atmospheric variation, as there could be an event on that particular day causing such variation. To obtain a broader view and a more explicit understanding of the temperature variation with latitude, a contour plot of Latitude-altitude distribution of temperature has been plotted.

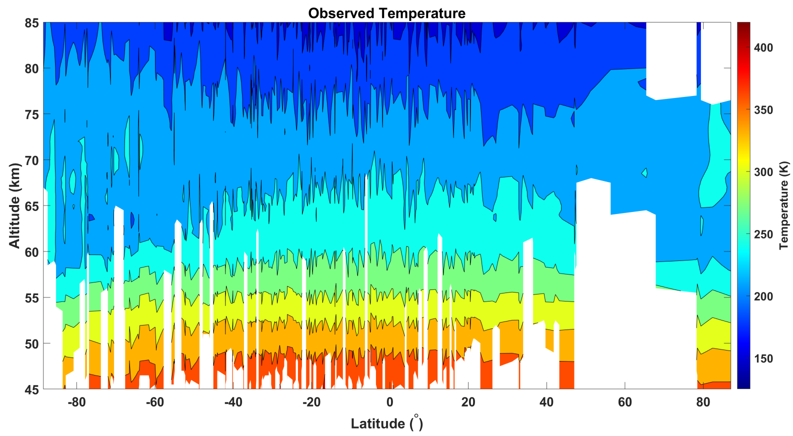


Figure 5.5: Latitude-height distribution of temperature obtained from VEX and Akatsuki radio occultation measurements

The contour plot encompasses all available data from 2006 to 2022 via Radio Occulation measurements, showcasing the temperature's dependency on both latitude and height. At lower altitudes, data gaps are apparent, resulting in discontinuities in the plot and visible white spaces. Additionally, as noted in figure 5.1 illustrating the spatial distribution, insufficient data in the northern hemisphere leads to significant gaps,hampering the study of polar regions.

From the plot, it's evident that temperature experiences a drastic increase at lower altitudes, with nearly a 100K change within a span of 10 km, specifically from 45-55 km. Beyond this range, the temperature decreases at a slower rate relative to altitude, but the influence of latitude becomes more prominent. Notably, between altitudes 60-65 km, the equatorial region exhibits higher temperatures compared to the poles, with temperatures decreasing as latitude increases, forming an inverted "U" curve across latitudes.

Between altitudes 60-75 km, regions with temperatures around 250K (illustrated by turquoise color) are observable at the polar regions, surrounded by cooler regions with temperatures around 200K. Notably, between 70-80 km, a contrasting behavior to the observations at lower altitudes emerges. Here, temperatures are lower at lower latitudes and higher at extreme latitudes, shaping the temperature profile to resemble a "U" shape.

5.2.2 Longitudinal temperature variation

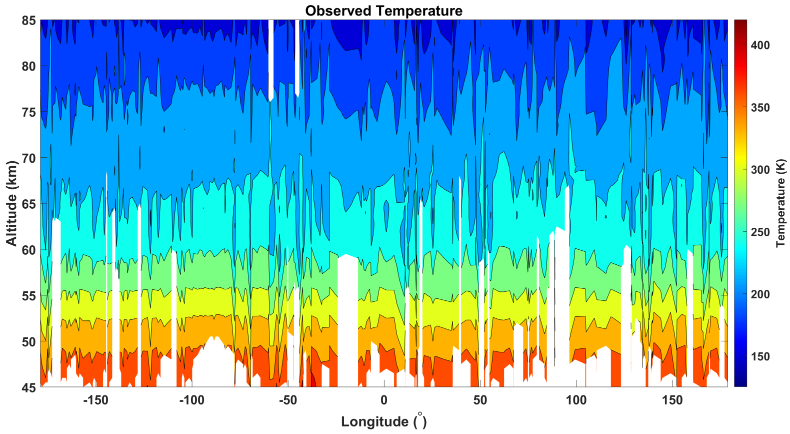


Figure 5.6: Longitudinal distribution of temperature obtained from VEX and Akatsuki radio occultation measurements

Temperature variation due to longitude on Venus is primarily influenced by topography and wind patterns. Notably, certain regions on Venus, such as Ishtar Terra spanning from -60 E to 75 E, Aphrodite Terra ranging from 60 E to 150 E, and Lada Terra from -60 E to 90 E, have been highlighted for their size and extent.

The contour plot illustrates the temperature's dependence on both longitude and altitude. Similar to the latitude plot, at lower altitudes, white gaps depicting NaN values are present. Interestingly, no significant variation of temperature with longitude is observed; however, the change in temperature with altitude is consistent across the longitudes. Minor fluctuations are visible throughout in temperature.

Remarkably, between 60-65 km at approximately ±50 E, 150 E, and near 0 E, significant fluctuations are observed, indicating deep drops in temperature between 60-65 km altitude.

5.2.3 Temporal Temperature Fluctuations

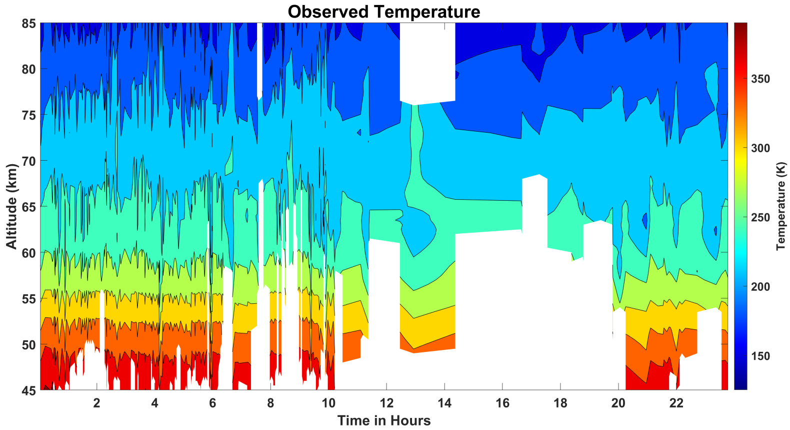


Figure 5.7: Temporal distribution of temperature obtained from VEX and Akatsuki radio occultation measurements

The temperature dependence on the time of observation in UTC is presented in the above figure. After midday, huge data gaps are visible at the lower altitudes. From midnight (00:00 am) till noon (12:00 noon), numerous small fluctuations are evident. Beyond noon, the fluctuations reduce significantly. A peculiar feature is observed from noon to afternoon (12:00 to 2:00 pm) between 60-65 km altitude, encircling a colder region. Due to insufficient data and possibly interpolation, such a feature might have occurred. However, the real reason is unknown and has not been observed before.

5.3 Analysis of solar zenith angle impact on temperature profiles

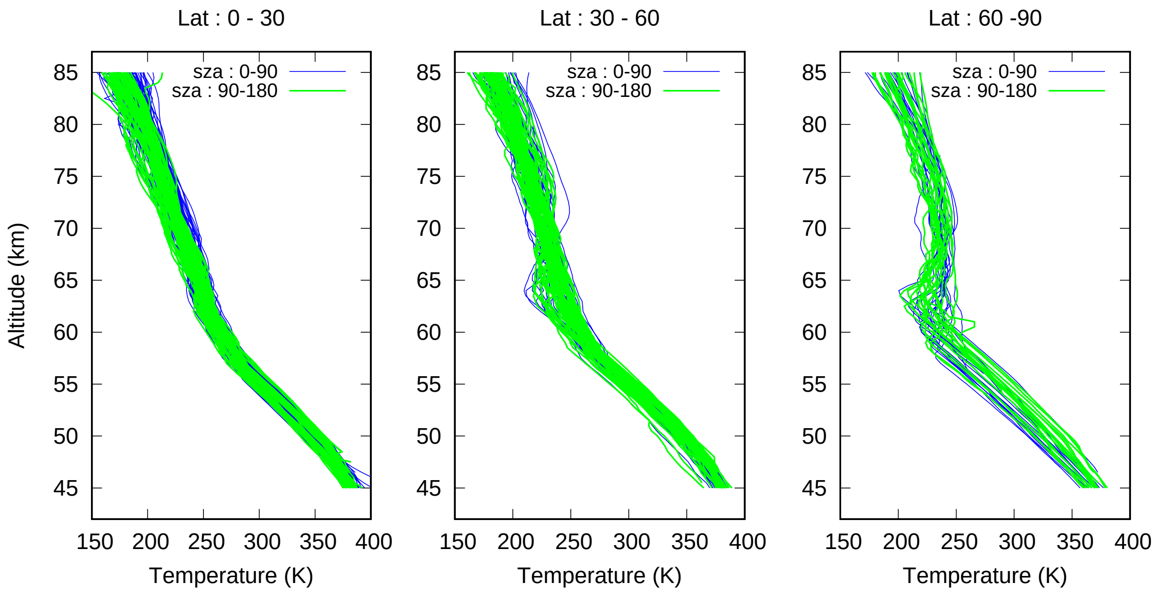


Figure 5.8: Comparison of temperature obtained from radio occultation measurements with respect to the solar zenith angle within latitudinal ranges (a) 0^o-30^o (b) 30^o-60^o (c) 60^o-90^o

We have examined the variation of temperature concerning both latitude and longitude. However, it's essential to consider other factors such as the solar zenith angle (SZA) that could impact these temperature changes. To investigate the influence of solar zenith angle, a plot combining all profiles has been constructed.

The plot aims to explore the dependency of temperature profiles on solar zenith angle across different latitudinal bands (0-30, 30-60, 60-90 degrees), minimizing the impact of latitude while recognizing the insignificant longitudinal variation. This analysis seeks to understand how the transition from day to night, as indicated by changes in SZA, affects temperature variations at various latitudes. By categorizing the temperature profiles within each latitude range based on SZA (¡90 for morning to noon and ¿90 for midday to dusk), the plot facilitates a focused examination of diurnal variations across latitudinal zones, offering insights into the dynamic behavior of Venus' atmosphere.

However, as observed from the plot, in the lower latitude bin (0-30 degrees), the dependence on solar zenith angle is not evident below 60 km altitude. Yet, a slight increase in temperature for solar zenith angles less than 90 is observed at higher altitudes. In the latitude range of 30-60 degrees, temperature fluctuations showing both decreases and increases concerning solar zenith angles less than 90 are only apparent at altitudes of 60 km and above compared to solar zenith angles greater than 90. For latitudes ranging from 60-90 degrees, temperature fluctuations are more pronounced. Since the dependence on solar zenith angle is not prominent across all three latitude bins, we cannot conclusively assert that solar zenith angle impacts the temperature profiles. Previous studies have primarily focused on observing and considering solar zenith angle at higher altitudes.

5.4 Tropopause

[9] defined the tropopause as the altitude at which the lapse rate shows a significant decrease. Since static stability as in equation 3.3.1 is the dry adiabatic lapse rate (≈ -10K/km subtracted from the observed lapse rate, the tropopause height can be also estimated from static stability profiles. From previous studies,tropopause height was calculated by setting a threshold, where the tropopause altitude is the point where the absolute static stability exceeds 8K/Km [9] or the lapse rate dT/dz is greater than -8K/km [24]. The reason for selecting this cutoff is not mentioned. However,to check if any other threshold value would suit better, the threshold value was changed to 6, 7, 7.5, 8, 9 K/km and even setting the condition as the first point of minimum static stability. The condition that suited most profiles was $S > 8$K/km or $dT/dz > 8$K/km, thus maintaining consistency with previous studies.

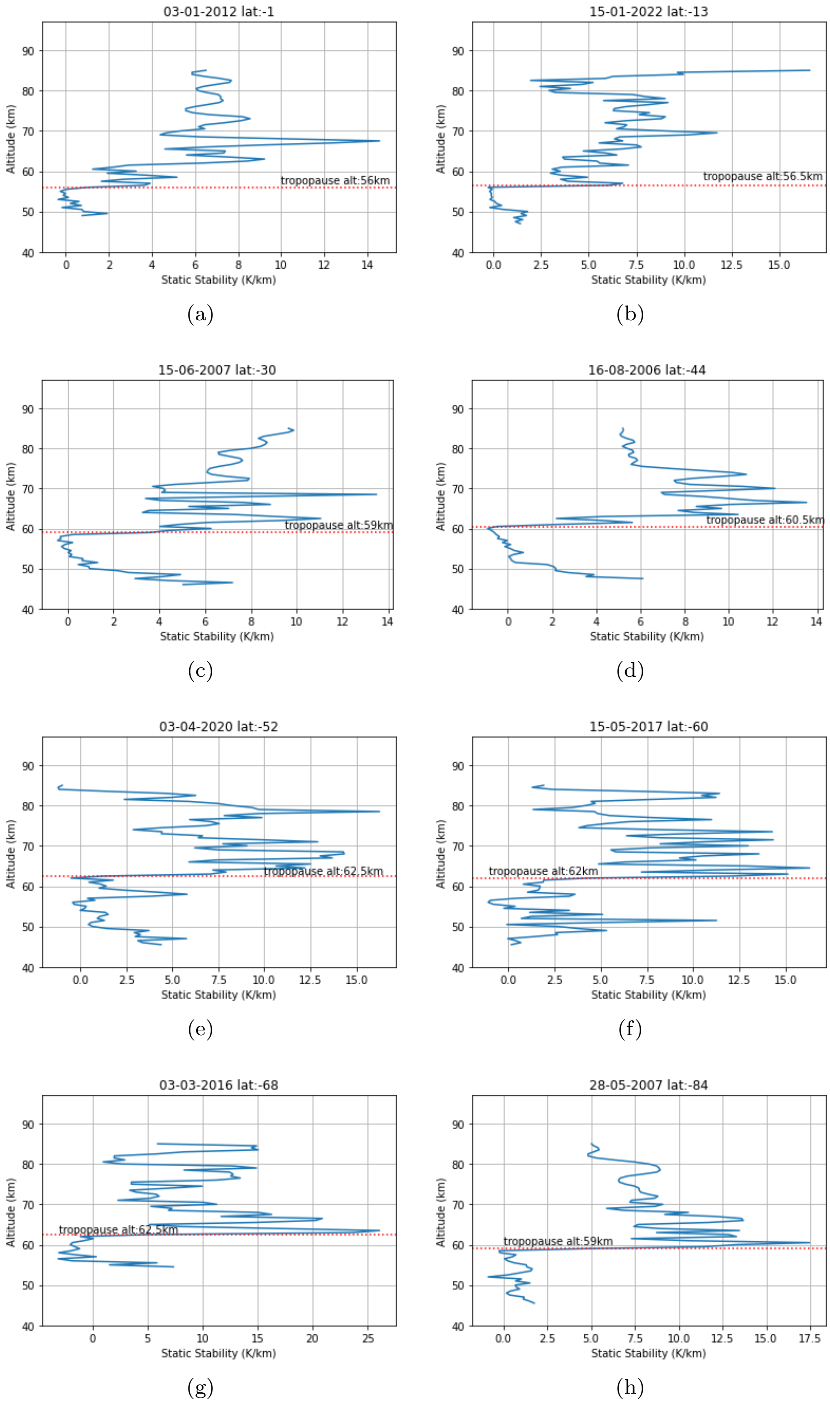


Figure 5.9: Tropopause height variation for individual profiles at varying latitudes

The tropopause height in the above figure 5.9 is manually selected, where we identify the point exhibiting a sudden increase in static stability. Locating the tropopause height at lower latitudes poses a challenge due to the weakened tropopause at equatorial latitudes, where the transition from troposphere to mesosphere is not prominent. Nonetheless, at lower latitudes, the tropopause height was found to be 65 km and 65.5 km (a) and (b), respectively. Moving to mid-latitudes, we observe an elevation in the tropopause height to 59 km for latitude -30 degrees and 60.5 km for latitude -44 degrees, as visible in figures (c) and (d).

Subsequent latitudinal profiles further underscore the dynamic nature of tropopause altitude. For latitude values (e) -52 degrees and (f) -60 degrees, and (g) -68 degrees in figure 5.9, the tropopause altitude continues the increasing trend, reaching a maximum of 62.5 km. At latitude -84 degrees, the tropopause height drops to 59 km.

As seen in (a) for lower latitudes, the condition S¿-8K/km does not hold true. Complementing previous findings, the tropopause is located at around 56 km in lower latitudes and increases with increasing latitudes until the cold collar region located at 70 degrees latitude, then dropping to as low as 50 km.

In the pursuit of understanding tropopause behavior, we must acknowledge the limitations of individual profiles, as they provide a rough overview of the tropopause temperature dependence on latitude. For that reason, a wider dataset like that used in this study will enable a more nuanced understanding of the tropopause.

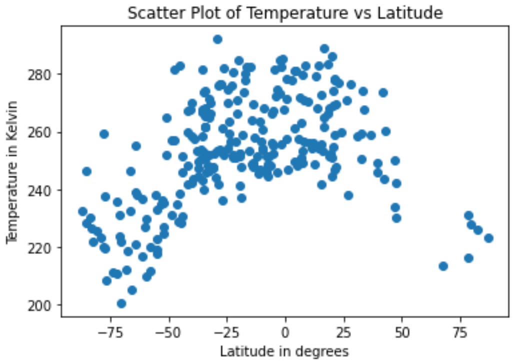
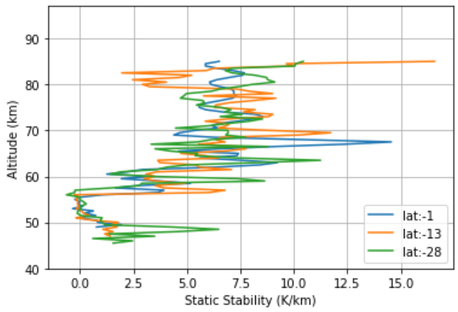


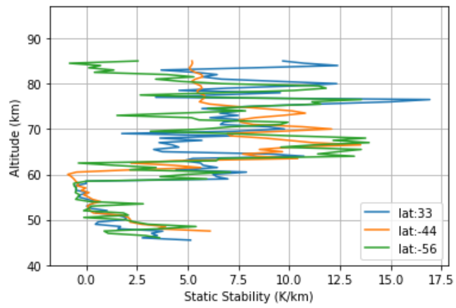
Figure 5.10: Tropopause temperature as a function of Latitude

The tropopause altitude was determined using the condition dT/dz >-8K/km, across all the profiles and visualised using scatter plot depicting the tropopause temperature as a function of latitude. As illustrated in the plot 5.10, at the equatorial latitudes a significant surge in temperature is observed ranging from 240-280K which gradually decreases towards the extreme latitudes, with a drop of up to 200K. At each latitude, the temperature of the tropopause should have exibited uniformity, with nearly overlapping points. But as visible in the figure the tropopause temperature is varying within a range of +- 20K for a given latitude.

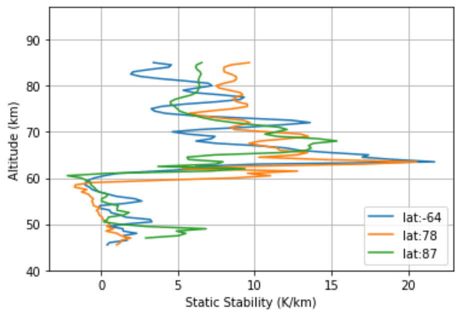
5.5 Static Stability across Latitudes



(a)



(b)



(c)

Figure 5.11: Trend in Static Stability with altitude for individual profiles at varying latitude ranges (a) 0^o-30^o (b) 30^o-60^o (c) 60^o-90^o

Static stability is a critical parameter in understanding atmospheric dynamics. When static stability is less than 1, it signifies an unstable convection region, while values greater than 1 indicate a stably stratified atmosphere. Further categorization of stable atmospheres includes low stability (0-1 K/km), moderately stratified (1-4 K/km), and highly stratified (¿4 K/km).

Examining the adiabatic behavior of the static stability profile can provide valuable information about radiative heating processes, cloud formation, and other atmospheric phenomena, shedding light on the underlying causes of varying static stability.

Although static stability is difference between the lapse rate dT/dz or the change in temperature with altitude and the dry adiabatic lapse rate (-10 K/km), it offers a unique perspective to interpret atmospheric conditions.

Implicitly studying static stability variation with altitude, profiles are sorted within the ranges of

0-30, 30-60, and 60-90 degrees latitude. From the figures it can be said that broadly the static stability remains stable across all altitudes, with a slight dip into negative stability between 50-60 km, indicating a shallow convective region.

While all profiles exhibit a similar trend and fluctuation is static stability across the latitude ranges, minor variations are noticeable within each range. Notably (a) for latitudes 0-30 degrees, stability decreases until approximately 60 km and then gradually increases with altitude. At higher latitudes, the transition from negative to highly positive stability is more pronounced. In (c), polar regions exhibit a peak in static stability between 60-65 km, followed by a decline at higher altitudes, whereas mid-latitudes in (b) demonstrate almost adiabatic static stability.

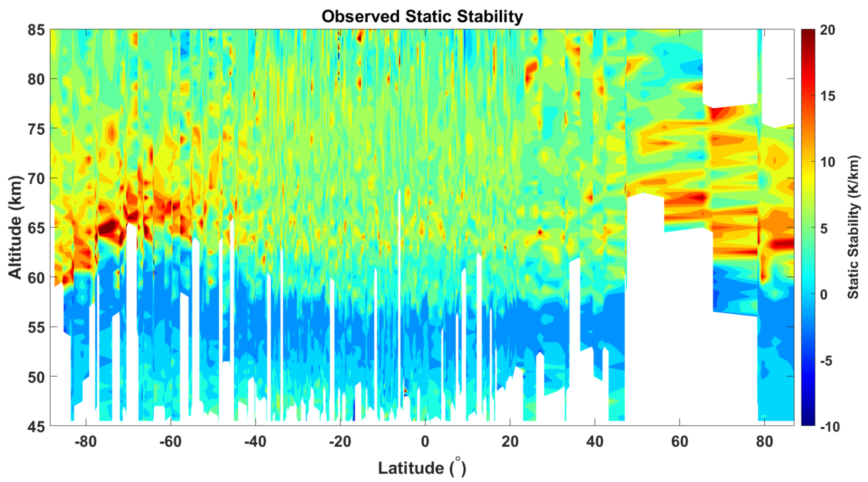


Figure 5.12: Latitude-height distribution of static stability

To delve deeper into the overall distribution of static stability, a contour plot illustrating the variation of static stability with latitude and altitude is presented. Observing the figure 5.12, the observed static stability profile shows low stability in the deep atmosphere, the region ranging from 45-50km in the equatorial region and spreading polewards till ≈ 55km. The static stability then drops to 0 to -5K/km, creating an unstable region which extends from 50 to 55km in the lower latitudes and opens out as it proceeds to higher latitudes becoming more prominent.The altitude range of the unstable region shift higher (55-62km) gradually polewards, till around 70^0 latitude and then takes a turn downwards at still higher latitudes. Beyond this height, the lower latitudes, $0^o - 40^o$ show a moderate static stability with slight increased stability fluctuations. In the southern hemisphere, between $40^o - 90^o$, a highly stratified layer is observed (≈ 7 and above K/km, forming an inverted 'U' shape, peaking at $\approx 70^o$ and extending from 60 to 75km. However, in the northern hemisphere a similar trend can be seen but due to insufficient data and interpolated values we can't certainly say. At higher altitudes beyond 75km, a moderately stratified region envelopes all latitude ranges.

Although occasional fluctuations in static stability may arise due to errors in individual profiles and are thus considered negligible.

6 Models' Comparison with Observation

6.1 Overview of models

In the last two decades,Models have turned out to be very useful tools to studying Venus and the role of different phenomena in the angular momentum transfer. Several numerical simulations by different GCMs have already reproduced the main characteristic of the Venus that is super-rotating atmosphere. [?]

6.1.1 Venus General Circulation Model

The Venus Climate Database (VCD) is a database of atmospheric statistics compiled from state-of-the art Global Climate Model (GCM) simulations of the Venusian atmosphere. Although the average temperature field has been reproduced adequately, no model has satisfactorily simulated one of its most puzzling properties: the polar temperature distribution, formed by highly variable vortices and cold air areas that surround the vortices permanently. [25] used the IPSL (Institut Pierre Simon Laplace) Venus GCM, that has a full radiative transfer module, to model the Venus atmosphere paying a special attention to polar regions. Their zonally and temporally averaged latitudinal profiles showed a small cold collar signature at the cloud top (≈70 km), located slightly higher than observed. In order to perform an in-depth study of the Venus polar atmosphere and try to better understand the origin and nature of the cold collar and warm vortex, we have adapted the IPSL Venus GCM by taking into account the latitudinal variation of the cloud structure.[25], [14]

6.1.2 Venus Global Reference Atmosphere Model

In 1978, exploration of Venus was flooded with seven missions, Venera 11, 12 , Pioneer Venus Orbiter and four descent probes. Pioneer Venus Orbiter was the longest mission at Venus with 14 years of service.[26] The Pioneer Venus Orbiter (PVO) spacecraft orbited Venus between 1978 and 1992. Extensive data returned by PVO and the related atmospheric probes, together with results from the Venera and Mariner missions, provided the base for the Venus International Reference Atmosphere (VIRA) PV-ORO experiment. [8], [24] [9] As the exploration of Venus is again beginning to set an exponentially increasing curve, an atmospheric model that calculates the mean values and variation of the atmospheric parameters is much needed. A model that can predict the atmospheric conditions can help engineers, scientists and mission planners to design vehicles that are compatible for Venus and will facilitate in making the mission a success. The Venus Global Reference Atmospheric Model alias Venus-GRAM is an engineering oriented model that provides critical information about our twin planet. This is an empirical model and is based on the data obtained from missions like the Pioneer Venus Orbiter and a few probes (Venera series). Venus-GRAM is a model that had greatly impacted the science field by offering flexibility in obtaining a number of parameters like temperature, pressure, density, wind speeds, atmospheric compositions. As we know Venus atmosphere is made of $\approx$ 96 % CO_2 and $\approx$ 3% of N_2 , and a few more known and unknown gases. Apprehending the constituent gases and their contribution in the atmospheric dynamics is also crucial. Venus-GRAM provides the number density of gases like CO2,N2,O,CO,He,N,H. Venus-GRAM provides the flexibility to study the variation of all the above described parameters with local time, latitude, longitude, solar zenith angle, time, etc. Variability in thermodynamic parameters, winds and density are included in Venus-GRAM, where these parameters vary with altitude based on VIRA.

In the low-altitude (0-100 km), VIRA shows dependence is on height and latitude, whereas in the middle-atmosphere (100-150 km) it is dependent on height and local solar time and the upper-altitude (150-250 km) depends on height and solar zenith angle. Venus-GRAM insures smooth variation between height regions by averaging values at the two transition heights (i.e. low and middle data are averaged at 100 km, and middle and high data are averaged at 150 km. For heights up to 100km, mean values of parameters determined are from VIRA data for latitudes less than 30^o. At higher altitudes 100 to 150 km mean values are from an average of VIRA daytime LST=12hr and nightime LST=0hr data. For still higher altitudes (150-250km) where the atmosphere shows solar dependence, mean values are from VIRA data for a Solar Zenith angle of 90^o. Solar Zenith angle changes are significant above about 150km. Variation of atmospheric density with solar activity is non- significant. Since it density variation during solar maxima and solar minima is $\approx$ 1.6 whereas for Earth it is $\approx$ 6.9. Due to the small dependence of density variation on solar activity, the solar zenith angle variation has not been explicitly included in the model.

A major limitation of Venus-GRAM is that it does not have a built-in solar flux dependence, so no further corrections can be done to fit the data to real observing conditions. The VIRA model tabulates density and temperature values at a fixed value of F10.7 $\approx$ 150

6.2 Comparison of observed data with model predictions

6.2.1 Comparison of Temperature: Models with RO measurements

To assess the credibility of models in predicting the Venus atmosphere, we first analyze the primary parameter, temperature, which exhibits significant dependence on latitude and altitude. The figure compares temperature profiles derived from (a) radio occultation data by VEX and Akatsuki, (b) VCD theoretical model, and (c) VenusGRAM empirical model.

In (a), missing data at the northern polar latitudes is noticeable, which impacts the study. To address this, we assume symmetry based on findings from [27]. Both models depict the prominent feature of the latitude-height distribution, namely the cold collar, with no significant deviation from observed profiles apparent. However, temperature fluctuations visible in the observed data are reproduced by VCD , whereas VenusGRAM produces a smoother contour plot, as its values are averaged.

Since no conclusive findings have emerged from the contour plots, examining individual profiles will provide a better understanding of model predictions.

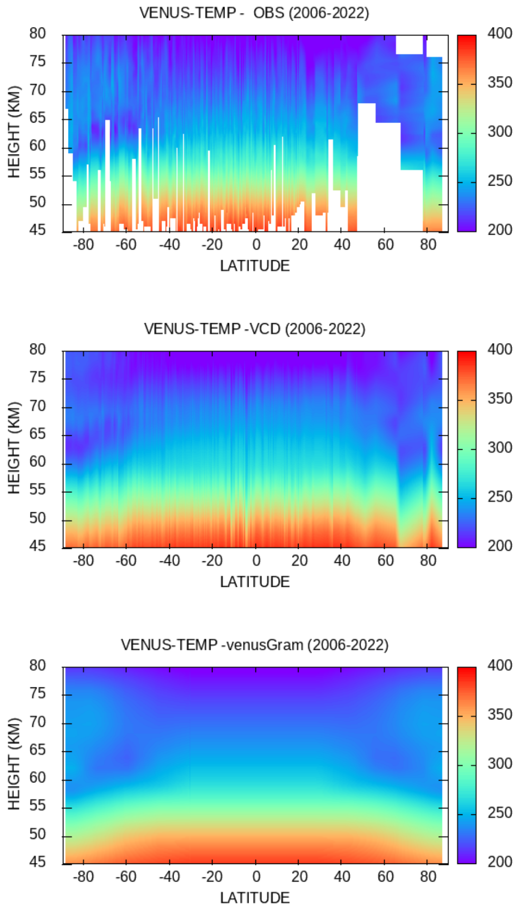


Figure 6.1: Latitude-height distribution of temperature for (a) measured(b) VCD (c) VenusGRAM

Examining individual profiles is crucial as it provides a detailed understanding of the specific regions within the atmosphere where discrepancies between observed data and models are most pronounced. By inspecting these individual profiles, researchers can identify areas of potential improvement in

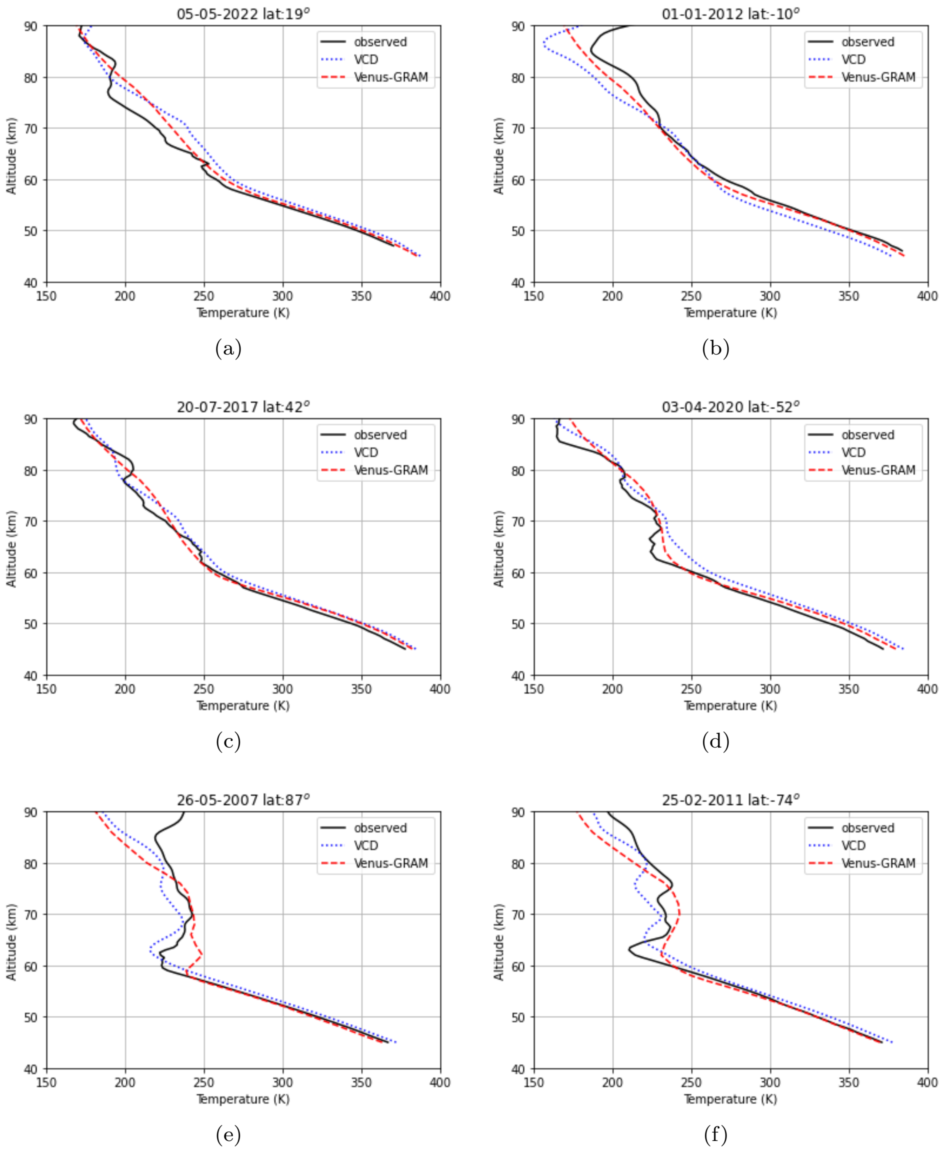


Figure 6.2: Comparision of individual Temperature profiles at varying latitudes

model representations and refine our comprehension of atmospheric dynamics and processes. Figure 4 presents individual profiles comparing Radio Occultation measurements, Venus Climate Database (VCD), and Venus-GRAM across various latitudes and solar zenith angles. Within the altitude range of approximately 0 to 60 kilometers, the models closely match the observed data in most of the cases. However, notable deviations between the observed data and models emerge within the altitude range corresponding to the tropopause (58-65 km), particularly at higher latitudes.

6.2.2 Examination of temperature difference between observed and modeled data

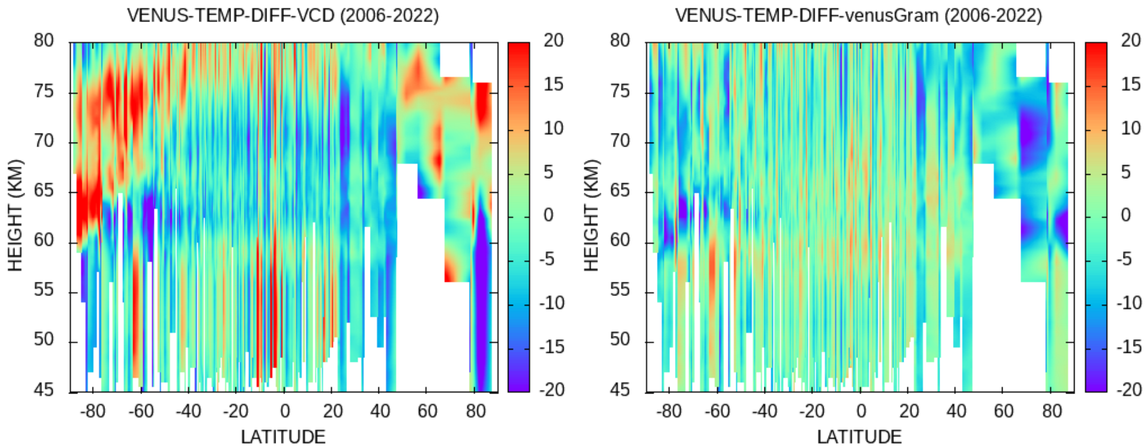


Figure 6.3: Latitude – height distribution showing discrepancy between RO observed data and models: Left for Venus Climate Database (GCM) and right for Venus-GRAM

The temperature differences between observed and modeled data are evident, particularly towards the poles. Notably, the Venus Climate Database (VCD) model demonstrates disparities of approximately 20K,particularly pronounced at higher latitudes. In contrast, the empirical model displays a remarkable level of accuracy, albeit with slight over-estimations in specific altitude ranges. However, it's important to note that conclusive results cannot be drawn from the northern hemisphere due to insufficient data. This data gap poses a challenge in fully understanding temperature dynamics in this region and warrants further investigation to enhance our understanding of atmospheric processes across the entire planet.

6.3 Correlation of Models with RO measurements

Correlation tells us how closely related any two variables are. Correlation coefficient is a statistic measure used to determine the strength of linear relationship between variables. The correlation is measure on a scale from -1 to 1, with 1 showing high positive correlation. Whereas, -1 conveying high negative correlation and zero, no correlation at all. This statistical measure can help understand how well the models predict the observed parameters.

6.3.1 Temperature

Since our study is mainly inclined towards temperature analysis, the correlation between temperature observed and modelled will provide valuable insights into the accuracy of the models.

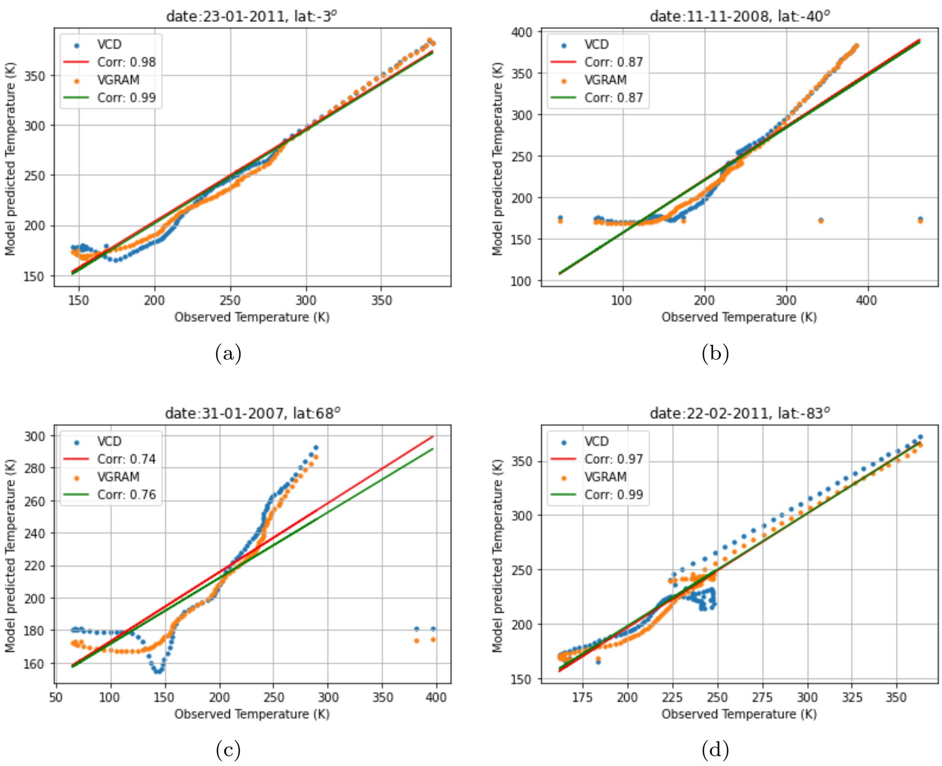


Figure 6.4: Correlation of temperature of individual profiles: Modelled vs Observed

Individual profiles are carefully selected to provide an overview spanning all latitudes. As illustrated in the figure 6.4, (a) -3^o latitude depicting the equatorial region, exhibits very high correlation.

In (b) and (c), representing the mid and lower polar latitudes, there is a decrease in correlation, although a fairly strong positive correlation is observed at (b)-44^o latitude, and a significant positive relationship at (c) -68^o latitude. Surprisingly, in (d) with latitude -83^o, the correlation peaks again.

This correlation dip could be due to the presence of cold collar or temperature inversion that begins at approximately 40^o latitude and reaches its maximum around 70^o latitude. Though both models, VCD and Venus-GRAM show similar correlation, Venus-GRAM performs better than VCD.

6.3.2 Static Stability

Static stability is determined from the change in temperature with altitude. Expecting this eminent parameter, static stability to be correlated too.The same profiles as in the analysis for temperature correlation are used to study the correlation of static stability between models namely, VCD and Venus-GRAM and the observation. However, as reflected in the figure6.5, there is a significant drop in the correlation in comparison to temperature profiles. In figure 6.5, (a)lat:-3^o and (b) lat:-40^o, the correlation is significant and positive with correlation of ≈ 0.7.In (c) lat: -68^o the correlation of Venus-GRAM is 0.62 showing a moderate positive correlation but VCD poorly related to observation with correlation coefficient of 0.44. Whereas in (d)lat:-83^o, Venus-GRAM performs well with correlation coefficient of 0.86 revealing strong and positive correlation and VCD with correlation coefficient 0.53 performs poorly. Overall, Venus-GRAM shows better correlation with observations than VCD.

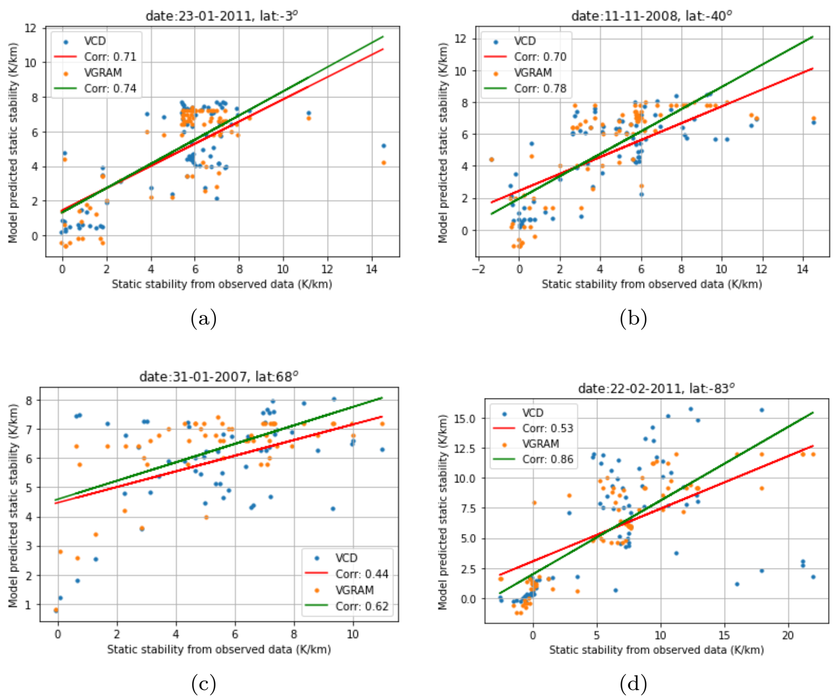
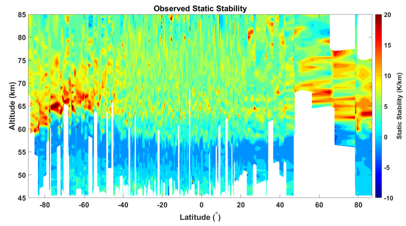


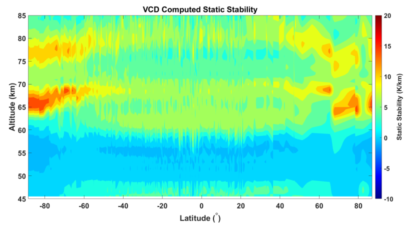
Figure 6.5: Correlation of static stability of individual profiles: Models vs Observed

6.4 Comparison of Static Stability: Models with RO measurements

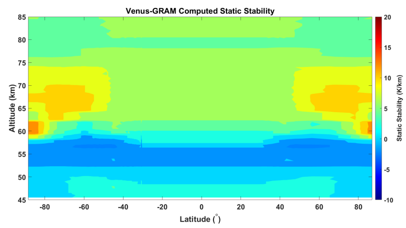
From temperature comparison of observed and modelled data Figure 6.1 the computed temperature change with latitude and height resembled the observed data remarkably. Since, the correlation of static stability was low when representing the latitude -height distribution of Static Stability for all profiles, all 3 plots tell a different story yet with some overview similarity . In the figure 6.6 (a), the observed static stability profile shows low stability in the deep atmosphere, the region ranging from 45-50km in the equatorial region and spreading polewards till $\approx$ 55km. The static stability then drops to 0 to -5K/km, creating an unstable region which extends from 50 to 55km in the lower latitudes and opens out as it proceeds to higher latitudes becoming more prominent.The altitude range of the unstable region shift higher (55-62km) gradually polewards, till around 70^0 latitude and then takes a turn downwards at still higher latitudes. Beyond this height, the lower latitudes, $0^o - 40^o$ show a moderate static stability with slight increased stability fluctuations. In the southern hemisphere, between $40^o - 90^o$, a highly stratified layer is observed ($\approx$ 7 and above K/km, forming an inverted 'U' shape, peaking at $\approx 70^o$ and extending from 60 to 75km. However, in the northern hemisphere a similar trend can be seen but due to insufficient data and interpolated values we can't certainly say. At higher altitudes beyond 75km, a moderately stratified region envelopes all latitude ranges.



(a)



(b)



(c)

Figure 6.6: Static Stability distribution as a function of Latitude and Altitude (a)Observed (b)VCD (c)Venus-GRAM

In figure 6.6(b) the static stability computed by the theoretical model, Venus Climate Database developed by LMD/IPSL and based on General circulation model. Below 50km, within the range 0^o-60^o in both hemispheres, an area of moderate static stability ($>$ 0 K/km and $<$5K/km) is distinguishable. Above that a broad unstable extends consistently from the equator to the poles of width $\approx$ 10km (from 50-60km) in penetrates below 50km at the poles. Exceeding 60km altitude a moderate static stability is observed except need the polar regions where two regions of high static stability are prominent at either of the poles. The lower highly stable region (S $\approx$15K/km) region beginning from the southern pole $\approx$63km till 70km and narrows while traversing to the lower latitudes, till it shifts to moderate stability at -40^o latitude. A similar structure is noticed between 75 to 80km but slightly lower stability (10K/km) than the prior mention stable region ($\approx$ 15K/km).

7 DISCUSSION

The attempt to understand the thermal structure of Venus' atmosphere has been hindered due to the thick cloud structure and limitations of technology to sustain its extreme conditions. But with every passing mission, followed by studies of the data, we are getting to know this baffling planet better. Radio Occultation providing reliable data in the lower atmosphere, especially in the cloud region where analysis of the atmosphere is challenging. However, with empirical model that average and interpolate to devise the atmosphere is areas where observational data is not available, and theoretical models that understand the dynamics and compute the atmospheric parameters, our understanding of Venus has noticeably progressed.

7.1 Interpretation of observations

In section 4.2.1, we investigated the impact of latitude on temperature by examining selected profiles across different latitudes, contour plot of all the data across latitudes We found that at lower latitudes, thee temperature decrease follows a linear pattern, whereas at higher latitudes, there is a noticeable temperature drop at approximately 60 kilometers, near the tropopause. This phenomenon, known as the "cold collar," which surrounds a warm vortex at each pole, has been previously documented by researchers such as [9], [?], and [?] Both the cold collar and warm vortex exhibit non-uniformity along latitudinal lines. Studies by [?] and [?] suggest that thermal tides and residual meridional circulation contribute significantly to the formation of the cold collar. Additionally, [?] proposed that the polar vortex may result from neutral barotropic Rossby waves. Garate-Lopez (2018) has pointed out that variations in cloud structure along latitudes due to differing rates of solar heating and infrared cooling could also contribute to the formation of the cold collar and warm vortex. In section 4.2.2, longitudinal variation is not very prominent. However, significant fluctuations in temperature at deeper levels could potentially be attributed to topographical influences. When examining the time-dependent behavior of temperature, we observed pronounced fluctuations occurring around the 12-hour mark and earlier, whereas fluctuations later on were comparatively less pronounced. Solar heating appears to be a plausible factor contributing to this observed pattern. Upon analyzing individual profiles up to 60 kilometers, we observed that the temperature decrease exhibited minimal dependence on latitude and occurred at a faster rate. However, above 60 kilometers, fluctuations in the temperature profile could be attributed to the presence of gravity waves.

In section 4.4, we examined the variation in tropopause height with latitude. [?] used a threshold condition for defining the tropopause as the altitude where the absolute difference between the observed temperature lapse rate and the adiabatic lapse rate exceeds 8K/km. However, this condition proved unsuitable for lower latitudes. Using this threshold, tropopause height values did not align with previous findings, which suggested a tropopause height of approximately 56 kilometers at equatorial latitudes, increasing to around 62 kilometers in the "cold collar" latitudes (60-70), and then decreasing again in the polar regions. The tropopause was found to exhibit a weak structure. Analyzing temperature variations of the tropopause across latitudes revealed a decrease from a maximum in lower latitudes to a minimum near $\pm 70^o$, followed by an increase polewards. Insufficient data prevented the study of the two hemispheres separately.

In section 4.3, we ahve studied the static stability variation with latitude and height. In figure5.11 it is evident that at higher latitudes, static stability exhibits a distinct sudden increase at the tropopause, facilitating tropopause detection. Conversely, static stability decreases with altitude beyond the tropopause in polar latitudes. Meanwhile, mid-latitudes demonstrate an adiabatic region with substantial fluctuations in static stability and low latitudes do not show significant increase in static stability which makes the tropopause detection difficult due to the fluctuations. We examined the static stability, revealing a notably high stability atmosphere in the upper cloud layer (60 kilometers and above), particularly evident in polar regions. Between 50 to 60 kilometers, a convective or low stability region is apparent, which intensifies at the poles. These findings support previous studies by [?] and [?].

Previous research proposed that convective motions at 50-60 kilometers are driven by infrared heating at cloud bottoms and infrared cooling of cloud tops, with these processes being more pronounced in polar regions, potentially resulting in a thicker convective layer there. Another theory suggests that mean meridional circulation or wave activity influences thermal structure, with Rossby-like waves generated by baroclinic instability producing planetary-scale cloud features in low stability layers[?]. [?] specifically mentions that at low latitudes the mean meridional circulations and disturbances contribute to the static stability variation and at mid and high latitudes the planetary scale atmospheric waves.

7.2 Insights into model performance and limitations

Modeling plays a pivotal role in unraveling the complexities of the atmosphere. Empirical models are instrumental in computing atmospheric parameters in data-scarce regions, offering insights into atmospheric dynamics. In comparative studies, it was observed that an empirical model based on 18th-century data performs adequately, but updating it with recent mission data could yield impressive results due to the broader dataset available. Venus-GRAM, a Fortran-based model, is user-friendly, yet incorporating multiple programming languages could enhance its capabilities. Additionally, considering factors like solar zenith angle and solar flux could further improve its accuracy. Theoretical models have evolved with ongoing research, providing deeper insights into atmospheric behavior. These models have successfully reproduced phenomena such as the cold collar by accounting for thermal tides, residual meridional circulation, barotropic Rossby waves, Hadley circulation, and superrotation. However, studying the Venus atmosphere with limited access remains a trial-and-error process. Static stability, influenced by factors like infrared heating and cooling, mean meridional circulation, and wave activity, poses challenges in theoretical modeling. Despite considering numerous parameters, modeling static stability remains a challenge. However, ongoing studies aim to enhance our understanding of Venus, referred to as Earth's "toxic twin."

7.3 Future scope

Scientists have developed instruments and techniques most suited of Venus, that can penetrate its thick cloud cover and provide valuable data about temperature profiles in its lower atmosphere. From remote sensing technologies to advanced modeling, these innovative approaches offer exciting possibilities to gain a deeper understanding of Venus' atmospheric dynamics.

Observations from individual profiles indicate temperature fluctuations above 60 kilometers, the underlying cause of which remains elusive. However, theories suggest that gravity waves may play a role. Investigating the potential energy of these waves based on temperature profiles presents a promising avenue for future research. Additionally, exploring the impact of solar cycles on temperature profiles could provide valuable insights, given the data span from 2006 to 2022. The lack of data in the northern hemisphere has limited our ability to assess whether static stability or tropopause height is symmetric at the poles. With sufficient data, conducting a more comprehensive study to address these questions becomes feasible.

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