



**IMPROVED PERFORMANCE BY THE TIE-GCM
WITH THE INCLUSION OF HELIUM AS A MAJOR
SPECIES**

THESIS

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AFIT-ENP-MS-16-M-081

**DEPARTMENT OF THE AIR FORCE
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Captain, USAF

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Abstract

When considering the neutral constituents in the upper thermosphere and exosphere, helium needs to be accounted for as a major species. As detailed by Emmert [2015], most first-principle models do not consider helium a major species when solving for diffusion and collisions within the atmosphere. First-principle, physics-based models hold a distinct advantage of seasonal variations and spatial resolution over empirical models which leads to a more realistic depiction of the atmosphere. The National Center for Atmospheric Research's (NCAR) self-consistent, physics-based Thermosphere-Ionosphere-Electrodynamic General Circulation Model (TIE-GCM) has been updated to take into account this neutral constituent in its calculations. A prior study by Kim [2011] shows over a 50% root mean square improvement in the neutral density values of the TIE-GCM when compared to the CHAMP satellite neutral densities when helium is included. This study incorporated weighted partial pressures of helium from the Naval Research Laboratory's Mass Spectrometer Incoherent Scatter Extension 2000 (NRLMSISE-00), an empirical model. This current research studied the difference in the TIE-GCM with helium calculated directly as a major species in the composition equation and scale height equations by Sutton [2015]. The major goal was to characterize this change to the TIE-GCM as a function of altitude as helium becomes a dominant species. A distinct improvement was found in the updated model during lower solar activity conditions and altitudes above 750 km altitudes.

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To my Wife

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Frederick R. Schmidt

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I. Introduction

1.1 General Issue

The accuracy of numerical models depicting atmospheric drag on satellites and other objects in the thermosphere and lower exosphere has been the focal point of scientists for over half a century. A 2012 National Research Council (NRC) report asserts that atmospheric drag is responsible for the largest amount of uncertainty in the position of low-perigee objects [31]. The majority of uncertainty results from the insufficiencies of modeling neutral density values in the atmosphere. Upper atmospheric modeling has been a common research focus over the last several years as many papers and studies have focused on improvements to existing models in the pursuit of higher precision of atmospheric drag [18, 45]. One of the earliest atmospheric drag models was created in 1962 by Luigi Jacchia [25], with several variations of his initial model being named after him years later [15, 18]. Other atmospheric models were created in the following decade with several improvements being incorporated over the last half century.

The primary intentions of atmospheric drag models are to reproduce the mass density of the atmosphere in the vicinity of a low earth orbit (LEO) satellite, enabling the

prediction of the satellite's precise orbits [15]. Precise orbits are determined from the prognostication of satellite trajectories and can vary significantly with sudden changes to the neutral density. Changes to the atmospheric neutral density vary due to solar and geomagnetic activity, and in order to have relevant, real-time information, all atmospheric drag models ingest real-time and/or predicted solar and geophysical parameters. At a minimum, the model will require a solar flux proxy – typically F10.7 is used – and a geomagnetic index such as K_p or A_p [18, 43, 45].

The current atmospheric drag models are used in the tracking of satellite debris and orbit prediction. One example includes NASA and its use of the LEO-to-GEO Environmental Debris (LEGEND) model and Orbital Debris Engineering Model (ORDEM) 3.0 to predict the location of space debris to avoid collisions with satellites or rocket launches [37]. This is incorporated with the United States Air Force (USAF) Strategic Command's (STRATCOM) Space Surveillance Network (SSN). As of 2008, over 18,500 objects are being tracked by the SSN [28]. However, there are still issues with tracking both debris and satellite orbits.

Two recent, highly publicized events involving space debris display the need for improved tracking. Coincidentally, both involve Russian COSMOS satellites. The first is the COSMOS 2421 (C2421) threatening the International Space Station (ISS), and the second is the COSMOS 2251 (C2251) colliding with the American commercial satellite Iridium 33 [23, 29].

The first incident occurred on June 2008 when parts of the C2421 fractured into several smaller pieces and were projected to collide with the ISS [29]. This potential impact forced operators to initiate a maneuver of the space station to reduce the risk of

impact with the satellite's space debris. Ultimately it was a false alarm, and it was determined that no action was required. However, it resulted in wasted fuel to maneuver the ISS to a lower orbit and return it after the threat had passed and the countless man-hours involved in executing the maneuver.

The second incident was an actual collision between two satellites. The collision of the C2251 with the Iridium 33 destroyed both satellites and caused a disruption of service to the Iridium communication company [23]. The short-term collateral was millions of dollars in equipment and transport. However, this event also resulted in over 1000 pieces of additional debris, increasing the overall probability of future collisions in LEO for decades to come. Both cases show the costly expense from the uncertainty that still exists today in locating objects in orbit that are affected by the drag force.

The improvement of atmospheric drag models for this purpose has been an ongoing research topic for the last half century [40]. As Vallado [45] points out, atmospheric models today still do not solve all our problems, and now there are many more to choose from [40]. Unfortunately, the majority of the models have reached a plateau in their improvement of depicting satellite drag. An analysis in 2005 showed that empirical models used to calculate thermospheric density are only able to achieve root mean squares (RMS) accuracies of 15-30% [30]. This has only improved very slightly as of today and has motivated some researchers to focus on a physics-based approach for thermospheric models. This study will take a first principles model and attempt to improve its performance in the upper thermosphere and lower exosphere regions of the atmosphere.

In order to improve an atmospheric drag model, it is important to identify the difficulty in calculating the atmospheric drag force. The drag force per mass, α , is given by

$$\alpha = \frac{1}{2} C_d \left(\frac{A}{M} \right) \rho V_s^2 \quad (1)$$

where C_d is the drag coefficient, A , is the area of the satellite, M is the mass of the satellite, ρ is the neutral density, and V_s is the velocity of the satellite. The atmospheric drag force is the force on an object that occurs when moving through the atmosphere. It is dependent on the number of particles in the atmosphere, which decreases with increasing altitude. The drag force per mass (acceleration) will take away energy from the orbit and ultimately decrease the orbital period. The variables listed above all contribute to the atmospheric drag acceleration calculation. However, the neutral mass density, ρ , is the biggest contribution and is the reason for atmospheric drag research over the past half century.

Neutral mass density is an account of the number of particles and their masses within a given volume. This does not include ions or electrons, which are several orders of magnitude less than the neutral density. Neutral mass density is extremely important because it introduces the largest uncertainty for LEO satellites. For simplicity, neutral mass density will be referred to a neutral density in this paper. Neutral density is difficult to determine due to the inability to directly measure the microscopic, physical quantity. It becomes even more difficult to indirectly measure a quantity due to a constantly varying, dynamic atmosphere. The information researchers have on these values is based upon indirectly derivations from the orbits of objects in the atmosphere, as will be covered in

Chapter II. The difficulty for researchers is the actual amount of accurate data available. However, this stems from the greater challenge of a satellite's orbit determination, which is pivotal to indirectly deriving neutral density values.

1.2 Research Focus and Motivation

As the drag force per mass equation (1) shows, several uncertainties arise from each term. The goal of this research is to focus on the neutral density variability, because it typically dominates the other variables in LEO. The first priority is finding accurate neutral density values that can be used for comparison purposes. As mentioned in section 1.1, there are two main methods that are used to acquire these values [21, 30]. This study uses data sets derived from the onboard accelerometer of the CHAllenging Mini-satellite Payload (CHAMP) and the Gravity and Recovery Climate Experiment (GRACE) satellites. Additionally, a ground-based orbit determination technique for spherically shaped satellites that indirectly derives accurate neutral density values is used. These datasets are treated as a comparison tool for model verification.

The model of choice for this research is a three-dimensional, first-principle, physics-based model called the Thermosphere-Ionosphere-Electrodynamics General Circulation Model (TIE-GCM). The model solves three-dimension momentum, Eulerian continuity, energy, and the aforementioned composition equation. In its most current version from NCAR, the TIE-GCM includes three major neutral species used in the composition equations (nitrogen (N_2), molecular oxygen (O_2) and atomic oxygen (O)) and three minor species: nitric oxide, atomic nitrogen, and excited atomic nitrogen [18, 38, 44]. The model ranges from 97 km to approximately 600 km, with the upper

boundary being dependent on solar conditions. The solar forcing can be specified by measurements or proxy models. The solar parameter input is the F10.7 daily index and the K_p index.

The objective of this research is to validate the TIE-GCM with the addition of helium (He) as major species accomplished by Sutton et al. [38]. A similar study was done by Kim et al. [27], but a different method of comparing the data was used. Kim's study involved a comparison with accelerometer-derived neutral densities from the CHAMP satellite, as well as with the empirical Mass Spectrometer Incoherent Scatter (MSIS) model. In his study, helium was added into the TIE-GCM via the MSIS. He showed that there is an increase in the metric accuracy of the TIE-GCM's neutral density with the addition of helium.

This study also attempts to show improvement to the accuracy of the TIE-GCM neutral density with the addition of helium through a self-consistent solution as described by Sutton et al. [38]. He updated the TIE-GCM to include helium as a major species in the composition equation which provides the self-consistent solution [38]. In order to verify any improvement, a direct comparison of the neutral density at varying satellite altitudes was made between the two iterations of the TIE-GCM. The iterations of the TIE-GCM refer to the model currently released by NCAR and the version updated with helium as a major species by Sutton et al. [38]. A wide range of satellites with various altitudes was acquired to analyze the difference in neutral density values at these heights. The change in the model from helium will differ at increasing altitudes which will be explained further in Chapter II. The satellite altitudes range from the lower boundary of the TIE-GCM including CHAMP (454 km) and GRACE (500 km), to the mid and upper

boundary of the model which includes the RIGIDSPHERE (770 km) and the CALSPHERE 1 (1010 km) with the latter two described in perigee height. In all, nine satellite datasets are available for comparison.

An improvement in the TIE-GCM would be the next step in the progression of first principle models to match the performance of their empirical counterpart. As Sutton et al. [38] indicates: ‘the TIE-GCM can simulate physical phenomena that have only previously been observed, such as the “winter helium bulge”’. The model’s capability to reproduce observed atmospheric features is important for advancements in research. Given enough improvement, the TIE-GCM could eventually outperform and replace current empirical models used operationally by the Air Force [42].

II. Background

There are many atmospheric drag models currently being used today for research and operations. The majority of these models aim to calculate neutral density, but they often use different methods to accomplish this feat. It is important to recognize how these models determine neutral density, because it plays a key role in improving an existing model. This paper focuses on the Thermosphere-Ionosphere-Electrodynamic General Circulation Model (TIE-GCM), and thus understanding this model's origin and progression will help explain the efforts being taken to improve it in this study. Since it is extremely difficult to directly measure total neutral density, indirect methods are used as an alternative. In order to verify the extent to which the model is improved, accurate neutral density values were acquired. This study utilizes two distinct and highly accurate data sets from completely different techniques, which will provide a good comparison tool for upper atmospheric model performance.

2.1 Introduction to Satellite Forces

The desire for atmospheric drag models became a field of research and development as soon as satellites were launched into orbit in 1957 [24, 25]. Scientists observed variations in the satellite orbits and sought to explain this deviation. In late 1959, Luigi Jacchia determined that upper atmospheric neutral density variations were responsible for orbit perturbations and theorized that the neutral mass density could be modeled [25]. Among the first perturbations Jacchia identified as important were deviations of the Earth's gravitational potential from that of a point mass [25]. The complexities of the gravitational potential were initially captured using zonal harmonics

alone, similar to the expansion in equation (2). As Jacchia pointed out, there is significant contribution through the third order harmonic that should be accounted for in model calculations. The gravitation potential is given by equation (2)

$$U = \frac{GM_{\oplus}}{r} \left[1 - \sum_{n=2}^{\infty} \frac{J_n}{r^n} P_n(\sin\delta) \right], \quad (2)$$

where G is the gravitational constant; $M_{\oplus}$ is the mass of the Earth; J_n is the empirical coefficient; r^n is the geocentric distance; P_n is the zonal harmonic of the n th order; and δ is the declination or geocentric latitude.

An additional perturbation is solar radiation pressure. Its magnitude is correlated with total solar irradiance, or the power produced by the sun. The effect of this perturbation increases on satellites with large frontal areas, as well as ones with eccentric orbits. The effect of solar radiation pressure is often described in changes in the period times the neutral density, $\rho(dP/dt)$ [25]. For a lower altitude and moderately eccentric orbiting satellite, this value is on the order of $1E^{-6}\rho A/m$, where A/m are the area and mass in m^2/kg . This value increases to $1E^{-8}\rho A/m$ at intermediate altitudes. This study utilized data from satellites that are mostly compact in shape, but six of the satellites have a varying range of eccentric orbits. The eccentricity of a satellite is defined as the variation of its orbit from a perfect circle. The orbit is then broken down into the perigee, which is distance of closest approach to the center of the planetary body being orbited, and apogee, which is the point farthest away from the same planetary body. Three of the satellites used in this study have differences in perigees and apogees greater than 100 km and may be impacted by radiation pressure.

This study does not focus on the specific effect of radiation pressure on the satellites. Instead, the solar irradiance that is correlated with the solar radiation pressure is very important to the neutral density calculations of the model. The power output from the sun plays an important role in the earth's atmospheric size and composition. The solar activity acts as a driver for this change within the model and is analyzed with the data in Chapter IV.

Solar activity will differ on two main timescales. First, there is the solar cycle. This is an approximate 11-year cycle of the Sun that changes from high to low solar activity [43]. This 'activity' is a result of the Sun's magnetic field becoming distorted from differences in latitudinal speeds. The distortions are sometimes viewed as dark features on the surface of the sun called sunspots [43]. Sunspots are considered a proxy for solar activity. The actual physical interaction with the earth comes from solar flares and coronal mass ejections which, in the simplest term, launch mass and electromagnetic radiation from the sun that, if it reaches earth, heats the atmosphere and expands it. When there is significant power output from sun measured by solar flux index, $F_{10.7}$, the solar cycle is considered to be in solar maximum. The average value of the $F_{10.7}$ index during the height of solar maximum in 2001 was 187. During this timeframe, the earth's atmosphere expanded and increased neutral density by an order of magnitude from the previous solar minimum in 1996. After the solar maximum peak, the power output from the sun is decreases and the earth's atmosphere contracts. The average $F_{10.7}$ index was 72 during the next solar minimum in 2008. Emmert et al. [17] studied this contraction of the atmosphere at 400 km under the extreme solar minimum in 2008-2009. A 28% drop from the average neutral density value expected at the nadir of solar minimum occurred. This

deep solar minimum was not expected by solar astrophysics and shows the importance of capturing these extremes realistically within a model. Since atmospheric drag is a direct result of neutral density, modeling of the density is the first priority.

Atmospheric drag models usually account for solar activity by utilizing solar flux measurements and geomagnetic indices. These indices are tools the models use to determine the changes in the atmosphere's height and density as a result of solar activity. The solar flux index is a measure of the 10.7 cm electromagnetic wavelength. This index is referred to as the $F_{10.7}$ index and is used as a proxy for EUV irradiance in the ionosphere and thermosphere. This particular wavelength is used because it has been measured consistently since 1946 [41, 43]. The reasoning is that the 10.7 cm wavelength is able to reach the Earth's surface without being absorbed by the atmosphere. The low cost of measuring it from the Earth's surface, as opposed to a satellite, has made this a timeless index to use. Additionally, it shows the current state of the solar cycle very well which will be explored in the Chapter IV analysis.

The small timescale events from the sun are measured by geomagnetic indices. They indicate the amount of disturbance of Earth's magnetic field from solar storms. The primary geomagnetic index used is the K index which is averaged over three-hour intervals. However, most atmospheric drag models utilize either the K_p or A_p , which is derived from twelve worldwide, predetermined stations between the geomagnetic latitudes of 48 and 63 degrees [43]. The subscript 'p' refers to planetary index. The K index is based upon a quasilogarithmic scale and cannot be averaged daily with any accuracy. There is a conversion between the K_p and A_p by an intermediate a_k index. This index converts the K_p index to a linear scale. The A_p is the daily averaged planetary index

that is derived from the K_p index using the linearization of the a_k index. The conversion between the K_p and the A_p index is given by Table 1 [43]. Chapter IV will utilize the A_p when describing geomagnetic storming, but the TIE-GCM uses the K_p index as an input into the model.

Table 1. Geomagnetic Conversion

K	0	0+	1-	1	1+	2-	2	2+	3-	3	3+	4-	4	4+
a	0	2	3	4	5	6	7	9	12	15	18	22	27	32
K	5-	5	5+	6-	6	6+	7-	7	7+	8-	8	8+	9-	9
a	39	48	56	67	80	94	111	132	154	179	207	236	300	400

2.2 Thermospheric Models

Several studies have been conducted over the last half-century to try and improve the performance of neutral density models. However, as the NRC report points out, there is still much more research to be accomplished to achieve an improved certainty of specific neutral density calculations in both the short and long term [31]. The next step for researchers to decide is what type of model to utilize when striving to improve current neutral density calculations.

The majority of research has focused on empirical models. This means a high confidence measurements or observations are taken somewhere in the atmosphere, and the rest of the atmosphere is constructed around that information. For operational applications, empirical models are the most heavily used today because they require limited computation time and are currently more accurate than their counterpart, physics-based atmospheric models.

Physics-based models were created with the desire to determine the evolution of atmospheric parameters from first-principles conservation equations. Instead of starting from pre-determined values, the atmosphere is ‘initiated’ through numerical calculations until it eventually reaches equilibrium. Currently, most physics-based model neutral density values have more error than empirical model values [27]. Despite larger error values, physics-based models resolve features within the atmosphere that are often missed entirely by empirical models. One commonly cited example is the observed ‘winter helium bulge’ that is heavily dependent on the resolution of individual neutral species within the model [38, 41]. This feature is detected by the TIE-GCM, the focus of this study.

A plethora of models have been created in the pursuit of accurately modeling atmospheric mass density. Vallado details several of the major models used for atmospheric calculations and their progression in his paper [44]. The first atmospheric density model post-satellite launch is Jacchia 1960 (J60). Along with other early models, it was based upon theoretical considerations of the thermosphere and exosphere [24, 25]. The model would take in values derived from atmospheric drag of existing satellites and incorporate them into the parameterization of the atmosphere. A method of accuracy used by the J60 model was to average various model iterations to achieve an accurate medium. Other models that were created around this time tried similar approaches [18, 44]. The progression of atmospheric models began with the assumption of total density from observed satellite drag. The theories and techniques improved over time, and several new models were based upon previous versions of an existing model.

The first Committee on Space Research (COSPAR) International Reference Atmosphere (CIRA) model took a different empirical approach to formulate the model [34]. It formulated the thermosphere from direct observational data such as air density data. These values were attained by deriving measurements of atmospheric drag effects on early satellites [34]. Similar methods are still used today and are included in this research.

The CIRA and other models advanced from their original assumptions as research revealed more information concerning the atmospheric structure. Researchers realized the individual neutral species' densities were extremely important in the atmospheric structure because of the variability over time. One of the earliest methods to determine individual particle densities is to use a neutral mass spectrometer (NMS) [18]. The early version of this instrument was capable of measuring N_2 , O_2 , O , Ar , and He . Uncertainty in the absolute value of each species arises from calibration issues. Additionally, the neutral species O is difficult to determine with high precision, because it is a highly reactive species. When colliding with the surface of the NMS and the satellite, O will often form O_2 . Improvements were made to the early NMS instruments, but no significant in situ data on neutral species has been collected since 1983 when the Dynamics EXPLORER 2 satellite mission was ended [18].

Another method to determine individual neutral densities is by inferring the amount from measurements of Earth's far ultraviolet (FUV) dayglow. This is possible during the daytime because of the photoelectron excitation that takes place from the incident solar radiation. This method is capable of measuring N_2 , O , and O_2 [18]. These species make up 99% of the total neutral mass density in the lower thermosphere [20].

With increasing altitude, helium becomes a more dominant species and will compose at least 10% of the total mass density above 500 km [18]. The FUV dayglow measurement technique does not apply to helium, so alternate methods have to account for its contribution. In addition to the dayglow measurements, an approximation of temperature is also associated with the same measurements. The temperature will lead to an estimation of helium density if lower thermospheric values are known. This technique is still used today for total mass density values.

There are other methods that have been researched regarding composition values. The majority of those focus specifically on the O concentration because it is the dominant species throughout much of the thermosphere. Among these techniques are incoherent scatter radar (ISR) data, infrared airglow, and atmospheric occultation. These techniques often involve a specific range of altitudes to determine a density profile. For instance, the airglow technique is generally for altitudes below 110 km, but the 63 micron emission line can infer O density within 130-175 km [18]. To get a complete total mass density profile, several of these techniques may have to be considered, as well as other methods such as modeling from scale height when the temperature is known or estimated.

Determining the atmospheric density and individual neutral species from the techniques detailed above is important for fitting the model equations accurately. Some of these models are designed to complete the Earth's entire density profile from a few values at one location in the atmosphere. Since the majority of atmospheric drag models are empirical models, they must vary from the measurements, assumptions, and equations used in their calculations. Ultimately, all of them will output a total density profile of the Earth with varying degrees of accuracy. There are many empirical models available for

use today. The advantages and disadvantages of these models in relation to the TIE-GCM will be discussed in section 2.2.1.

Another model category that Vallado details is the general circulation model (GCM) [44]. GCMs are numerical models that focus on the progression of the global flow of the atmosphere as an interconnected system. These models arose from the need for better weather forecasts given the limited computer power in the late 1940's and early 1950's. Precursor models to GCMs were regional and generally took too much time to complete the computation necessary for a real-time forecast of an area. The desire in the meteorological community was to use the computing power for forecasts that were not as time-sensitive. While at Princeton University, Norman Phillips accepted the challenge of creating a global weather model [46]. In 1955, Phillips created the first GCM which had a two layer atmosphere within a cylindrical column that initiated by introducing heat into the lower atmosphere. It created a jet stream-like feature and realistic weather systems that evolved over the course of a month. The proof of concept was established, and the success of the model gave other researchers the government funds necessary to make a complete GCM that was based upon first-principle equations.

Two of the fundamental physics equations considered are the pressure gradient force and gravity. These are assumed to be in hydrostatic equilibrium at every point in the atmosphere. This reduces some complexity of the model by removing the vertical component of the momentum equation by constraining the vertical velocity. As Emmert [18] summarizes, the assumption is accurate under low geomagnetic activity. However, under-estimates of thermospheric density during rapid changes of geomagnetic activity are common for hydrostatic GCM models.

The altitude ranges of GCMs vary depending on the purpose of the model and the physical assumptions made. As detailed by Emmert [18], the top boundary of the models is usually 600 km. This choice is based upon the assumption that diffusive equilibrium starts at this altitude. For the TIE-GCM, this boundary varies depending on the expansion of the atmosphere during solar maximum and contraction of the atmosphere during solar minimum. As a result, diffusive equilibrium occurs at different altitudes as the solar conditions change. The lower boundary of GCMs varies across the span of models. The primary reason for this difference is the altitude region the model is intended to depict. In particular, the TIE-GCM starts at 97 km with the lower boundary composition determined by the Global Scale Wave Model [35]. By contrast, the Whole Atmosphere Model (WAM) and the Whole Atmosphere Community Climate Model Extension (WACCM-X) are ‘whole-atmosphere’ models that begin their lower boundary at the surface.

2.2.1 Minor Species vs Major Species

An aspect of physics-based models and GCMs is the delineation between major and minor species. The primary focus of this research is to study the difference in the TIE-GCM performance with helium as a major species. Further explanation is required to understand what a major species is in the model and how it is contrasted with a minor species.

When a GCM solves for the mutual diffusion of a species, that species is considered to be major. The major species are calculated in a composition equation that

included mass and momentum continuity. The continuity equation that is used by Sutton et al. [38] for this research is given in equation (3).

$$\begin{aligned} \frac{\partial}{\partial z} \left[\tau^{-1} \left(\frac{T_{00}}{T} \right)^{0.25} \frac{\bar{m}}{m_N} \boldsymbol{\alpha}^{-1} \mathbf{L} \boldsymbol{\Psi} - K_E e^{-z} \left(\frac{\partial}{\partial z} + \frac{1}{\bar{m}} \frac{\partial \bar{m}}{\partial z} \right) \boldsymbol{\Psi} \right] \\ = e^{-z} \left(\mathbf{s} - \frac{\partial \boldsymbol{\Psi}}{\partial t} - \mathbf{V} \cdot \nabla \boldsymbol{\Psi} - \omega \frac{\partial}{\partial z} \boldsymbol{\Psi} \right), \end{aligned} \quad (3)$$

The variable τ is the characteristic diffusion timescale, T_{00} is the temperature at the molecular scale height for nitrogen, T is the temperature, $\bar{m}$ is the mean mass, m_N is the mass of a species N , $\boldsymbol{\alpha}$ is the diffusion matrix, $\mathbf{L}$ is the normalized pressure forces matrix, and $\boldsymbol{\Psi}$ is the vector of mass fractions,

The major species differs from a minor species when several terms within equation (3) are small. This makes the major species dynamically decoupled from the minor species. The negligible for a minor species are the diffusion matrix, $\boldsymbol{\alpha}$ and the mean mass, $\bar{m}$. The diffusion matrix is neglected to avoid momentum transfer and acceleration caused by minor species on major species. One additional difference of the minor species in the TIE-GCM is the exclusion from the pressure scale height.

The three major species that most physics-based models consider are N_2 , O_2 , and O [18]. The included minor species varies depending on the region of the atmosphere of interest. In the case of the Thermosphere-Ionosphere-Mesosphere-Electrodynamic General Circulation Model, there are 17 minor species, where the mesosphere region of the model includes most of the minor species [18]. The TIE-GCM has only three minor species which are nitric oxide (NO), atomic nitrogen, $\text{N}(^2\text{D})$, and excited atomic nitrogen, $\text{N}(^4\text{S})$. These species are included in the model because of their importance in the energy

balance of the thermosphere and overall atmosphere temperature structure. NO is a source of radiational cooling in thermosphere by being an efficient emitter in the infrared spectrum [1, 36]. The concentration is small enough to ignore in the diffusion matrix, mean mass, and scale height but the ‘minor’ species are important in heat transfer that takes place around 120 km in the model. As will be discussed in section 2.2.3, helium was included in an early version of the TIE-GCM as a minor species but encountered some issues in the calculations [38].

2.2.2 The TIE-GCM

As mentioned previously, the model of choice for this study is NCAR’s TIE-GCM. This is a physics-based model that uses first-principle equations in its description of the ionosphere and thermosphere. These equations include the Eulerian continuity equation, momentum equation, energy equation, and composition equations. Precursors to this model include Thermosphere General Circulation Model (TGCM) [9, 10, 11] and Thermosphere-Ionosphere General Circulation Model (TIGCM) [35]. Prior models included a subset of the equations that are solved in the current version of the TIE-GCM as the model has been improved over several decades of research.

The genesis of the current TIE-GCM came from a desire to conform modeled temperatures of the thermosphere to observed values at equinox conditions. In 1975, Dickenson et al. [9] published results of an early TGCM capable of circulating temperatures and providing a decent depiction of the thermosphere at consistent solar activity conditions. The deficiency came from the amount of solar heating and how to apply it as a boundary condition to the model. Dickinson et al. [9] discovered the key to

an accurate thermosphere circulation model was adding heat from Joule dissipation of the high latitude electric current systems. This discovery led to the electrodynamic component that has remained a part of the model to present day. By 1981, the NCAR model was officially named the TGCM, but researchers continued to make improvements. One important aspect of the TGCM that changed was the inclusion of neutral density composition. Initially the TGCM's composition was defined by ad hoc values based on mass spectrometer measurements made onboard the Orbiting Geophysical Observatory 6 (OGO-6) satellite. Hedin et al. [20] created an empirical model derived from almost two years of spectrometer data. The composition values and profiles can be utilized in models such as was done with the TGCM. Hedin's model was eventually known as the Mass Spectrometer and Incoherent Scatter Radar (MSIS) and advancements of the model are still used today.

As Dickinson et al. [10] points out, efforts were made in the 1970's to calculate composition variations as part of a GCM. The underlying assumption used to calculate atmospheric composition was a diffusive equilibrium environment. This assumption was proven insufficient due to other significant processes occurring throughout the thermosphere [10]. In particular, the atomic oxygen species profile diverged from the profile created from the diffusive equilibrium assumption due to the photodissociation process that occurs to molecular oxygen during the daytime hours. Early GCMs calculated too much atomic oxygen in the summer regions due to this process. Dickinson cites several studies that demonstrated the overabundance of O in the summer hemisphere should be transported via the horizontal meridional winds to the winter hemisphere. Not

only did this help future model performance, but it also helped describe the energy balance in the thermosphere.

In addition to accounting for photoproduction and transport of atomic oxygen in the thermosphere, the interaction of neutral species during diffusion in the atmosphere is another feature that was added into the model. Accounting for this process is determined through the mass mixing ratio shown in equation (4).

$$\psi_i = n_i m_i \left(\sum_{j=1}^3 n_j m_j \right)^{-1} \quad (4)$$

The coefficients n_i and m_i are the neutral species number density and mass, respectively. In the case of the TGCM, the three species calculated are N_2 , O_2 , and O . Since N_2 is the dominant species at the lower boundary of the model, the mass mixing ratio is defined as

$$\psi_{N_2} = 1 - \psi_{O_2} - \psi_O, \quad (5)$$

where ψ is the mixing ratio with the associated constituent as a subscript. The mass mixing ratio is not constant in time and therefore a time dependent mass mixing ratio for each individual species is written as

$$\begin{aligned} \frac{\partial}{\partial t} \psi = & -e^z \tau^{-1} \frac{\partial}{\partial z} \left[\frac{\bar{m}}{m_i} \left(\frac{T_{00}}{T} \right)^{0.25} \alpha^{-1} \mathbf{L} \Psi \right] \\ & + e^z \frac{\partial}{\partial z} \left(K(z) e^{-z} \frac{\partial}{\partial z} \psi \right) - \left(\mathbf{v} \cdot \nabla \Psi + w \frac{\partial}{\partial z} \psi \right) + \mathbf{S} - \mathbf{R}. \end{aligned} \quad (6)$$

The most important values of this equation include the vertical coordinate, $z = \ln(P_0/p)$, which is the logarithmic pressure. The diffusion time scale, given by $\tau = (P_0 H_0^2 / P_{00} D_0)$, where P_0 is a reference pressure, and H_0 is the characteristic molecular scale height for nitrogen; the temperature at this scale height is $T_{00} = 273 \text{ K}$,

and the pressure $P_{00} = 10^5$ Pa. A characteristic diffusion coefficient $D_0 = 2E^{-5} \text{ m}^2$ is also defined at T_{00} and P_{00} . $K(z)$ is the eddy diffusion coefficient, $\mathbf{V}$ is the horizontal velocity along a constant-pressure surface, and $w = \frac{dz}{dt}$ is the vertical motion with respect to a given pressure level. The two mass variables are the mass averaged mass, $\bar{m}$, and the mass of a species i , m_i . The variable α is the normalized molecular diffusion matrix, $\mathbf{L}$ is a matrix operator that defines diffusive equilibrium solutions, and Ψ is the vector of mass mixing ratios. At the upper boundary of the model, the product of the vector of mass fractions and the diffusion matrix, $\mathbf{L}\Psi$, is assumed to be zero. This assumption defines the point where turbulent mixing and photochemical process cease, and the neutral species can be assumed to be strictly under diffusive equilibrium. Since the mass mixing ratio is dependent on temperature and height, this boundary will change based upon the solar activity and how much heat is reaching the atmosphere. The solar activity also affects the final two coefficients, $\mathbf{S}$ and $\mathbf{R}$, which are the production and loss mechanism of two main chemical processes, respectively. $\mathbf{S}$ includes the molecular oxygen photodissociation rate, and $\mathbf{R}$ includes the O to O₂ chemical recombination rate. In general, equation (6) has remained in this general form since Dickinson et al. [11] and more recent publications [36, 38]. In section 2.2.3, a description of adding helium into the time dependent mass mixing ratio via equations (4) and (5) will be made.

While Dickinson et al. [11] added dynamic, time-varying composition into the TGCM, they also discovered a suitable range for the model that is still used today. The model's upper boundary is defined by Dickinson et al. [1] as 500 km. However, this is a result of assumed solar minimum and equinox conditions. This boundary will change in

later improvements of the model. The top boundary will average 600 km and have an approximate 100 km range above and below the model. Specifically, the atmosphere expands during higher solar activity and can be complicated with sudden changes occurring. One way the TGCM and TIE-GCM respond to the higher solar activity is by extending the upper boundary to include photochemical processes within the expanded atmosphere. The upper boundary is still dictated by the $\mathbf{L}\Psi = \mathbf{0}$, where diffusive equilibrium can be assumed. The lower boundary of the TGCM has changed slightly over time but settled at 97 km during TGCM composition improvement. The 97 km value was determined by the observation that atomic oxygen has a peak concentration at this altitude. The conservation of total oxygen and the assumption of the lower boundary are the basis for the mass mixing ratio, equation (5). The composition is coupled with the hydrostatic equation

$$\frac{\partial \Phi'}{\partial z} = \frac{RT'}{m}, \quad (7)$$

where Φ' is the geopotential, z is the height in logarithmic pressure, R is the universal gas constant, T' is the temperature, and m is the mass. This is done in order to describe dynamics of vertical variation. The vertical integral of variations in mean mass provides several parameters that are mass dependent, but the most important is the variation in geopotential. This was an important factor in defining the upper boundary of the early TGCM. The lower boundary composition helps to define how the model will diffuse composition with height. The TGCM utilized the 1976 U.S. Standard Atmosphere to define the composition [11]. The current TIE-GCM uses the Global Scale Wave Model for tidal forcing in order to get proper mixing of the neutral density below 97 km [38].

Another update to the TGCM occurred in 1988 when Richmond et al. [35] included an aeronomic scheme of the ionosphere and thermosphere. The aeronomic scheme was self-consistent and utilized an Eulerian coordinate system. The Eulerian is in contrast to the Lagrangian approach that is used in other ionospheric model calculations. Both approaches specify a field flow, but the simplest way to differentiate between the two is to consider the reference frame of the observer. In the Lagrangian approach, the reference frame follows a particular parcel within the flow of the atmosphere. In contrast, the Eulerian approach remains stationary at a specified place in the atmosphere and observes the flow or change of the atmosphere at that point. This choice of coordinates was made to be consistent with the aeronomic scheme already developed for the thermospheric portion of the code. It was easier to apply the change in coordinates and equations to match this coupling than develop the coupling in Lagrangian coordinates. In theory, both approaches should yield similar results.

The ionosphere and thermosphere coupling accounted for the photochemical processes that occur in the ionosphere. Before this point, the only photochemical process was the photodissociation of molecular oxygen, which did not account for all the daytime ions. The newly named Thermosphere Ionosphere General Circulation Model (TIGCM) was able to calculate the global distribution of O^+ , O_2^+ , NO^+ , N^+ , N_2^+ , all the ion temperatures, and the electron density. This addition was blended with the major composition, winds, and temperatures that the model was already capable of calculating.

The last significant upgrade to the TIE-GCM occurred in 1992. This upgrade focused on the dynamo effects of the thermospheric winds [Richmond et al., 36]. An electrodynamic forcing term was already applied to an earlier iteration of the model, but

there are inherent electric fields that result from the global circulation of the winds. These electric fields are a major factor in describing the neutral and plasma flow. In addition to applying the International Geomagnetic Reference Field, an accurate and realistic geomagnetic field model, the general circulation model calculated localized daily winds that are not resolved without the additional forces. Variations between night and day winds due to the significant contribution of ion drag during the day could then be simulated. Additionally, an eastward component to the electric field helped to reduce ion drag on the neutral wind which in turn resulted in a stronger eastward wind in the evening hours. The addition of the electrodynamics into the coupled ionosphere and thermosphere model led to the renaming of the TIGCM to the TIE-GCM.

This change to the TIE-GCM in 1992 closely resembles its current state. NCAR has released versions and updates to the model code over the course of this timeframe and is most recently on version 1.95 [44]. This last release of the TIE-GCM is dated 21 June 2013 and is available for download from the NCAR High Altitude Observation website [44]. The most current release of the model has a horizontal resolution of five by five degrees. The altitude is described in log pressure levels at half scale heights. The vertical range of the model has remained consistent from earlier versions with a lower boundary of 97 km and the upper boundary ranging from 500 km to 700 km. As mentioned, the upper boundary depends on solar activity. The inputs the model takes for solar activity is either the $F_{10.7}$ index or direct measurements of EUV radiations [38, 44]. As described in section 2.1, the $F_{10.7}$ index is converted to an approximate measurement of EUV radiation to properly drive the heating of the thermosphere. Other inputs include

geophysical parameters such as the K_p index, IMF and solar wind interaction, or specified cross-cap potential and hemispheric power.

The composition portion of the TIE-GCM has changed since 1992. The Richmond et al. [36] paper mentions solutions to helium and argon (Ar) as minor species that were removed from the code within the last two decades [38]. The TIE-GCM, in its current state, has the same three major species, N_2 , O, O_2 , as used by Dickenson et al. [11]. The model also includes three minor species. These are nitric oxide, atomic nitrogen, and excited atomic nitrogen. In the following section, the recent inclusion of helium as a major species by Sutton et al. [38] will be discussed.

2.2.3 Inclusion of Helium

As mentioned in section 2.2.1, early versions of the TIE-GCM included helium as a minor species [36, 38]. Recently a 2011 study by Kim et al. [27] included helium from the MSIS model and found an improvement in the RMS error by 50%. In 2014, a study by Lui et al. included helium as a minor species into the composition equations [38]. Due to an unrealistic buildup of helium densities at the poles during long simulations, an ad hoc inclusion of helium into the scale height calculation was required. Most recently, Sutton et al. [38] included helium as a major species in the model. During simulations of the model, he was able to simulate known features with helium such as the ‘winter helium bulge’ documented in prior research [38, 41]. Sutton’s modification to the TIE-GCM will be the version validated in this study.

The only change in the TIE-GCM was the inclusion of helium into the major species composition equations, as described by Sutton et al. [38]. Molecular diffusion

becomes the dominant process with increasing height and is more important at higher altitudes with lighter species such as helium and hydrogen becoming dominant. The basic vector diffusion equation for major species in the TIE-GCM is

$$\mathbf{L}\Psi = \tau \frac{gm_{N_2}}{p_0 \bar{m}} \left(\frac{T}{T_{00}} \right)^{0.25} \alpha \mathbf{W}. \quad (8)$$

Equation (8) represents continuity of momentum of the individual species in relation to the most dominant species at the top of the turbopause, molecular nitrogen. Additionally, the values typically associated with a pressure balance equation such as gravitational acceleration (g), reference pressure (p_0), temperature (T), molecular mass of nitrogen (m_{N_2}), and mean molecular mass ($\bar{m}$) are included. The bold variables are vector and matrix quantities and contain more information on diffusion, pressure, and mass. The two mass variables are the vertical mass fluxes ($\mathbf{W}$), shown in equation (9), and the vector of mass fractions or mass mixing ratio (Ψ), given in equation (10). Both vectors in equations (9) and (10) are based around molecular nitrogen. Excluding helium from equation (11) will result in equation (5) from section 2.2.2.

$$\mathbf{W} = \begin{bmatrix} \rho_{O_2} & W_{O_2} \\ \rho_O & W_O \\ \rho_{He} & W_{He} \end{bmatrix} \quad (9)$$

$$\Psi = \begin{bmatrix} \psi_{O_2} \\ \psi_O \\ \psi_{He} \end{bmatrix} \quad (10)$$

$$\psi_{N_2} = 1 - \psi_{O_2} - \psi_O - \psi_{He} \quad (11)$$

The remaining two variables are the diagonal differential matrix operator of normalized pressure forces ($\mathbf{L}$) and the diffusion matrix (α), which were also defined in sections 2.2.1 and 2.2.2. The normalized pressure forces matrix can be seen in equation (12).

$$\mathbf{L} = \begin{bmatrix} 1 & & \\ & 1 & \\ & & 1 \end{bmatrix} * \left(\frac{\partial}{\partial z} - 1 + \frac{m_i}{\bar{m}} + \frac{1}{\bar{m}} \frac{\partial \bar{m}}{\partial z} + \frac{\alpha_{Ti}}{T} \frac{\partial T}{\partial z} \right) \quad (12)$$

Equation (8) is combined with a continuity equation in order to get the full diffusion equation that is in the TIE-GCM. Treating helium as a major species in the model is expected to increase the overall neutral density values at higher altitudes [38].

Additionally, helium is responsible for seasonal variations occurring within the atmosphere [18, 38, 41]. The TIE-GCM's ability to resolve these phenomena is not a main objective in this paper but should be included in future studies.

As Sutton et al. [38], Kim et al. [27], and Emmert et al. [17] discuss, helium is an important contribution to the thermosphere and lower exosphere. A significant increase in the temperature occurs in this region of the atmosphere that is further amplified during solar maximum conditions as discussed in section 2.1. Chemical processes such as photodissociation, ionization, and photo-excitation of the neutral species take place in this region. An interesting and significant feature of this region is the gravitational separation of the individual neutral species by diffusion due to mass differences. In the lowest 95 km of the atmosphere, the composition is dominated by two main neutral species: N₂ (78%) and O (21%). Ar (0.9%) and lighter species, such as hydrogen and helium, account for the remaining 0.1% in the lower 95 km of the atmosphere. The lighter species become more relevant at higher altitudes within the thermosphere and exosphere. For example, at 400 km the percentage of helium is 25% at solar minimum. Figures 1 and 2 show profiles made by the TIE-GCM with the addition of helium as a major species. The profiles are a plot of neutral mass density with increasing altitude and

show how the species concentration changes with height. These profiles closely resemble composition figures in Schunk et al. [41].

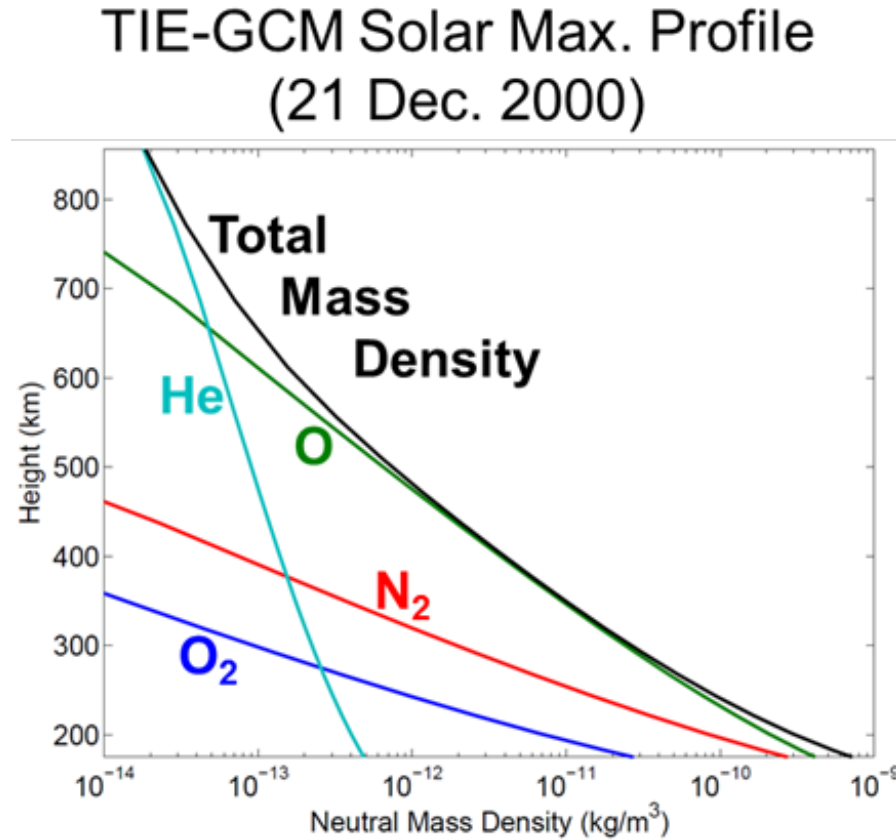


Figure 1. TIE-GCM Solar Max. Profile. Altitude profiles of the neutral mass densities as modeled by the TIE-GCM during the winter solstice.

The rate at which the individual neutral species diffuse with height plays a significant role in determining the composition at various altitudes. Molecular nitrogen (N₂) and oxygen (O₂) are much more prevalent around 200 km, but they decrease drastically with height. Around 400 km, they can be two to three orders of magnitude smaller than the dominant species at this height, atomic oxygen (O). One important

feature to note from Figure 1 is the transition between an atomic oxygen-dominated atmosphere and one that is dominated by helium. During solar minimum, helium becomes more prevalent than N_2 at 320 km. This altitude increases to 400 km during solar maximum; and in both instances helium is only about an order and a half of magnitude smaller than the total neutral density. The altitude where helium surpasses O and becomes the dominant species is more variable between solar minimum and maximum, ranging from a low of ~460 km at solar minimum to a maximum of ~670 km during solar maximum.

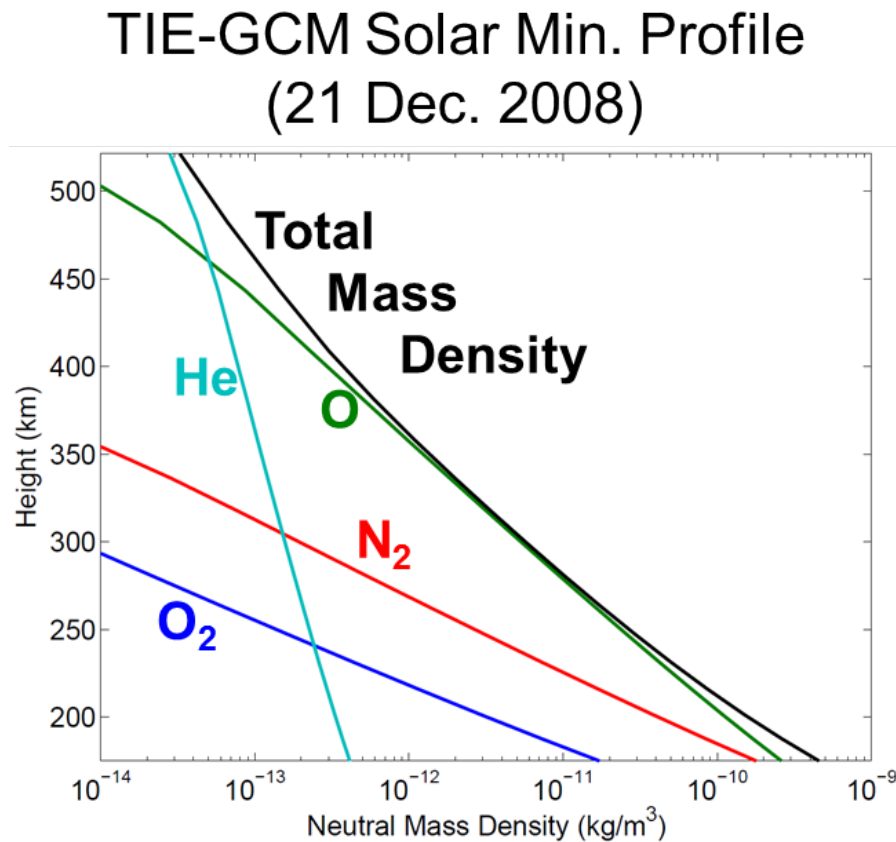


Figure 2. TIE-GCM Solar Min. Profile. Altitude profiles of the neutral densities as modeled by the TIE-GCM during the winter solstice.

Figures 1 and 2 show how the total mass density decreases orders of magnitude with increasing altitude. This will decrease the amount of acceleration calculated in the drag acceleration equation, equation (1). This region where helium becomes a dominant species in the atmosphere is collocated with the region where thousands of Low Earth Orbiting (LEO) satellites orbit and orbital debris is located as shown in Figure 3.

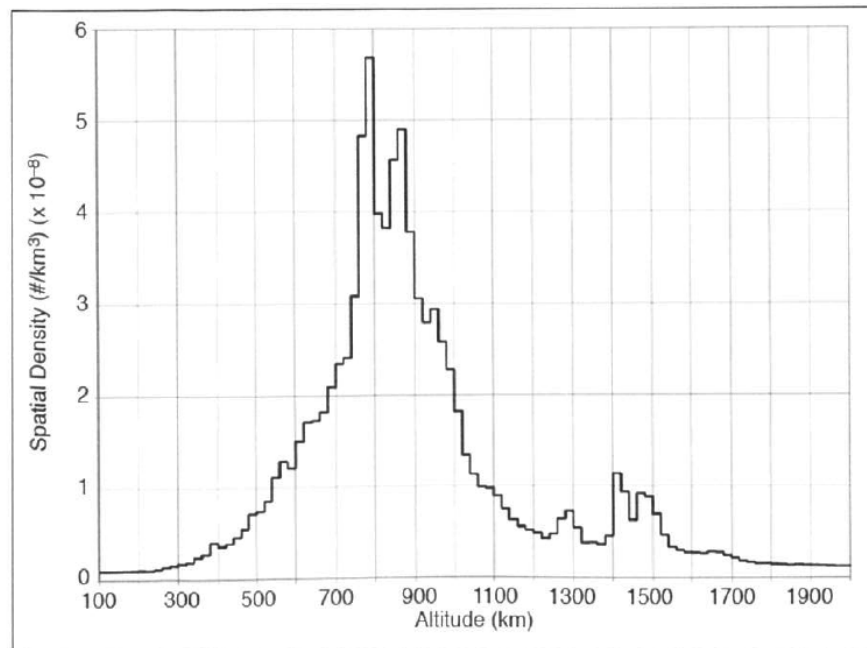


Figure 3. Large Orbital Debris Spatial Density. This histogram shows the categorization of large spatial debris with altitude. The vertical axis is in units of number/ $\text{km}^3 \text{E}^{-8}$. Image Credit: National Aeronautics Space Administration (NASA).

2.2.4 Empirical vs. First Principle

The majority of the early models created were based upon ingesting parameters of satellite measurements or indirect calculations of the atmosphere from ground-based sites. Jacchia's first empirical model was created using atmospheric drag derived from tracking early satellites [24, 25]. It was understood that several of his assumptions left

room for a significant amount of error. As research improved in the area of atmospheric drag, the assumptions were revised, which led to better model calculations and improved performance.

Even today, the majority of atmospheric drag models are a variation of an empirical model with advancements occurring within the last five years. Zhou, Hedin, Kim, and Gasposchkin all researched atmospheric drag using empirical models [15, 20, 27, 49]. Most of the research involves a variant of Jacchia, a variant of MSIS, or a variant of the Drag Temperature Model (DTM). Kim [27] compares the Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar-2000 (NRLMSIS-00), the TIE-GCM, and the Jacchia-Bowman 2008 (JB2008) and shows that the NRLMSIS-00 and JB2008 are far superior to the TIE-GCM. Kim improves the TIE-GCM by almost 50% RMS by including helium from the MSIS. This improvement is an example of what makes atmospheric empirical models more accurate than physics-based models. Other empirical examples include the Accelerometer Density Model and the Global Average Mass Density Model [18]. These models fit accelerometer data and orbit derived density into the calculations. The ability to take measured data and fit it into a model improves initial conditions.

Despite the inherent advantage of empirical models, there is interest in using physical models that stems from their ability to resolve seasonal variability. GCMs excel at handling gradual changes to the neutral density composition within the atmosphere [15, 23, 35, 41]. The seasonal variability is important to the composition of the atmosphere. Most of the information on atmospheric composition comes from the MSIS model [18, 20, 40, 49]. The composition profiles have been used as a baseline for

comparison and in the case of the research by Kim et al. [27], it can be used as evidence to improve current models neutral density values. Figure 4 compares the helium mass density concentration of the MSIS to the Jacchia Bowman 2008 (JB08) which were used in the Kim et al. [27] research.

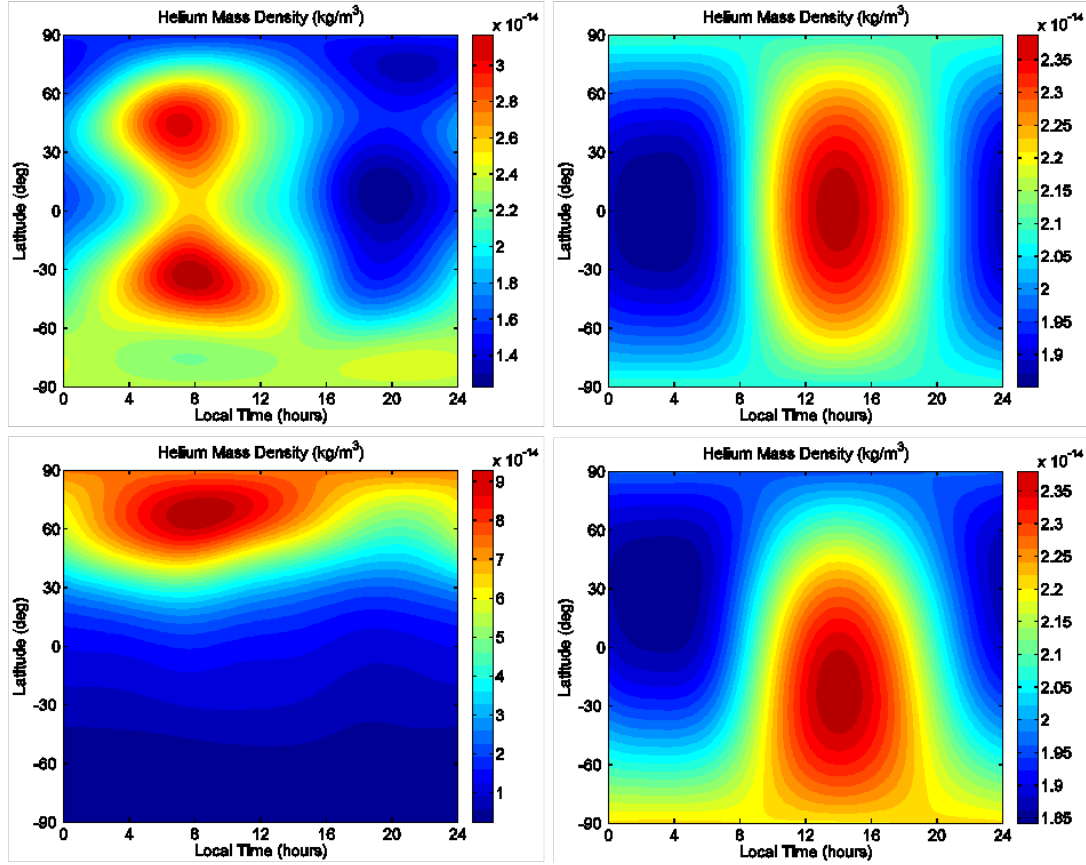


Figure 4. MSIS and JB08 Comparison. A side-by-side comparison of the MSIS (left) and JB08 (right) at equinox (top) and solstice (bottom) at 400 km. The $F_{10.7}$ index input into the model was during low solar minimum conditions, $F_{10.7} = 80$.

The current operational model used by the United States Air Force (USAF) is a variant of the Jacchia-Bowman 2008 (JB08) model [40]. This model was created from the Jacchia 1970 (J70), an update of the original Jacchia model in 1961. It does not benefit from the

mass spectrometer measurements that elucidated the ‘winter helium bulge’ phenomena in the early 1970’s as discussed in section 2.2. The phenomenon is depicted clearly in the bottom left panel of Figure 4 by the MSIS helium mass density profile. Additionally, helium has been documented to have a morning preference in the atmosphere [38, 40]. The MSIS output shows this morning preference during equinox and solstice timeframes. In contrast, Figure 4 shows the JB08 model output has an afternoon bias that resembles a temperature profile for both equinox and solstice timeframes.

A comparison is made between the MSIS and JB08 models to show the deficiency in specific composition depicted in the JB08. The accurate helium depiction in the MSIS is also displayed in the TIE-GCM output. Sutton et al. [38] also compared the TIE-GCM to the MSIS model directly with horizontal depictions of helium mass density. The comparison showed very similar profiles at 250 km. The morning preference discussed from Figure 4 was depicted in the TIE-GCM with a similar output to the MSIS. Additionally, the ‘winter helium bulge’ was also depicted by both models. The importance for this depiction of helium is its contribution to the total neutral density. The data sources for the validation of the model performance are discussed in the next section.

2.3 Neutral Density Data

Acquiring accurate neutral density data in the upper atmosphere is an ongoing challenge. Several methods have been attempted over the past half century including Jacchia’s models that makes assumptions about the forces impacting a satellite, and the mass spectrometer that measures the composition of individual species to obtain the total

neutral density. These early techniques have been expanded upon and provide the highly accurate neutral density data of the CHAMP, GRACE, and spherical satellites used in this study.

2.3.1 CHAMP and GRACE Satellites

The difficulty in determining accurate neutral density values has already been detailed in this paper. When the CHAMP and GRACE satellites were launched in the early 2000's, several atmospheric drag researchers took the opportunity to utilize the increased instrument sensitivity of the accelerometer instruments [21, 39]. The accuracy of measurements from the accelerometers increased by several factors of 10 since the early 90's, which increased the interest for including these instruments on several research-based satellites. The drag acceleration is decreasing with altitude but is still occurring and can increase relatively quickly with increased solar activity. Both the CHAMP and GRACE research satellites were equipped with state-of-the-art accelerometers that provided high quality measurements still used heavily today [21, 27, 48]. There have been more missions launched or planned in recent years such as the Gravity Field and Steady-state Ocean Circulation Explorer satellite (GOCE) and the future GRACE Follow-On missions that continue these measurements for research [48]. The former two satellites have had data post-processed and calibrated over the course of several years and share similar timeframes. As a result, they will be used for neutral density comparison in this research.

The Challenging Minisatellite Payload (CHAMP) satellite was a German-made spacecraft and was launched from Plesetsk, Russia on 15 July 2000 [6, 22]. The designed

lifetime of the satellite was five years, but it exceeded this expectation and eclipsed a 10-year orbital lifespan while successfully taking measurements. The orbit was initially near-circular and quasi-polar at an altitude of 454 km. The primary mission of CHAMP was to map the global gravity field and the magnetic field with temporal variations. Additionally, the satellite took atmospheric and ionospheric soundings for climatological, weather forecasting, and other global readings.

The advantage of a near-circular and quasi-polar orbit was to deliver consistent global coverage at a constant altitude. Most variations in the data resulted from latitudinal, solar, and gravitational differences. The uniformity in orbit and data was accomplished consistently until increased solar activity degraded the satellite's orbit. Consequently, several orbit changes were made in 2002 to account for the increased drag from solar maximum. This continued throughout CHAMP's lifetime with periodic solar activity occurring. Eventually, the satellite was allowed to decay in orbit and eventually burn up in the lower atmosphere of Earth.

The CHAMP satellite was equipped with seven instruments on board its 522 kg frame. Two magnetometers, a laser reflector, a global positioning system (GPS) receiver, a stellar compass, a digital Ion Drift Meter, and a high-precision accelerometer comprised the satellite's suite of instruments. The Spatial Triaxial Accelerometer for Research (STAR) accelerometer is a focus of this research because it gives the most accurate measurements for neutral density for comparison purposes [22, 49]. This accelerometer was manufactured by the Office National d'Etudes et de Recherches Aerospatiales (ONERA) of France and was equipped on the CHAMP satellite by the Centre National d'Etudes Spatiales (CNES). The governing idea behind the accelerometer is the balance

of electrostatic forces. The STAR accelerometer has a cage-like cavity that suspends a proof-mass in place by electrostatic forces. The acceleration required to keep the proof-mass motionless is used to determine the drag force. Accelerations are usually the result of variations in normal orbiting parameters such as density, gravity, and velocity. The drag acceleration from equation (1) is not measured directly, but the electrostatic force (or acceleration) is used to determine its value.

The American counterpart of the CHAMP satellite is the Gravity Recovery and Climate Experiment (GRACE) mission [19]. The GRACE mission consists of twin satellites that were launched on 17 March 2002. They are in a circular polar orbit. Their average orbital altitude and distance apart are 500 km and 220 km, respectively. Similar to the CHAMP satellite, the primary mission of the GRACE satellites is to provide an extremely precise mapping of the Earth's gravitational field. Additional science objectives include profiling the Earth's atmosphere more accurately and collecting data related to climate change studies.

The GRACE satellites are equipped with the SuperSTAR accelerometer, which is the next generation to the STAR Accelerometer on CHAMP. The process of measuring all non-gravitational acceleration effects is the same; it is simply a slightly more precise instrument. The GRACE mission twin satellites also provide an inherent advantage to the accelerometer measurements in that measurements from each of the two satellites can be compared and verified for consistency. This 220 km displacement between the two satellites does not result in significantly different measurements. The datasets from each satellite are near-identical and have been compared to each other to verify this fact. Any difference that is identified is a result of slight orientation differences [40].

2.3.2 Spherically Shaped Satellites

Satellites are designed with several shapes and sizes that serve various purposes in regard to the intent of the user. Early satellites launched in the late 1950's were often more compact with limited instruments onboard in order to limit the complexity of construction and make the orbit more predictable. Orbital scientists theorized that spherically shaped satellites would increase orbit predictability and could be tracked from the ground more consistently. Eventually this theory was proven accurate, and several more spherical satellites were launched as a result.

Several of the early spherical satellites that were launched in the 1950's through 1970's are no longer taking measurements and are essentially inertly orbiting the Earth. There are also several research satellites that were launched with the sole purpose of being tracked with ground-based radars. The orbital lifetime of several of these satellites are hundreds of years because of the high altitudes at which they are orbiting. All known satellites are currently being tracked by North American Aerospace Defense Command (NORAD) and have a dataset called two-line element (TLE) associated with them [30]. The unclassified TLE is available for public download from a variety of online sources. The 'two-lines' of data consists of six points of information that can be used to infer the location of a satellite. The TLE data is not considered a highly precise set of tracking data but can give the user the rough location of a space object. The TLE data as it pertains to spherically shaped satellites will be described further in the next section.

In addition to the CHAMP and GRACE satellites, six satellites are used for comparison in this research, with five of those being spherical and one conically

symmetric. The earliest of these satellites is Vanguard 2 (NORAD tracking ID 00011). It was made primarily of magnesium, weighing 9.8 kg and measuring 50.8 cm in diameter. Its outer shell was coated with aluminum and silicon oxide with the purpose of maintaining thermal control of the instruments. The satellite was launched on 17 February 1959 from Cape Canaveral into a highly elliptical orbit [32]. The apogee height is over five times the distance of the perigee height at 2948 km and 557 km, respectively. The primary mission of Vanguard 2 was to measure the distribution of cloud-cover during the daylight hours. According to researchers, the telemetry data is considered poor due to a wobble from an unsatisfactory orientation of the spin axis. Before the signal degraded too much to be useful, it recorded approximately 19 days of usable data. The mercury battery has long since died, but the orbit of the Vanguard is still highly predictable. Jacchia identified the usefulness of the spherical satellite, and it has been used for passive tracking to this day [25].

The next satellite used for neutral density comparison is the Explorer 7 satellite (NORAD tracking ID 00022). This is the seventh satellite in the 94-mission Explorer series, which is still active today [32]. Explorer 7 was launched on 21 October 1959 and has a perigee and apogee height of 501 km and 697 km, respectively. Its primary mission was measuring the solar X-ray, Lyman alpha flux, heavy cosmic rays, and trapped energetic particles. It was also tasked with observing micrometeoroids entering the atmosphere and observing the heat balance of the Earth's upper atmosphere [32]. Explorer 7 is the only satellite used in this study that is not a sphere with the exception of the CHAMP and GRACE satellite which provide neutral density from a different method. Explorer 7 is a double cone shape that measures 75 cm in height and 75 cm at its largest

width. This conical symmetry makes the drag coefficient predictable enough for the satellite to be used for neutral density estimations in a manner similar to completely spherical satellites. Consistent data was sent from the satellite until February 1961, and intermittent data continued until August 1961. After the power went out on the satellite, it was deemed an inert object in orbit. It was later realized by drag scientists that Explorer 7 is still a viable object to track for atmospheric drag purposes.

The third satellite used in this study is the CALSPHERE 1 (NORAD tracking ID 00900). This 0.98 kg satellite was launched on 6 October 1964 from Vandenberg Air Force Base (AFB) [32]. CALSPHERE 1 was funded by the Naval Research Laboratory to be an electronic intelligence satellite. There is not much information available for the composition and dimensions. However, the current perigee height is the highest of the six satellites at 974 km. Its orbit is nearly circular with an apogee of 1018 km. It is known as passive satellite for calibration purposes.

The Naval Research Laboratory made several other calibration satellites in addition to the CALSPHERE series. Starting in 1962, the SURveillance CALibration (SURCAL) satellites first launched from Vandenberg AFB. There were 15 satellites in total, with a variety of shapes and sizes. Two SURCAL satellites will be used for this study, SURCAL 150B and SURCAL 160 [32]. They were two of four satellites launched on 31 May 1967 onboard the same rocket, the Thor Augmented Delta-Agena. The SURCAL 150B is the smaller of the two satellites at 40.64 cm diameter and 1.5 kg in mass. Its orbit's current perigee and apogee height is 697 km and 713 km, respectively. The SURCAL 160 is 50.8 cm in diameter and 2.4 kg in mass. The current orbital perigee and apogee heights are 736 km and 751 km, respectively.

The final satellite used for this study is the RIGIDSPHERE 2. This is an aluminum spherical satellite that is 1.11 m in diameter and is 34 kg in mass. This is another calibration sphere and was manufactured in Rohr Corporation in Chula Vista, California for the Lincoln Laboratory in Massachusetts [32]. It was one of seven satellites that were part of a spherical satellite research project called Lincoln Calibration Sphere (LCS) 4. This was the last of the LCS series where only LCS 1 and LCS 4 were successfully launched and are still operational today. The RIGIDSPHERE's current perigee and apogee heights are 729 km and 828 km, respectively. A basic overview of the six satellites is given in Table 2. The information provided is for 1998, the beginning of the datasets used for analysis.

Table 2. Spherical Satellite Information, 1998

Spherical Satellites Information					
Satellite Name	Satellite ID	Launch Date	Apogee	Perigee	Shape
EXPLORER 7	22	OCT 1959	725	530	Double cone
VANGUARD 2	11	FEB 1959	2978	557	Sphere
RIGIDSPHERE 2	5398	AUG 1971	870	770	Sphere
SURCAL 150B	2909	MAY 1967	830	815	Sphere
SURCAL 160	2826	MAY 1967	845	830	Sphere
CALSPHERE 1	900	OCT 1964	1045	1005	Sphere

2.3.3 Neutral Density Derived from Orbital Integrators

The previous six satellites mentioned are not equipped with an accelerometer. Atmospheric drag researchers infer actual neutral density values from satellite orbit evolution. The TLE data from ground-based tracking has allowed the neutral density of

the atmosphere surrounding spherically-shaped satellites to be inferred. To get a true estimate of neutral density, the collisions of the all individual particles on the satellite have to be considered. These collisions affect the drag coefficient in equation (1). It can be very difficult to determine accurately for most satellites due a wide-range of shapes, however, the spherical satellites have a predictable drag coefficient because of their compact and symmetric shape. This is the primary reason they are used in this research.

There have been several techniques created over the past few decades to determine the mass density of the upper atmosphere. One of these methods uses TLE data mentioned in section 2.2.2. Software is used to convert TLE data into satellite drag information daily that is applied to empirical models [13]. Initially, one of the setbacks in using TLE data was the time it took to determine total mass density in the upper atmosphere. Picone et al. [30] has developed a method to limit the computational time for processing TLE data. Additionally, TLE data had RMS density model error of ~30%. Improvements by Doornbos et al. [13] has been able to drop the RMS error to as low as 12%. Precision and computational time is constantly being improved by hardware upgrades and better techniques; however, researchers assert that there is still room for progress [13].

Another method utilizing the TLE is the Simplified General Perturbations (SGP) model. It was first developed in the 1960's as an attempt to model an artificial satellite's orbit from TLE data [12]. Similar to early atmospheric drag models, the SGP series was based upon analytical theories. The SGP models theorized how an artificial satellite moved through the atmosphere. However, the drag density effects were not initially considered and had to be taken into account using additional analytical techniques. For

example, the original SGP model estimated the drag effect by rate of changes to the mean motion while the next model, SGP4, used a power density function [16]. Along with the two variants just mentioned, there are three additional SGP models that propagate a satellite through the atmosphere. To help distinguish the purpose of the models when used in conjunction with other models in this research, the SGP models will be referred to as propagators.

One challenge of using the SGP propagators with TLE data is identifying which one to use. The different propagators available are a result of accounting for rare, operational cases that may not be needed for the idealized orbit. Generally, the propagator is chosen for consistency which ends up being a judgment call by the user. The SGP series propagators have been improved and updated to be consistent for users. Officially, the SGP propagators are a Department of Defense (DoD) product, but in the early 1980's several users made changes to the code that was disseminated and not always compatible with the TLE data (which had also changed format) [46]. This was particularly an issue for the SGP4 standalone code which has had many modifications from its original release. Vallado et al. sought to document the official SGP4 code released by Air Force Space Command (AFSPC) in hopes to discourage continued use undocumented variations of the code [46].

While documentation of the original code and following improvements has been more substantial today, it is the improved code that is relevant to this paper. Bruce Bowman, previously of the Space Analyst Division of the Air Force Space Command (AFSPC), created a program utilizing phased array radar data in conjunction with a high fidelity orbit propagator called the Special Perturbations propagator and the Precise Orbit

Determination (POD) software to accurately determine a satellite's orbit fit [3]. This method also employs a daily averaged variation in the energy dissipation rate [4]. Under normal circumstances, the energy dissipation, or decay rates, is an average over several days rather than a daily average. This will lead to inaccuracies in the orbit fit which becomes a trickledown effect on the values obtained for the ballistic coefficient and neutral density values. For consistency with his work, the method Bowman employs and is used in this study will be referred to as the Special Perturbations method.

The ballistic coefficient is a manipulation of the drag coefficient that is referenced in Chapter II of this paper. The drag coefficient was given by equation (1) and is a simplistic view of the physics of atmospheric drag. Often times, atmospheric drag scientists will use the 'ballistic coefficient' as an operational parameter because it removes the dependence on the area and mass of the satellite. The ballistic coefficient is very important when trying to determine accurate energy dissipation rates. This is only possible if accurate ballistic coefficients are found first.

Ballistic coefficients will typically be highly variable over a one and two-day span. As Bowman describes, "these variations cannot be attributed to real density variations since the solar flux values are mainly constant during the most of the fit span time period" [4]. He describes the need for at least a three-day observation span for the orbits in order to get an acceptable ballistic coefficient value. Since this pertains to accurate orbit fitting over a sufficiently long observation span, a differential orbit correction program is used to make sure the values acquired from each orbit have limited error. The corrected orbit fits are obtained using a weighted least squares method which is part of the special perturbations program.

One aspect of the special perturbations orbit integration program is utilizing accurate geopotential. Geopotential is orders of magnitude greater than the neutral density values so accurate calculations are imperative for finding the spherical satellite density solutions. For his special perturbations program, Bowman used the Earth Gravitational Model 1996 (EGM96) geopotential model. This model calculated the geopotential of the Earth using spherical harmonics to the 360 order and degree. The EGM96 is a 70x70 degree solution model of the earth's gravitational field [14]. This is much too big to get timely calculations for the ballistic coefficient. Bowman truncated the model to 48x48 degree solutions and was able to get a value within an acceptable amount of error that was less than 4%.

Bowman uses the ballistic coefficient to solve for the energy dissipation rates (EDRs) [4]. EDRs are variables that describe the changes in orbit over a predetermined timeframe. Bowman used EDRs to calculate temperature and eventually neutral density, but he applied additional techniques to improve their accuracy. EDR values typically spanned three to eight days; however, Bowman overlapped the data by shifting the observation span by one day and calculated daily averages from this method being applied repeatedly. A weighting method was used to favor the values at the middle of the observation span rather than at the beginning and end. A simple computation of the EDRs is given by equation (14).

$$\bar{\varepsilon} = \frac{B}{2\Delta t} \int_0^{\Delta t} \rho V_{REL} (\vec{V}_{REL} \cdot \vec{V}_{SAT}) dt \quad (13)$$

The ρ is the atmospheric model density from the modified Jacchia 1970 model. The relative velocity ($\vec{V}_{REL}$) is the velocity relative to the rotating atmosphere, and the

satellite velocity ($\vec{V}_{SAT}$) is the velocity from the satellite reference frame. The Δt variable is the time span over which the EDR is computed in seconds. Finally, B is the ballistic coefficient that is given by equation (13).

Bowman details a further process of making daily EDR computations by constraining the average daily EDR values. These daily values are then used to calculate daily temperature values. The temperature computations take into account observed daily ($\bar{\epsilon}_{OBS}$) and corrected ($\bar{\epsilon}_{COR}$) EDR values, equation (15).

$$\bar{\epsilon}_{OBS} = \bar{\epsilon}_{COR} + \Delta T_c \frac{\partial \bar{\epsilon}_{COR}}{\partial T_c} + \frac{1}{2} \Delta T_c^2 \frac{\partial^2 \bar{\epsilon}_{COR}}{\partial T_c^2} \quad (14)$$

The ΔT_c variable is used to calculate the daily neutral density values. Utilizing the modified Jacchia 1970 model with the daily $F_{10.7}$ index, 81-day average $F_{10.7}$ index, the three-hour geomagnetic index a_p , the perigee time, perigee latitude, and perigee altitude in local solar time, an average daily density was found. In order to remove density variation due to variations over a satellite's orbit, a reference perigee height based upon years of historical perigee heights of a specific satellite is used in the same calculation. The combination of these two values will tend to lower the apogee but leave the perigee altitude unaltered. More information on the neutral density calculation process can be found from Bowman's paper [4].

The aforementioned paper includes five of the six spherical satellites used in this study. The missing satellite is the double-cone shaped Explorer 7. Bowman utilizes the purely spherical satellites first during his research but made the additional data for Explorer 7 available for this study's use. Bowman validated that his satellite data was much more accurate than traditional orbital propagators such as the SGP and SGP4,

respectively. The data is only available for the same timeframes for all six satellites from 1998 through 2004. As Chapter IV will detail, this data is centered on the solar maximum of 2002 and does not cover an entire solar minimum cycle.

III. Methodology

The goal of this research is to validate improved neutral density values in the TIE-GCM by adding helium as a major species and indicate the extent of the improvement. The first step is to run the TIE-GCM before the addition of helium into the model. The current published state of the TIE-GCM code without helium was available for download from National Center for Atmospheric Research (NCAR). As detailed in Chapter II, the model has been developed and improved since the early 1970's and is considered well-established for this research's purpose. Other than the inclusion of helium in the TIE-GCM's composition and diffusion equations, the raw code from NCAR was un-altered.

3.1 TIE-GCM Run without Helium

The TIE-GCM model was loaded onto the Air Force Research Laboratory's (AFRL) High Performance Computers (HPC). The model is not an overly computationally expensive code but for the ability to simulate near operational run times, the HPCs were deemed the most realistic and efficient tool for this research.

The TIE-GCM is initiated using a .run file within the HPC operating window. This file has several commands to direct the model according to the pre-determined initial conditions, which are contained within two additional parameterization files. The start date is specified by the user with a Julian year where the first day of the year is one and the last is 365 (366 for leap years). The model doesn't account for the leap years automatically, so it is incumbent upon the user to extend the year to 366 days, if necessary. Another parameter that can be specified is the time resolution. The NCAR website recommends 120 seconds which is what was used for this research.

The timespan of the TIE-GCM runs is based on the availability of comparison data. Simultaneous CHAMP and GRACE satellite data is available from 2002 - 2010. However, the start of the model run must be well in advance of the start of the comparison data in order to facilitate “spinning up” the model. Typical spin-ups of the TIE-GCM require 10-20 days; however, the simulated atmosphere in this study initially starts devoid of helium and allows it to flow in at the lower boundary. This requires about three months for the model to reach a realistic quasi-equilibrium in the thermosphere. The CHAMP launch date of 15 July 2000 dictates a model start date of 15 April 2000 at the latest, and this aligns well with the chosen model start date of 21 March. The TIE-GCM was completed on 31 December 2010 to coincide with the end of the comparison data.

The other set of data was acquired after the initial comparison of the TIE-GCM to CHAMP and GRACE. This data, which will be referred to as the spherical satellite data, begins on 1 January 1998 for all six satellites. The earlier date required re-initializing the model to a start date of day 80 in 1996. A start date in 1996 was chosen over 1997 because there was potential data for 1997 available during this research, but it was ultimately not used because it did not apply to all of the spherical satellites. All the spherical satellite data did span to 2004, which determined the end of the model run. It is worth noting that the TIE-GCM run could have been stopped at the end of 2000 to only cover the time not covered in the initial model run. The model is self-consistent and despite changes in the start date, the values from day-to-day and year-to-year from different runs will be near-identical [40]. However, the time spent covering the additional three years again was easy to accomplish operationally and did not spend a significant amount of the HPC allotted hours budget. Having contingency data available was also

deemed beneficial to the research. The no-helium run for the TIE-GCM took around four and a half hours, real time, to accomplish.

3.2 TIE-GCM Run with Helium

The procedure of the TIE-GCM helium run was nearly identical to the run without helium. The only difference required specifying in the .run file to use the helium variation of the model. During the span of the model run a disruption in the model occurred.

The TIE-GCM helium run was initiated during the northern hemisphere spring equinox with the same two-minute time step as the no-helium run described in section 3.1. There were no issues with the helium variation of the TIE-GCM until a disruption was encountered on day 140 of 2002. This disruption did not occur in the no-helium model run. Generally speaking, the model is relatively stable and does not abruptly stop even when it used on computers outside of NCAR. Further review of the date shows that a geomagnetic storm affected the Earth during this day. The K_p index went from 1 to 7 in a short time. This abrupt change is speculated to be the likely culprit for the crash. However, the increase was not as great as other events that occurred within the timeframe of the model run. One such event is the ‘Halloween Storm’ of 2003. In this event, a coronal mass ejection (CME) impacted the Earth with a near-direct hit. The resulting K_p indices were far greater relative to the one that crashed the model. The event that crashed the model was over a shorter timeframe which is likely the reason for the crash. In order to continue the model run with as little interference as possible, Dr. Sutton of AFRL suggested reducing the time step of the model for one day. A single day was chosen to

account for the K_p index increase for the maximum duration of the solar storm. This technique was applied to the TIE-GCM, and it required restarting it twice due to the model needing to be switched back to the 120 second time-step. After the disruption and restoration, the model continued until 2010 when it was scheduled to stop.

It could be argued that the model should have been run on the 60 second time step that fixed the disruption during the helium iteration. When it comes to numerical modelling, there are concessions that have to be made in order to accomplish the goal of the model. Decreasing the time step to 60 seconds would have doubled the computational time. However, the TIE-GCM is recommended to run on a 120 second time step for the pre-helium version available from NCAR. In order to limit the research to the suggested time step, the consistent time step of 120 seconds was used when possible.

3.3 Sampling the TIE-GCM at Satellite Orbits

Once the TIE-GCM runs were complete, two sets of data for the full three dimensional model were available. A comparison between the two models is possible, but it doesn't reveal how well the model performs in relation to physical data. The next objective was to match the model data with the satellite orbit locations so a direct comparison in neutral density values can be made between the two TIE-GCM runs.

A comparison of the model data to the satellite data required identifying where the satellite orbits occurred within the TIE-GCM data. Since the model is a four dimensional depiction of the atmosphere from 97 km to approximately 600 km on a log-pressure scale, the model will need to be converted to an altitude scale and sampled at each of the satellite's orbits to simulate the position in the atmosphere where the satellite

is located. This requires matching the altitude, time, and spatial variables of the TIE-GCM to that of each satellite.

The conversion from log pressure scale to altitude utilizes the logarithmic pressure (log-pressure) from Chapter II, $z = \ln(P_0/p)$. In order to convert from a log-pressure level to an altitude, hydrostatic balance has to be assumed. The pressure scale height, $H(z) = kT(z)/m(z)g$, is used to make this conversion with each value determined by the model. In the case of temperature, the model uses the conservation of energy equation to calculate a value for each log-pressure level. Numerical integration of the scale height can be accomplished to convert to altitude. The assumptions made with this conversion are constant gravity and the height of the bottom log-pressure level is known. The conversion to altitude is part of the TIE-GCM sampling process.

The sampling of the satellite data to the TIE-GCM was completed using a MATLAB function that loaded in both sets of data. In order for the function to work, the satellite data requires information on the altitude, local time, time of each data point (in seconds), latitude, and longitude. Additional information can be included with the dataset and is not limited by the function. For example, a satellite dataset can include information on a measurement of temperature. This data has nothing to do with sampling the TIE-GCM, but it will be included in the output of the MATLAB function. The satellite data is required to be in a .txt file or a file that is similarly formatted where each unique subset of information is arranged in columns. Once the satellite and TIE-GCM data is read into MATLAB, the function takes the TIE-GCM's longitudinal domain timeframe and converts it to solar local time (LT) to match the satellite's frame of reference. The TIE-GCM does not distinguish between 0:00 local time LT and 24:00 LT in the data file. In

order to output into daily files, the function also converts the 23.66667 hour satellite day output into the 0:00 to 24:00 LT of the satellite.

After the time conversion is completed on a daily scale, the most important aspect of the sampling function takes place. The altitude of the satellite is extremely important to the process of sampling each satellite's location within the model. As detailed in section 2.2.2, the TIE-GCM's upper boundary averages around 600 km but can range from 500 – 700 km depending on solar activity. The CHAMP and GRACE satellite were at average starting altitudes of 454 km and 500 km in circular orbits, respectively. With the exception of extremely low solar activity conditions when the atmosphere is contracted lower than the 500 km range, these three satellites are within the confines of the model data. The sampling of the CHAMP and GRACE data is direct interpolation of the satellite's orbit. In the case of the spherical satellites used in this study with perigee heights ranging from 500-1000 km, the majority of the orbits go outside the model's upper boundary. For example, the two lower perigee height satellites, Vanguard 2 and Explorer 7, have elliptical orbits that will occasionally go above the 500 – 700 km altitude range. This requires an assumption about the model to get relevant data at higher altitudes.

As discussed in section 2.2.2, the model's composition output is a result of diffusion of the individual species with interactions considered. Coupled with ionospheric photochemical processes, the model can physically describe the composition of the major species throughout the thermosphere and lower exosphere. In this study, the model needs to be extended to sample the higher altitude orbits of the spherical satellite data. This is accomplished by assuming complete diffusive equilibrium above the model's upper

boundary. Diffusive equilibrium is defined as a steady state where the individual species disperse independently of one another because the collision frequency is small [38]. Instead of the photochemical processes and interactions taken into account at lower boundaries, the neutral density species diffuse according to their scale height. According to Figures 1 and 2 in Chapter II, the total neutral density value at 500 km for solar minimum and solar maximum ranges from 10^{-12} - 10^{-13} . The upper boundary of the TIE-GCM is approximately the lower portion of the exosphere. Within the exosphere of a planet, the mean-free-path is considered to be sufficiently long enough to allow particles to follow ballistic trajectories [38]. Classically, this means that the neutral density particles no longer collide with one another. Banks et al. describes diffusive equilibrium as a reasonable approximation of the lower exosphere [1]. It should be noted that only particles with sufficient energy continue to travel at extremely high altitudes. Above approximately 1000 km, the diffusive equilibrium assumption begins to fall apart. There are apogee heights of two satellites used in this study that extend above this limit. As the next section will describe, those neutral density values will not impact the comparison that takes place due to a weighted average technique applied to the data.

Once the MATLAB function takes into account extrapolation by diffusive equilibrium for relevant satellites, it will officially sample all data points of the satellite data. The amount of data that is output as arrays after it is sampled is dependent on how much data goes in. The output of the MATLAB script is divided into days and each day contains several arrays of the data that were inputted into the function. Additional information outputted is the total neutral density of the TIE-GCM at the satellite's location and a binary index of whether extrapolation was used sample this data. More

values are available from the TIE-GCM model run dataset, but the neutral density values are sufficient for this study. The individual array sizes depend on the amount of data points recorded along an orbit. In most cases, this is a time interval that is recorded at a predetermined period. The raw data was binned into 0.1 Hz for the CHAMP satellite and .2 Hz for the GRACE satellites into 3-degree latitude bins. This resulted in an average of 1800 and 1850 data points per day for CHAMP and GRACE, respectively. The spherical satellite data could be divided into a user specified amount of data points by altering the time interval. This was due to the fact that the satellites' orbits were propagated using TLEs with the SGP4 propagator, rather than relying on the orbital ephemeris from an instrument measurement data file. A 30 second time interval was used for these satellites which translates to 2880 data points for each day.

3.4 Creating Daily Averages

As mentioned in the previous section, a large amount of data is available for just one day. The total data spans almost a decade for CHAMP and GRACE. There are many nuances that occur within a day concerning a satellites orbit. The atmosphere expands and contracts diurnally as well as seasonally and due to changes in solar activity. A study into the diurnal changes will not be completed for this study. The primary reason behind this decision is because the elliptical satellites will not capture the diurnal variations consistently with neutral density values varying along the satellites' orbit. Averaging the entire orbit of each satellite daily will provide more consistent data and will still give information on the solar cycle variability. Additionally, all the satellites take approximately 12 – 16 orbits within a day, so a daily average was considered sufficiently

long to limit the extremes that can occur unique to each satellite's orbit. Finally, periods of missing data from four of the nine datasets didn't significantly impact the average. Due to the difference between circular and elliptical orbits, two different averaging equations were used to make daily averages.

3.4.1 CHAMP and GRACE Daily Averages

The averaging of the CHAMP and GRACE satellite data was straightforward to compute due to the satellites' circular orbits. This means that the orbits did not alter in altitude significantly. Variations recorded along their orbit by the accelerometer were a result of latitudinal and local time changes. A daily average was computed by simply adding each data point for that day and dividing by the total number of data points. Missing data was more common from the instruments on these satellites for a variety of reasons. The main reason data was missing from these satellites was due to quality control. Repositioning the satellite with thrusters resulted in bad data. Additionally, bad data resulted from the star trackers on the satellite that keep it in position losing a lock and caused a different orientation of the satellite [40]. Other potential disruptions in data occur during software upgrades and other computer related processes. These reasons collectively have limited the total daily averaged number by over a month for the three satellites.

3.4.2 Spherical Satellite Daily Weighted Averages

In general, missing data was less common for the spherical satellites due to relative consistency from ground-based tracking. The elliptical orbits required a different averaging approach than the circular orbits of CHAMP and GRACE. The relevant neutral

density values can be extreme between the apogee and perigee height. In order to limit artificially low values of neutral density at the apogee of a satellite, a ‘weighted average’ is needed. The neutral density values at more relevant altitudes are found at the perigee of the satellites. The perigee of an elliptically orbiting satellite is also where the velocity is highest. As a result, the velocities will be used as the ‘weight’ of neutral density values near perigee. This approach was also used in a similar study by Emmert et al. [16] with the weights seen in equation (15).

$$\lambda_i = \rho_{mod,i} v_i^3 F \quad (15)$$

The density from the TIE-GCM sampled at the spherical satellite orbits is $\rho_{mod,i}$ and the velocity of the satellite is given by v^3 where it is cubed. The velocities were determined by the initial TLE data and SGP4 propagator output. The subscript ‘ i ’ is for each data point in a day. The variable ‘ F ’ is a correction factor to account for the co-rotation velocity on the orbit and winds. For purposes of simplicity, a value of one was used for this study. Changing this value would be a simple correction factor if deemed necessary for future studies. This will be detailed further in Chapter V. The weighted average daily density value is given by equation (16)

$$\bar{\rho} = \frac{\sum_i [\lambda_i \rho_{mod,i}]}{\sum_i [\lambda_i]}, \quad (16)$$

Where λ_i is the weight from equation (15). The weighted average approach was also calculated for the altitude of each satellite, equation (17)

$$\bar{h} = \frac{\sum_i [\lambda_i h_i]}{\sum_i [\lambda_i]}, \quad (17)$$

where h_i is the altitude from the TLE and SGP4 data.

In order to visualize the emphasized portion of the orbit, Figure 5 depicts two different satellite orbits. The largest weights in the elliptical orbit's daily average are near perigee because of the velocity. The two black lines on the figure are roughly where the cutoff is for the influence on the weighted average magnitude, equation (16). Figure 5 shows a simplistic representation of the satellite orbits. The circular orbits can be averaged evenly since the neutral density values are representative of a constant altitude. The values at apogee of the elliptical orbit will be much different than the values near perigee since neutral density decreases exponentially with altitude.

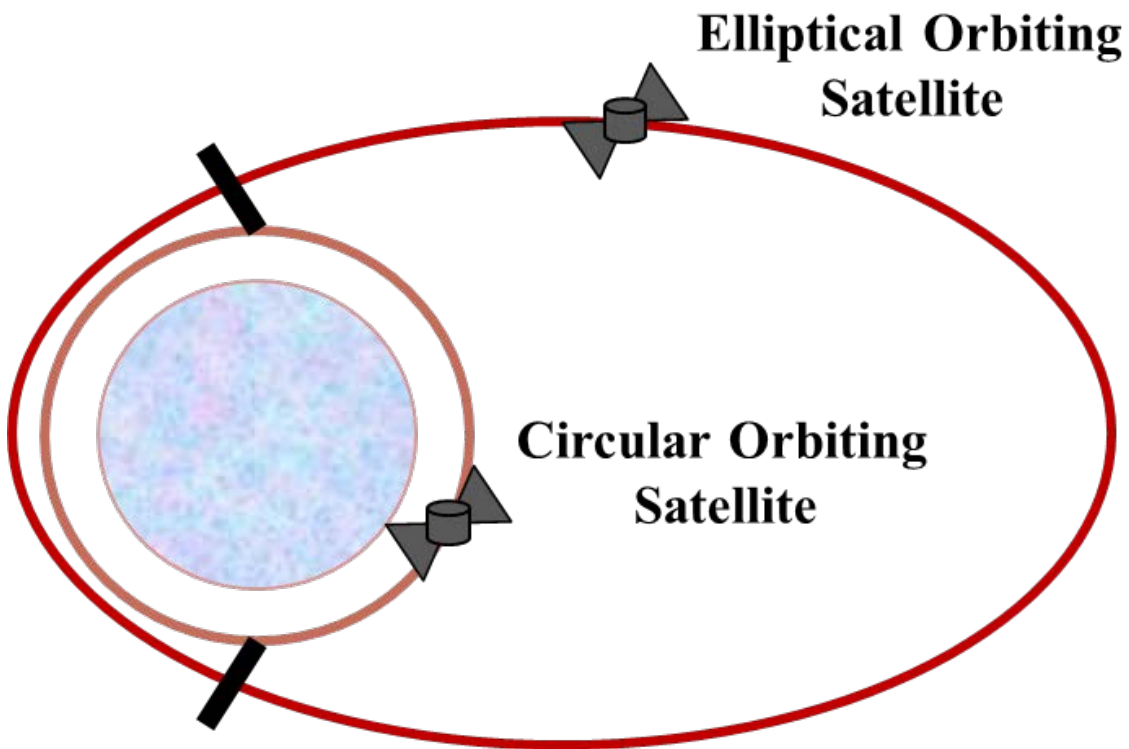


Figure 5. Satellite Orbit Types.

After the weighted average calculations were completed, TIE-GCM data at nine different satellite orbits was available for comparison. The analysis of data was done in the order of the data available. The first comparison was done for the CHAMP and GRACE satellites. The spherical satellite neutral density data was acquired at a later date. It should be noted that another set of spherical satellite data was provided towards the end of this research timeframe.

IV. Results and Analysis

The most important aspect of the data analysis is a comparison of the total neutral density values between the satellite data and the two model runs. There are nine satellite datasets available for analysis but only eight are used because of the near-identical data of the two GRACE satellites. The information is displayed graphically, in tabular form, or both. Further analysis includes solar activity and error correlation across the entire set of data. The timeframes when the two TIE-GCM runs differ the most is the biggest point of emphasis for analysis.

4.1 The Data and Analysis Techniques

As mentioned, eight of the nine available satellite datasets are analyzed in this chapter. The main comparisons that take place are total neutral density and error. However, solar flux and geomagnetic activity are also plotted for use in the comparison. Each satellite has neutral density and error plotted over the available timeframe. However, the two solar activity parameters are initially plotted from day one of 1998 to day 211 of 2010; the entire span of data. Yearly plots are made when necessary to show features not seen at a larger scale.

Solar flux and geomagnetic activity are paramount to the TIE-GCM because together these parameters serve as a driver for changes in the model outside of the normal circulation of the atmosphere. The solar flux represents the overall state of the atmosphere in relation to how much it has expanded or contracted due to output from the Sun. As described in Chapter II, the $F_{10.7}$ index is used as a proxy for the amount of

photoionization occurring within the model and can be used to illustrate why there are longer-timescale differences in the neutral density. The solar flux is plotted in Figure 6.

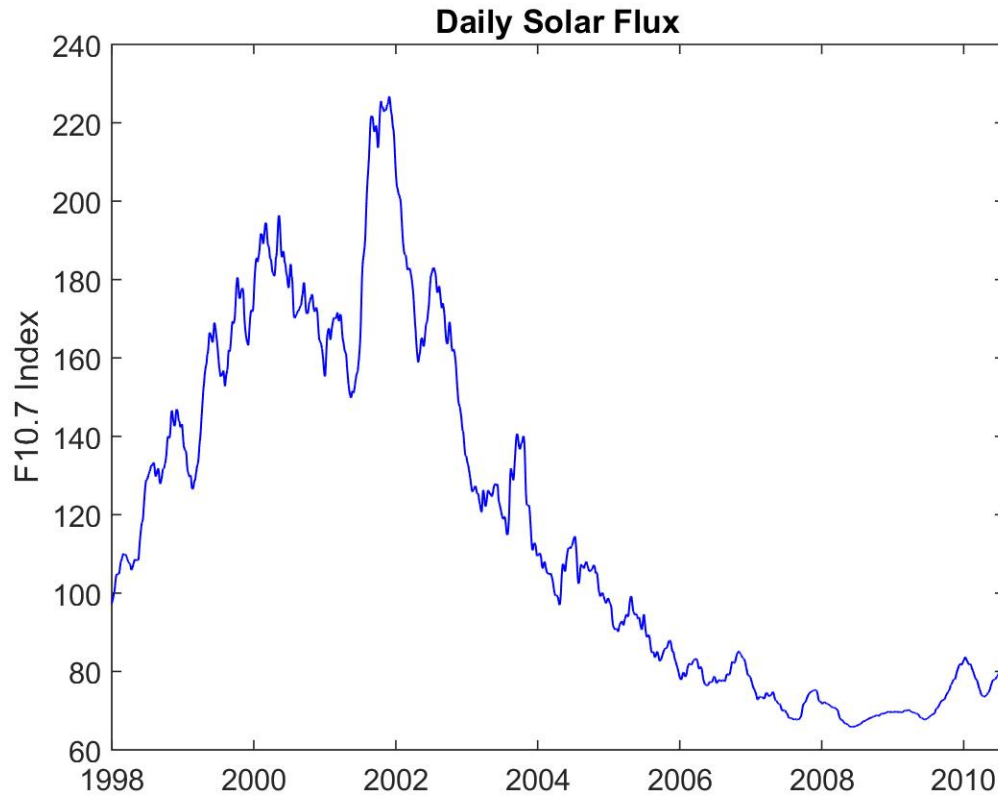


Figure 6. 81-Day Averaged Solar Flux. The $F_{10.7}$ index was averaged over 81 days (approximately three solar rotations) for the combined timeframes of the satellite data.

Figure 6 shows the 81-day average $F_{10.7}$ index to get a general idea of how much power is reaching the Earth from the sun. The 81-day average is used to limit the extremes within the daily $F_{10.7}$ index and get a clearer indication of the solar cycle. In general, the $F_{10.7}$ index is not indicative of shorter-timescale events such as solar flares or coronal mass ejections. Figure 6 does display the solar maximum and solar minimum very well within the data. The peak of solar maximum occurs in December 2000, which

is displaced from the highest peak in Figure 6. The neutral density data for all the satellites will show the impact of the increased activity in the data with respect to the expansion of the atmosphere. The solar minimum occurs in December 2008. Towards the end of the timeframe of the data, an increase in the solar flux is noticeable as solar activity starts to increase. In general, the most extreme solar minimum conditions of 2008-2009 is when helium is most prevalent in the atmosphere.

The solar flux is a proxy for large-scale variations but does not account for the rapid changes that can happen within minutes to hours. A better representation of these changes is the K_p index mentioned in Chapter II. In order to represent this in graphical format for comparison purpose, the A_p index is plotted in Figure 7. Recall from Chapter II that the K_p and A_p indices show the same data. The A_p index is a linearization of the K_p index.

Higher index values in Figures 6 and 7 occur in the early 2000's during increased solar activity. However, the highest magnitude peak in Figure 6 occurs in late 2001 and early 2002. This does not coincide with the highest amount of geomagnetic storming in Figure 7. The greatest amount of geomagnetic activity occurs toward the end of 2003 when events such as the 'Halloween Storm' occurred. The solar flux increased as the series of geomagnetic storms were occurring, but it was in an overall decline starting from the beginning of 2002 through solar minimum in 2008 and 2009. Overall, Figures 6 and 7 illustrate that the indices do not mirror each other, and individually each index can coincide with various features in the neutral density data. The various effects of each index is revealed in the analysis of the individual satellites.

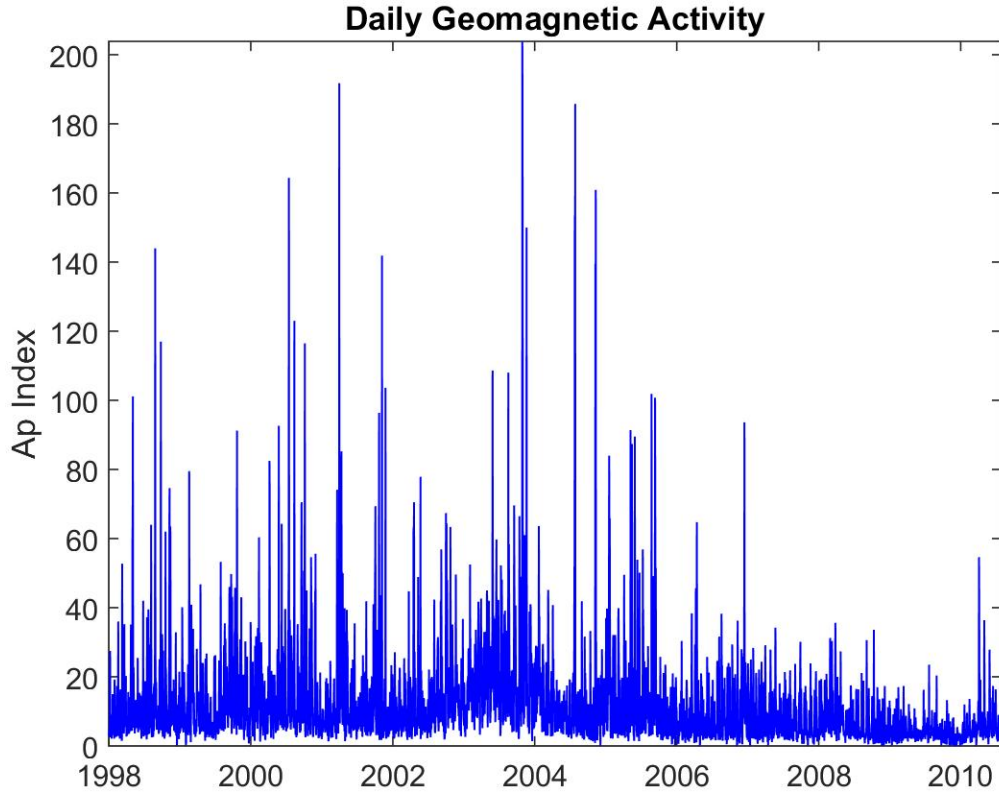


Figure 7. Daily Geomagnetic Activity. The A_p index is a daily average of the a_p index.

The satellite data plots include the total neutral density and percentage error. The neutral density figures are comprised of three plots that include the two TIE-GCM runs and the satellite data. The error plots are derived using equation (18).

$$Error(\%) = \left| \frac{(\rho_{mod} - \rho_{sat})}{(\rho_{sat})} \right| \times 100 \quad (18)$$

The ρ_{mod} variable is the model density and the ρ_{sat} variable is the satellite density. Care should be taken when analyzing the error data. The neutral density magnitude is on the order of 10^{-12} to 10^{-17} . As a result, TIE-GCM neutral density values that are above the satellite data can have errors well above 100%. This can potentially lead to extreme error

values but the majority of the time the model data does not exceed the satellite data.

When the model data is below the satellite data, there is a limit to how high the error can be. The maximum amount of error that can be calculated is 100% and this only occurs if the model data is zero. When the difference between the model data and the satellite data is greater than two orders of magnitude, the error is between 99% and 100%. Future studies should improve upon this error calculation.

The total neutral density is plotted consecutively from the beginning of the data through the end on a semi-logarithmic plot. For simplicity's sake, the TIE-GCM run with helium as a major species is referred to as 'With Helium' and the 'Without Helium' run without helium as a major species is referred to as 'Without Helium'. The data was plotted in the order of the legend, which is the 'With Helium', 'Without Helium', and the satellite data. One potential consequence of this is the plots will cover each other if they are close in magnitude. This is the case for lower-altitude satellites as the impact of the addition of helium is not as significant.

Oftentimes the seven to nine year scale is too large to make out what is occurring within the data. In order to see features more thoroughly, the neutral density, error, and solar activity are plotted for individual years. Occasionally, the same year is plotted for multiple satellites to compare, but this does not apply to all satellites in order to limit the number of figures shown.

4.2 TIE-GCM Sampled at CHAMP and GRACE Altitudes

The sampling of the CHAMP and GRACE satellites within the model was chronologically the first to be accomplished in this study. Included helium as a major

species in the TIE-GCM at the CHAMP and GRACE satellite altitudes (454 km and 500 km) is relatively low because the heavier elements of O₂ and O are still dominant.

Recalling Figures 1 and 2 in Chapter II, helium does not start to become the dominant neutral species until approximately 450 km for solar minimum and 660 km for solar maximum. Therefore, changes in the TIE-GCM's performance only occur during solar minimum for these satellites.

4.2.1 CHAMP Analysis

Starting in August 2002, the neutral density at the CHAMP altitude is plotted for both model runs and the satellite in Figure 8. The most notable characteristic of Figure 8 or lack thereof is the missing 'With Helium' plot. As mentioned in section 4.1, this is a result of the 'Without Helium' run being plotted over the 'With Helium' run because of near identical values. The three datasets align very consistently across the nine years with only a little deviation between the model and satellite visible. Even when the atmosphere expanded due to solar activity during the beginning of 2002, the model's neutral density values do not deviate from the satellite derived data. The rise in total neutral density starting in mid-2009 through 2010 is not associated with the increased solar activity. Instead, the CHAMP satellite was at the end of its orbit and was allowed to decay in altitude without impediment.

Overall, there is very low error between the TIE-GCM and the CHAMP neutral density data. This is depicted in Figure 9 using percent error calculated from equation (18). Through the majority of the nine years, the error remains well below 50%. This includes both runs of the model as the blue 'With Helium' plot is only slightly visible on

the figure. The actual average error across the entire dataset was: 15.92% and 15.62% for ‘With Helium’ and ‘Without Helium’, respectively. This includes the few spikes in the error that result from anomalies in the satellite data. It should be noted that the 2008 error spike anomalies are likely the result of measurements that were not included in the quality control since the error is concentrated on a single day. Aside from the spikes, the two average error values are relatively low. This small deviation between the models indicates that the contribution of helium at this altitude is low. This is expected considering that helium doesn’t become the dominant species until ~460 km at solar minimum.

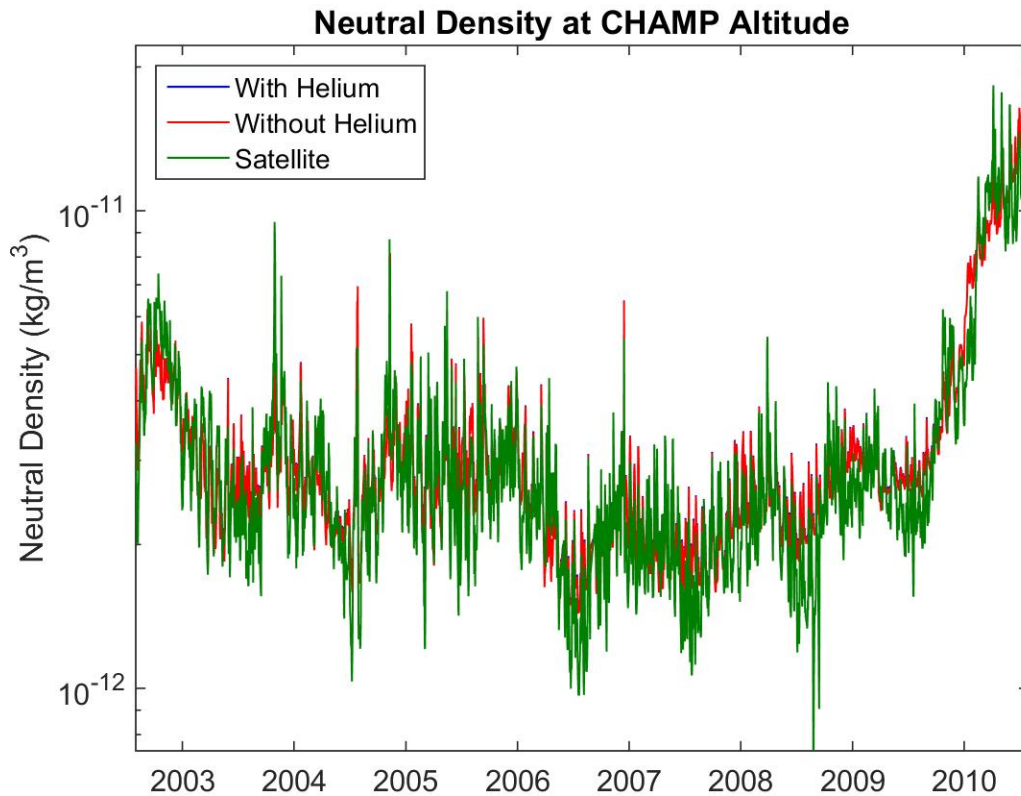


Figure 8. Neutral Density at CHAMP Altitude. The total neutral density at the CHAMP satellite altitude is plotted for the satellite (green) and the both runs of the TIE-GCM (blue) and (red). The satellite is in a circular orbit with a starting altitude of 454 km.

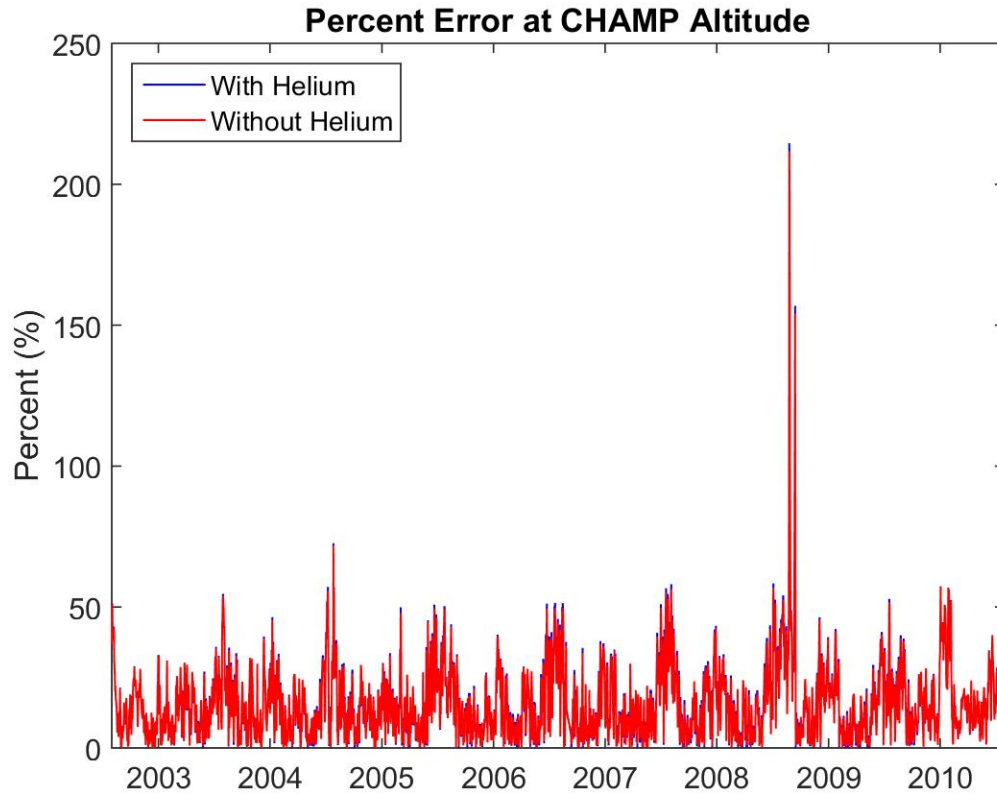


Figure 9. Percent Error at CHAMP Altitude. The percentage of error between the TIE-GCM ‘With Helium’ (blue) and the ‘Without Helium’ run (red) are plotted. The satellite is in a circular orbit with a starting altitude of 454 km.

4.2.2 GRACE B Analysis

The GRACE satellites start at an altitude that is approximately 50 km higher than the beginning CHAMP satellite altitude. Even with this increase in altitude, the difference between the two model runs is expected to be low. As mentioned, only one (GRACE B) of the GRACE satellites is analyzed. With the orbits averaging only 220 km distance apart, the data is assumed to be near-identical. That being said, the GRACE B satellite was chosen because it had a few less error spikes in the data. The neutral density plot of the GRACE B satellite is given in Figure 10.

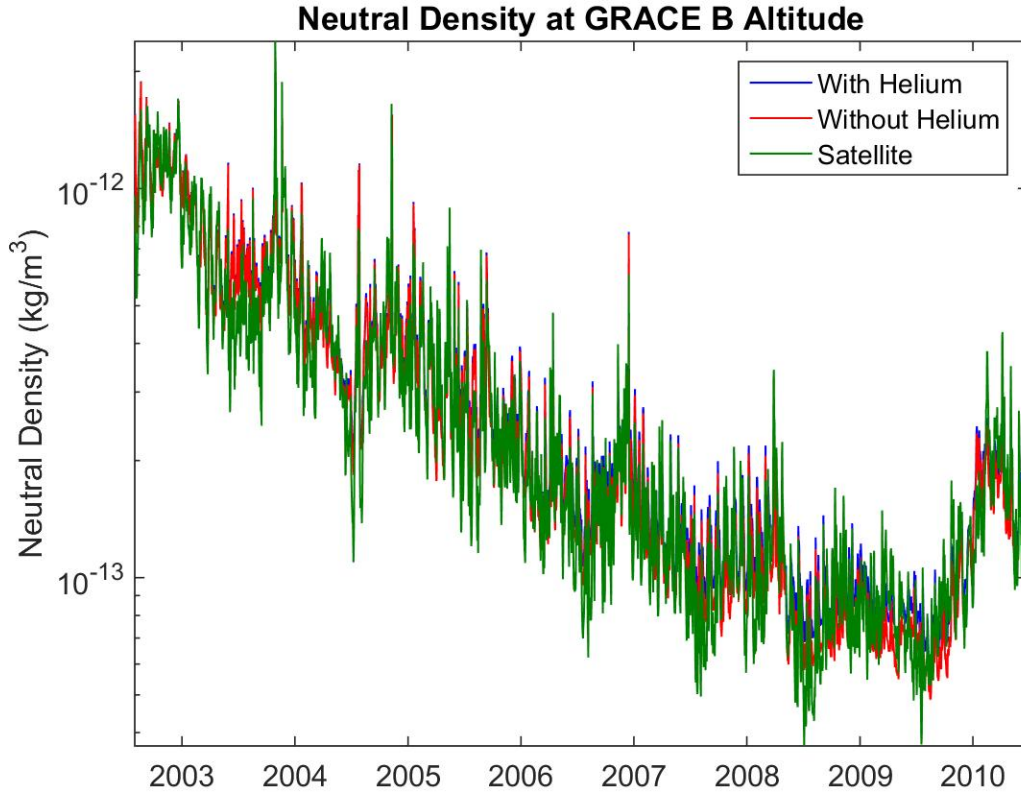


Figure 10. Neutral Density at GRACE B Altitude. The total neutral density at the GRACE B satellite altitude is plotted for the satellite (green) and the both runs of the TIE-GCM (blue) and (red). The satellite is in a circular orbit with a starting altitude of 500 km.

The GRACE B neutral density profile differs from the CHAMP data because it better captures the contraction of the atmosphere as the data moves from solar maximum to solar minimum. The change of neutral density by an order of magnitude correlates to the clear decrease in solar flux shown in Figure 6. Additionally, the increase in neutral density at the end of the data partially correlates with the increase in solar flux but it actually better aligns with the increase in A_p index.

Figure 11 shows a moderate increase in the $F_{10.7}$ index starting in the latter half of 2009, while the A_p index remains very low during the same timeframe. The atmosphere

does expand and the neutral density increases as a result of the $F_{10.7}$ index. However, there is a dip in the $F_{10.7}$ index from January to March of 2010. The neutral density continues to increase during this same period. The A_p index increases at the minimum of the $F_{10.7}$ index in March 2010 and is responsible for the higher peak seen in the neutral density data of Figure 10. The decrease in neutral density at the end of the plotted data is the atmosphere contracting after the quick expansion from the geomagnetic activity depicted by the peaks in the A_p index in Figure 11.

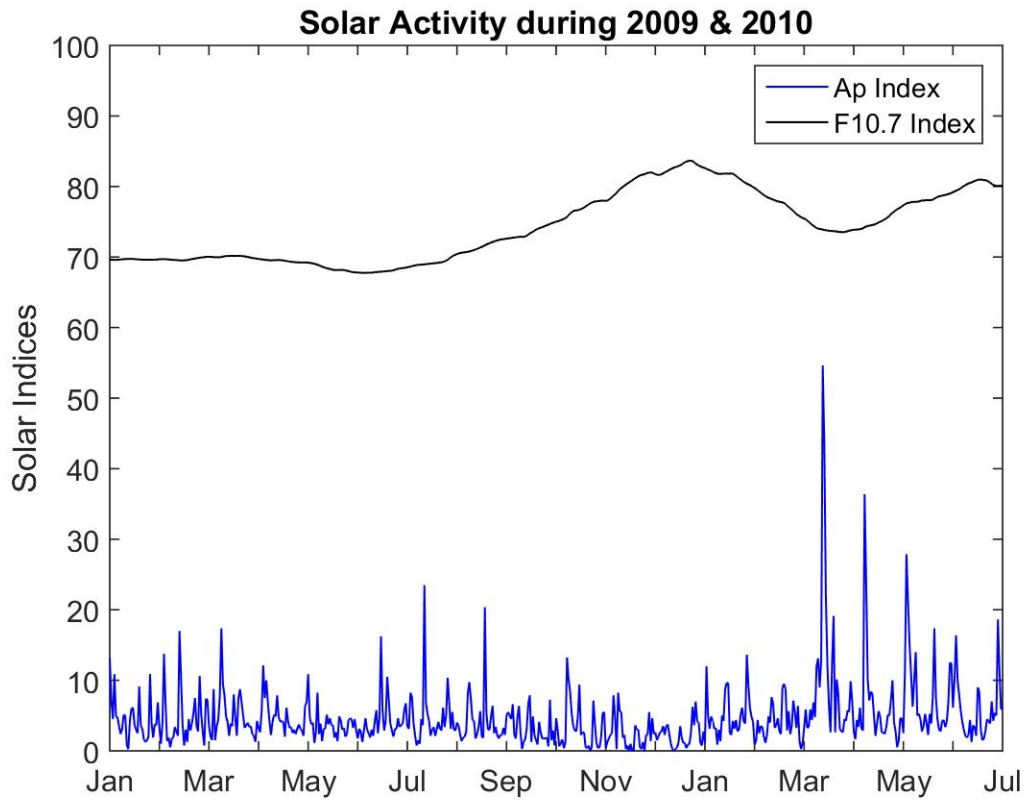


Figure 11. Solar Activity during 2009 - 2010. A daily averaged plot of the A_p index (blue) and the $F_{10.7}$ index (black) for 2009 and mid-2010.

This analysis demonstrates the changes in the neutral density as a result of the solar activity. Both TIE-GCM runs account for this change because of the input of these indices into the model. More error would result from the model not being able to account for the changes in neutral density from the heating and cooling of the atmosphere. The error in the model at the GRACE B altitude is plotting in Figure 12.

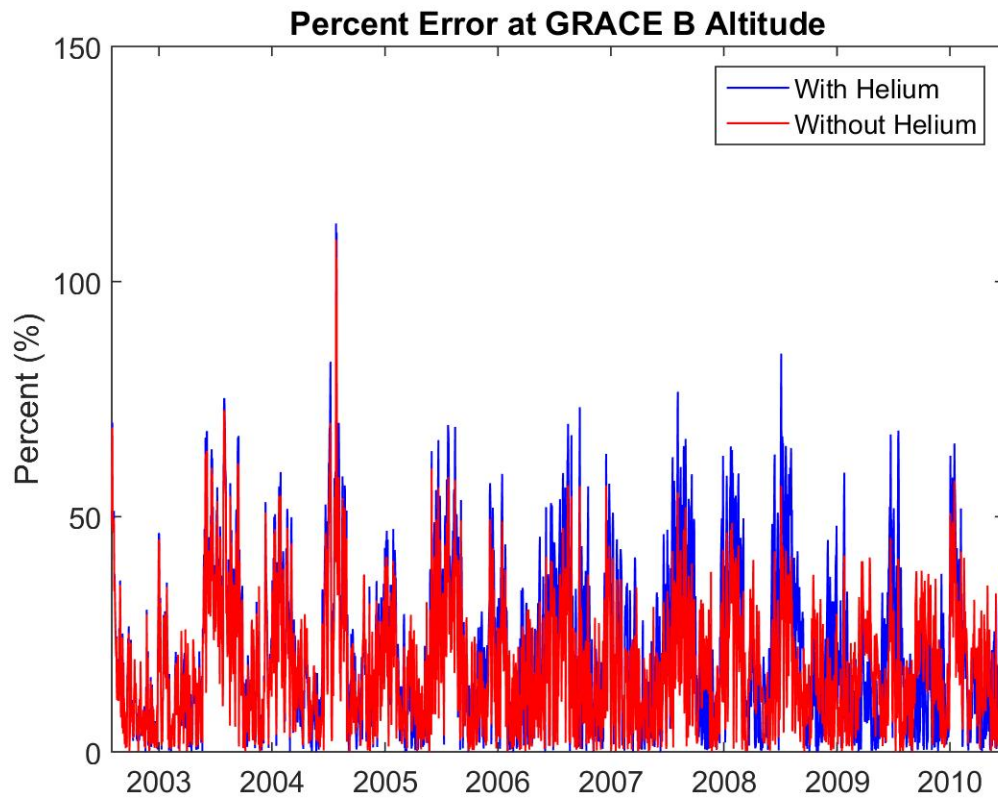


Figure 12. Percent Error at GRACE B Altitude. The percentage of error between the TIE-GCM 'With Helium' run (blue) and the 'Without Helium' run (red) are plotted. The satellite is in a circular orbit with a starting altitude of 500 km.

There are clear differences in error between the model runs seen in Figure 12. These differences were also visible to a lesser degree in Figure 11. It is during the periods

of low solar activity where the difference between the two model runs is greatest. There is more error in the TIE-GCM at the GRACE satellite altitude compared to the CHAMP altitude error data. Over the entire span of the data, the 'With Helium' run error averages 20.73% and the 'Without Helium' run averages 17.92%. This nearly 3% difference in model performance shows that the TIE-GCM does not necessarily improve with the addition of helium as a major species, but as the analysis in the following sections will show, this is a relatively minor difference in performance. Even so, the addition of helium as a major species into the TIE-GCM decreases its neutral density calculation at the 500 km altitude range of the model. A closer look at the error during lower solar activity conditions in the last five years reveals that the error is slightly lower for both model runs with the 'With Helium' and the 'Without Helium' runs having 20.17% and 16.91% error, respectively. However, the 3% difference in performance remains.

The GRACE B error is slightly higher than CHAMP but it is still relatively low for both model runs. Figure 12 shows that there is a semi-annual periodicity profile. The model has seasonal differences that can become apparent when looking closer at the two model runs. The best range of data to observe is from 2008-2009 because it is during the lowest solar flux conditions, and a difference between the two model runs is greatest.

Figures 13 and 14 plot the error for the individual years of 2008 and 2009.

There is a clear oscillatory nature in the error plot during an individual year. The error percentage peaks seasonally with the greatest magnitude occurring during the periods of Dec-Feb and Jun-Aug. During these time periods, the 'With Helium' run has the greatest amount of error, surpassing the 'Without Helium' run. However, during the periods of Mar-May and Sep-Nov, the 'Without Helium' model iteration has a larger

error percentage. The ‘With Helium’ run error for the solstice time period is 38.01% and the Mar-May and Sep-Nov time period is 12.63%. In contrast, the ‘Without Helium’ run error for the Dec-Feb and Jun-Aug time period is 24.19% and the Mar-May and Sep-Nov time period is 13.66%. While the ‘With Helium’ run does slightly improve during Mar-May and Sep-Nov timeframe, the Dec-Feb and Jun-Aug periods show why this iteration is performing worse overall.

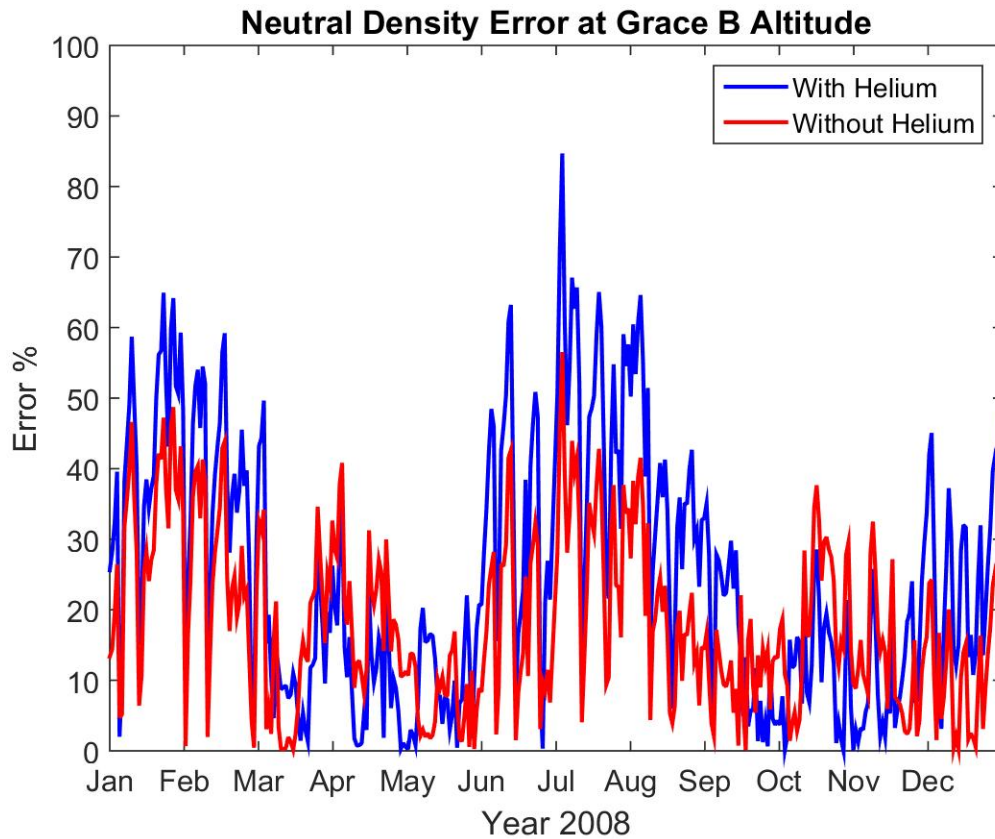


Figure 13. Percent Error at GRACE B Altitude, 2008.

The error plot for 2009 was made to verify that the biases seen in 2008 are not independent of year. Figure 14 shows the same oscillatory features seen in Figure 13.

Again, the lower error percentage occurs during the Mar-May and Sep-Nov timeframes for the 'With Helium' model run and Dec-Feb and Jun-Aug timeframes for the 'Without Helium' run. Based upon the plot, the difference in error is not as drastic as in 2008 and the 'With Helium' run performs better overall. The 'With Helium' run error for the Dec-Feb and Jun-Aug time period is 18.88% and the Mar-May and Sep-Nov time period is 11.58%. The 'Without Helium' run error is greater for the Mar-May and Sep-Nov timeframe at 18.76% and is lower for the Dec-Feb and Jun-Aug period at 12.07%.

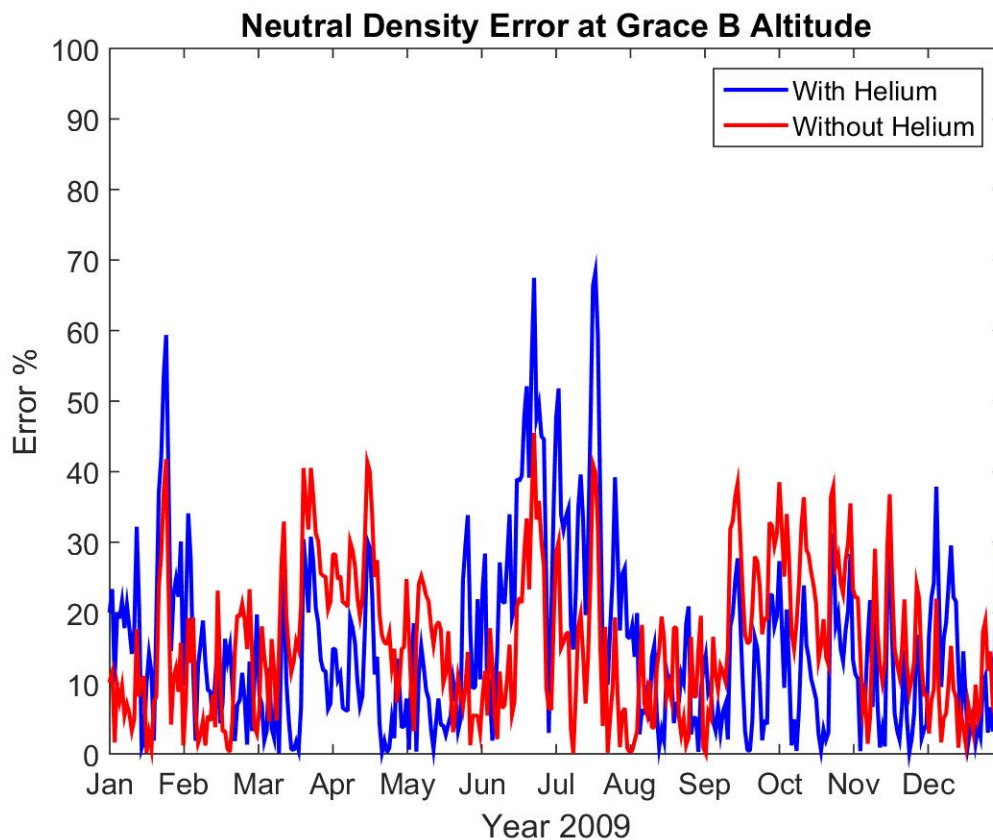


Figure 14. Percent Error at GRACE B Altitude, 2009.

The higher values of error are a result of the neutral density values of the model exceeding the satellite neutral density values. Figure 15 plots the neutral density values for 2008 and the satellite data shows a wider magnitude range than the model data. The two TIE-GCM runs follow generally the same density profile as the satellite data but do not reach the extremes of the data. The seasonal dependence that is depicted in Figures 13 and 14 is a result of the satellite measured density being higher during the Mar-May and Sep-Nov time frames and lower during the Dec-Feb and Jun-Aug periods. The error is higher during the Dec-Feb and Jun-Aug periods as a result. Ultimately, the model does not differ significantly between the two runs, but the 'With Helium' run is consistently higher. This difference is noticeable because of the lower solar activity when helium can contribute to the total neutral density.

As mentioned, the extremes in magnitude are not as pronounced for the model, but this characteristic plays a role in the difference of error between the two model runs. The 'With Helium' run's neutral density values are consistently higher in terms of total neutral density than the 'Without Helium' run's values. This means that the inclusion of helium as a major species in the TIE-GCM at approximately 500 km during solar minimum condition raises the total neutral density value. The solar flux increase slightly in 2009, but the same general pattern is seen in the neutral density values in Figure 16.

Overall, the model performs relatively consistently from 2008 and 2009. Towards the end of 2009, an increase in the overall neutral density profile is apparent. This coincides with the increase in solar activity that takes place during that time period. With the neutral density increasing even during the December solstice timeframe, it shows that the TIE-GCM accounts for the solar activity change fairly well. In fact, the increase

during the latter part of December is closer to the helium run which is a deviation from the other solstice time periods analyzed. A closer look at the solar flux conditions from 2008-2009 is shown in Figure 17. One characteristic to note from Figure 17 is that there is no clear correlation between the solar activity and the Mar-May and Sep-Nov maxima that were observed through 2008 and 2009. Both TIE-GCM runs show the general profile of the satellite data but are missing the seasonal extremes.

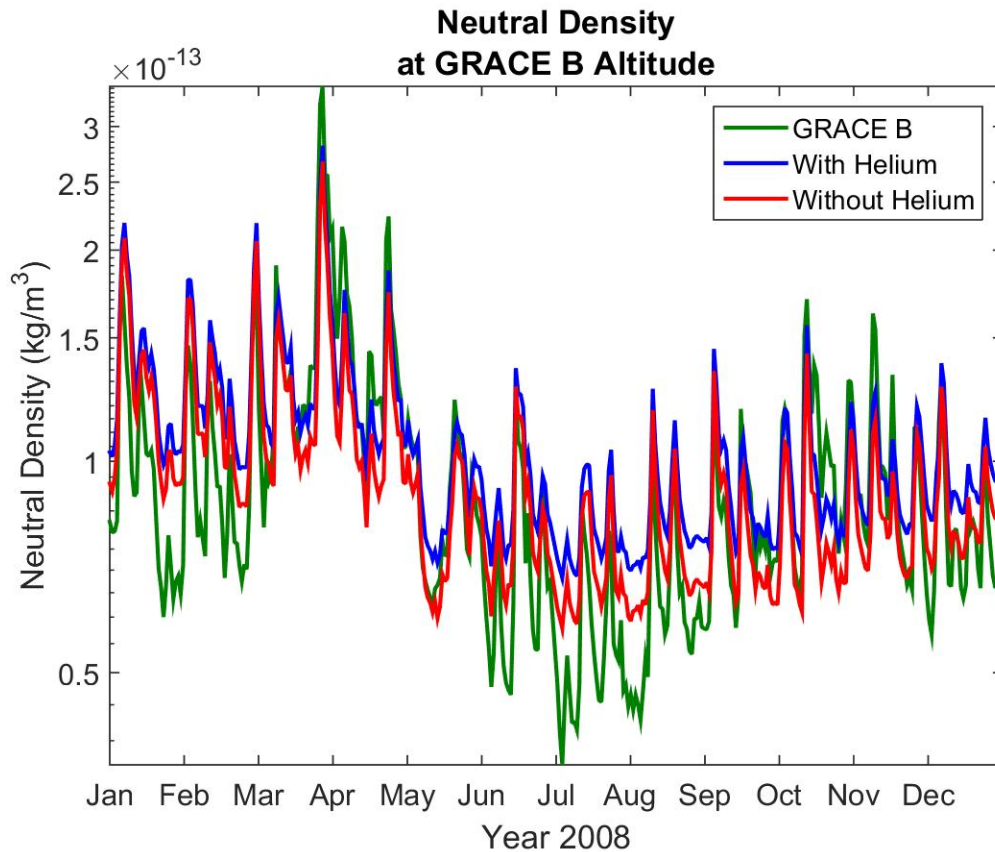


Figure 15. Neutral Density at GRACE B Altitude, 2008.

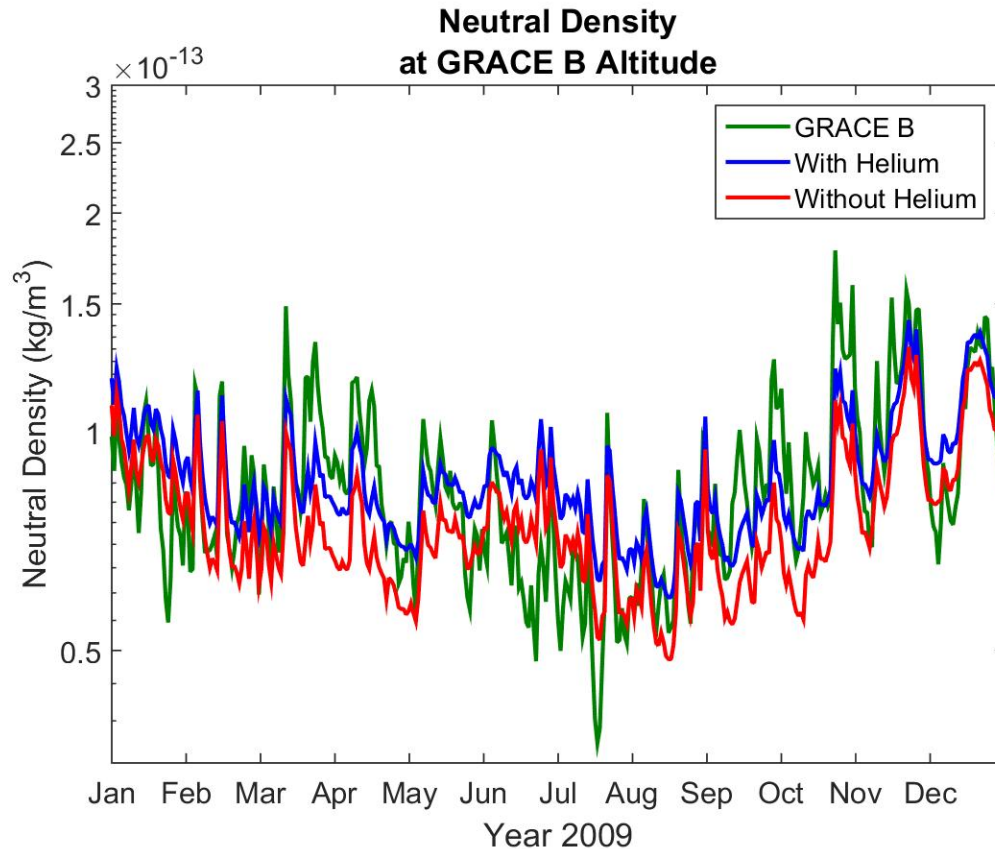


Figure 16. Neutral Density at GRACE B Altitude, 2009.

The CHAMP and GRACE satellites help illustrate the TIE-GCM's performance in the upper thermosphere where helium is starting to become the dominant neutral species. The addition of helium as a major constituent has served to nominally increase the total neutral density. This increase is more apparent at 500 km than at 454 km. However, the higher neutral density values of the 'With Helium' run are not indicative of higher values at all altitudes of the TIE-GCM between the two variations of the model. Further analysis is needed to show whether helium inclusion results in higher values regardless of altitude. The spherical satellites span several altitudes and will serve to further validate the upgraded TIE-GCM.

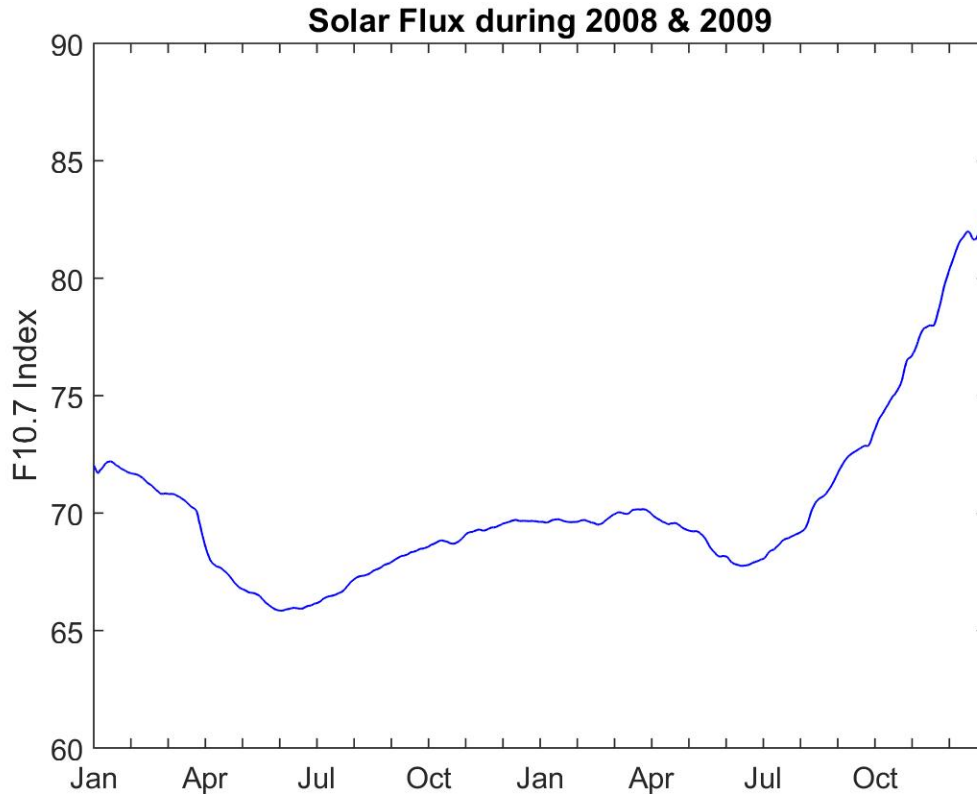


Figure 17. Solar Flux during 2008 and 2009. A daily averaged plot of the $F_{10.7}$ index for 2008 and 2009.

4.3 TIE-GCM Sampled at Vanguard 2 and Explorer 7 Altitudes

The next two satellites analyzed are the Vanguard 2 and Explorer 7 satellites. They have the lowest perigee of the six spherical satellites. With perigees starting at an average of 530 km and 557 km in 1998, respectively, they are approximately 30-60 km higher than the GRACE satellites. These two satellites possess the greatest elliptical orbits and the neutral density weighted and averaged near perigee height is what is being compared.

As detailed in Chapter III, the neutral density values derived for the spherical satellites began on 1 January 1998 and continued through 31 December 2004. This period

covers the solar maximum of 2000 and the transition periods around this peak. Because the spherical data is only available during the moderate to high solar activity conditions, helium's contribution as a major species in the TIE-GCM won't be observed as clearly when the atmosphere is contracted during solar minimum, and helium becomes the dominant species at lower altitudes. However, useful information is still available in the data, but a larger dataset that includes a solar minimum would be preferable for future research.

4.3.1 Explorer 7 Analysis

The neutral density plot for Explorer 7 starting in 1998 can be seen in Figure 18. Similar to the CHAMP and GRACE satellites, the 'With Helium' plot is not visible due to the similarity in values with the 'Without Helium' plot. The visible 'Without Helium' plot follows the general pattern of the satellite data, but there is a consistent difference in values around the maxima and minima. The satellite data appears to show well-defined semi-annual oscillations across the entire span of data. These oscillations are unusual because they can vary by an order of magnitude within a given year. This characteristic in the data is a result of the elliptical orbits and the seasonal variability of the Explorer 7 satellite data. The GRACE B satellite data, in section 4.2.2, displayed the maxima in the error for the 'With Helium' run during the Dec-Feb and Jun-Aug period. This occurs again, but this time there are maxima in the neutral density profile to magnify this. The minima peak also coincides with the Mar-May and Sep-Nov timeframe. These maximums and minimums within the data are the primary source of error, shown in

Figure 19, between the TIE-GCM and the data and since the transition between these two peaks is quick, the overall error is higher as a result.

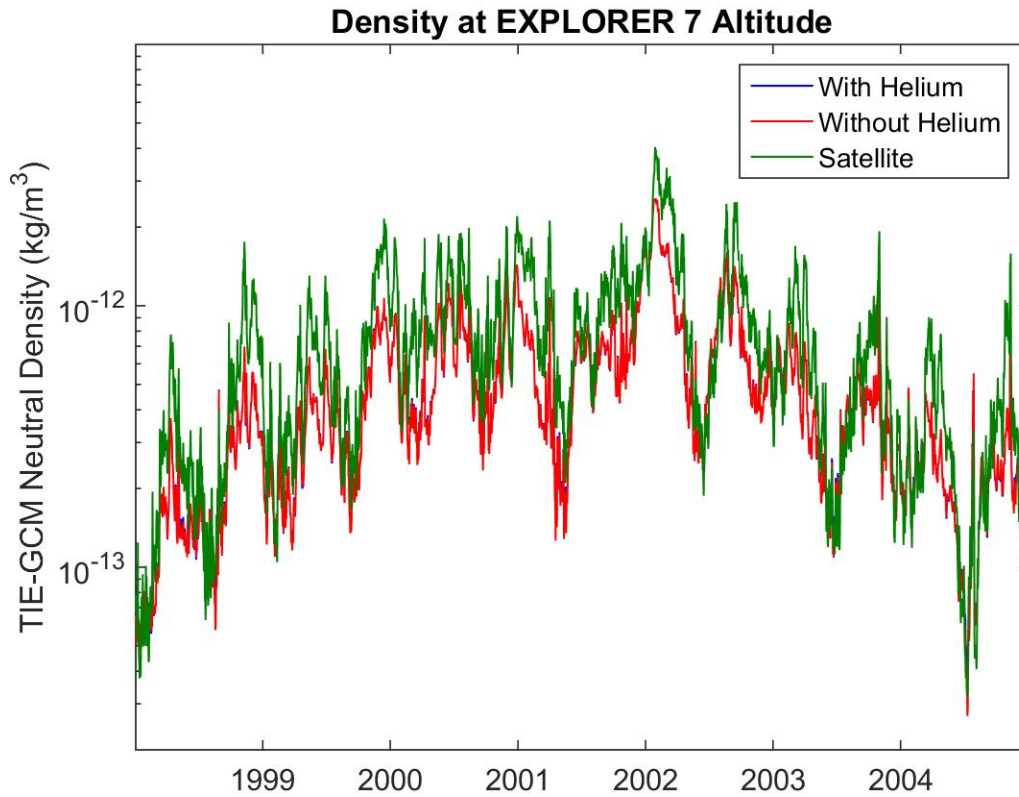


Figure 18. Neutral Density at Explorer 7 Altitude. The total neutral density at the Explorer 7 satellite (NORAD tracking ID: 00022) altitude is plotted for the satellite (green) and the both runs of the TIE-GCM (blue) and (red). The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 530 km and 725 km.

As expected, the oscillatory features are visible in the error data but the overall magnitude of the plot is consistently higher. This is quantified in the average errors for the ‘With Helium’ and ‘Without Helium’ model runs which are 32.31% and 32.50%, respectively. The average error is nearly identical which leads to the ‘Without Helium’ error almost always being plotted over the ‘With Helium’ error. The majority of the

model neutral density plots are below that satellite data. This means the error plot is relatively consistent in magnitude and the minute difference between the plots is more indicative that the model runs were near identical. A deficiency in the model occurred in July 2004 when a strong geomagnetic storm raised the A_p index over 180, the largest for that year. During that year (at 490-520 km average perigee height), the TIE-GCM reacts too strongly to this particular solar event. This geomagnetic storm also led to that largest error in the data. This is partially inflated because the model data went above the satellite data.

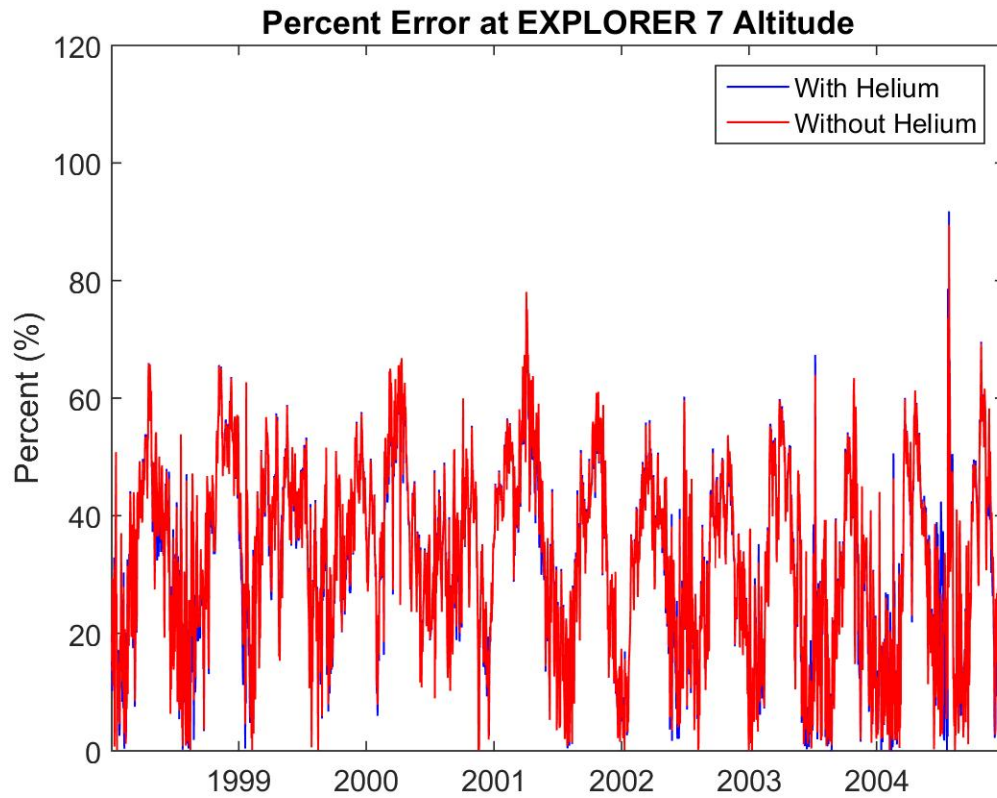


Figure 19. Percent Error at Explorer 7 Altitude. The percentage of error at the Explorer 7 (NORAD tracking ID: 00022) satellite altitude between the TIE-GCM 'With Helium' run (blue) and the 'Without Helium' run (red) are plotted. The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 530 km and 725 km.

Overall, there was no quantifiable impact from adding helium into the model. Due to the timeframe of the data, the atmosphere was simply too expanded for the fraction of helium into the total neutral density to be significant. The data also showed that the Explorer 7 satellite was consistent with the GRACE B satellite for neutral density values. A contraction in the data was recorded by both data sets in 2004 during a period of prolonged minimal geomagnetic activity. This shows that the weighted averaging had no noticeable effect on the data. The Explorer 7 had the second largest difference in apogee and perigee height of 200 km. The difference is expanded greatly for the Vanguard 2 satellite.

4.3.2 Vanguard 2 Analysis

The Vanguard 2 starting apogee is nearly 3000 km and is the primary reason why the weighted average approach was taken with the spherical satellites. The starting perigee is still relatively low in the atmosphere at 557 km in relation to He as a major species. The highly elliptical orbit of this satellite results in a higher magnitude difference between the maximum and minimum values of the neutral density as seen in Figure 20. As a result, the neutral density is occasionally higher than the Explorer 7 satellite, despite the higher perigee height. However, the overall neutral density plot is very similar to the Explorer 7 plot in Figure 18. There is a broad increase in the total density during the solar maximum years and a steady, near-order-of magnitude decrease occurs after the beginning of 2002. Over the entire period, the difference between the two model runs is still limited. The 'With Helium' plot is not visible at this scale. Also important to note,

the satellite derived neutral density values are almost always higher than the model data output. This is likely due to an influence of values from the apogee height portion of the orbit. The weighted average will limit the influence of these values, but it will not remove it entirely. Since the majority of neutral density values are lesser in magnitude to the satellite values, consistent error plots are shown in Figure 21.

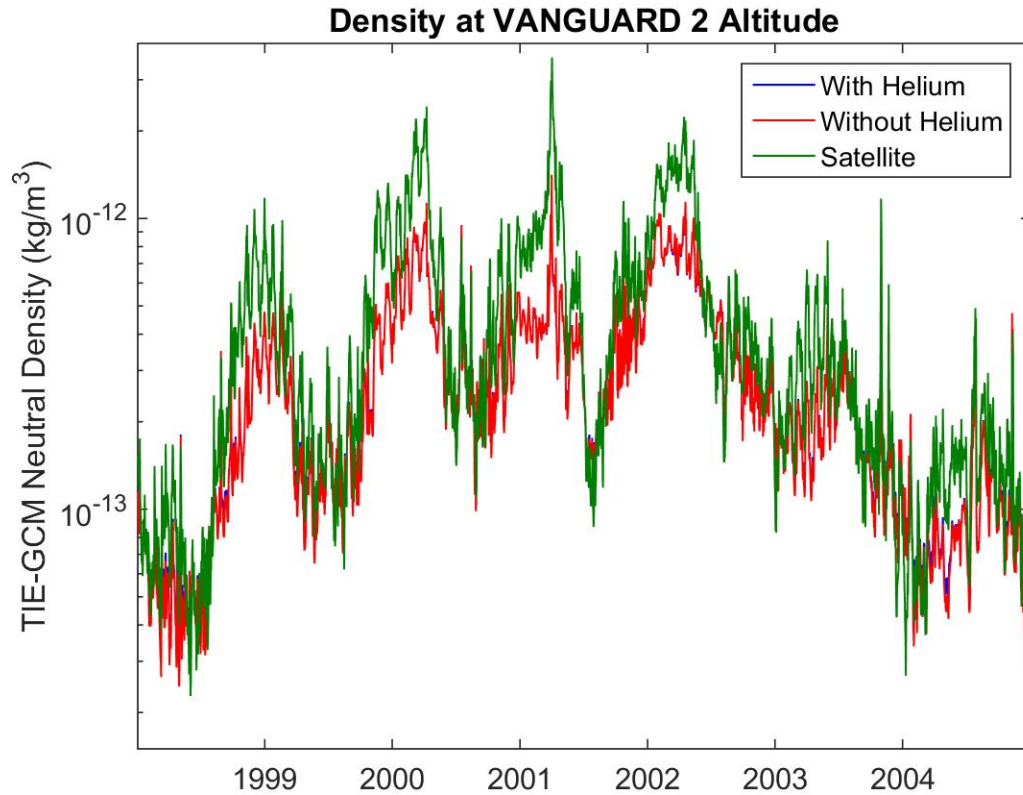


Figure 20. Neutral Density at Vanguard 2 Altitude. The total neutral density at the Vanguard 2 satellite (NORAD tracking ID: 00011) altitude is plotted for the satellite (green) and the both runs of the TIE-GCM (blue) and (red). The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 557 km and 2978 km.

The Vanguard 2 error is very similar to the Explorer 7 error with seasonal variations apparent and at a magnitude higher than the CHAMP and GRACE satellites.

The percentage error for the ‘With Helium’ and ‘Without Helium’ are 32.29% and 33.01%, respectively. These percentages are slightly higher than the Explorer 7 error but the difference is still within 1%. Also similar to the Explorer 7 satellite is the slight difference in the two model runs during 1998 and 2004. A large spike in the error occurs for both model runs during the beginning of 2004. An error spike this large is only possible for model values above the satellite data. As Figure 22 shows, the satellite data is well below the model data when the spike occurs in January 2004.

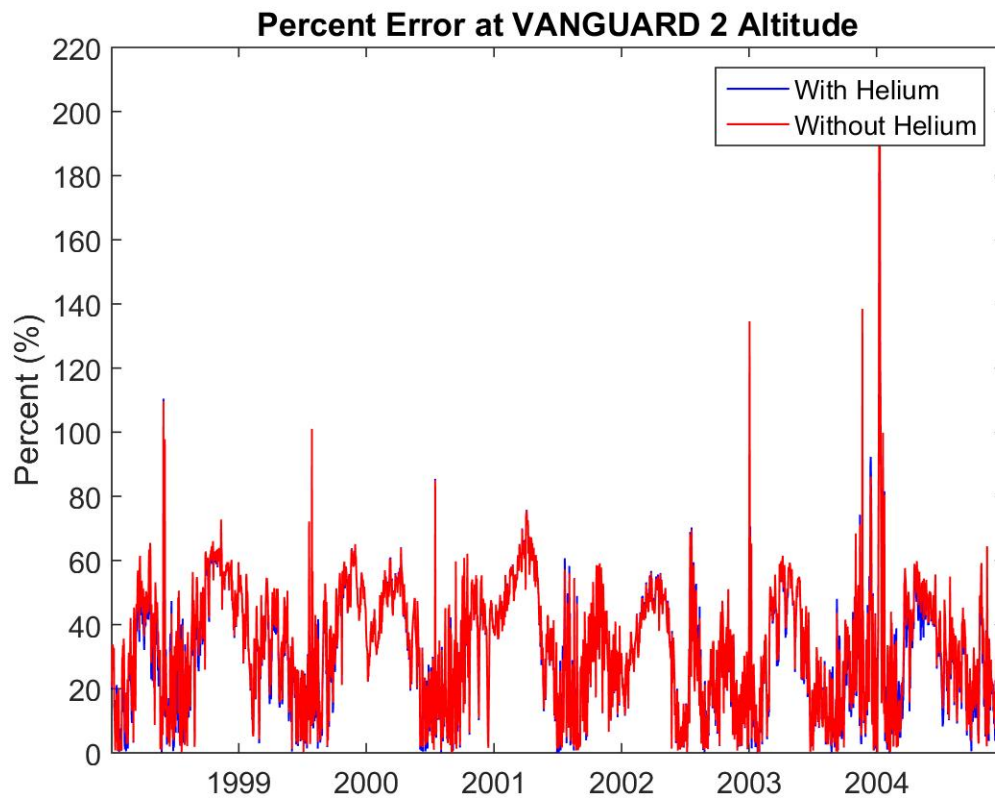


Figure 21. Percent Error at Vanguard 2 Altitude. The percentage of error at the Vanguard 2 (NORAD tracking ID: 00011) satellite altitude between the TIE-GCM ‘With Helium’ run (blue) and the ‘Without Helium’ run (red) are plotted. The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 557 km and 2978 km.

Figure 22 also shows how close the two model runs are. The largest deviation between the two plots is in May. This coincides with the prolonged period of low geomagnetic activity. Additionally, the model data appears to better handle the two large increases in the A_p index in July and November.

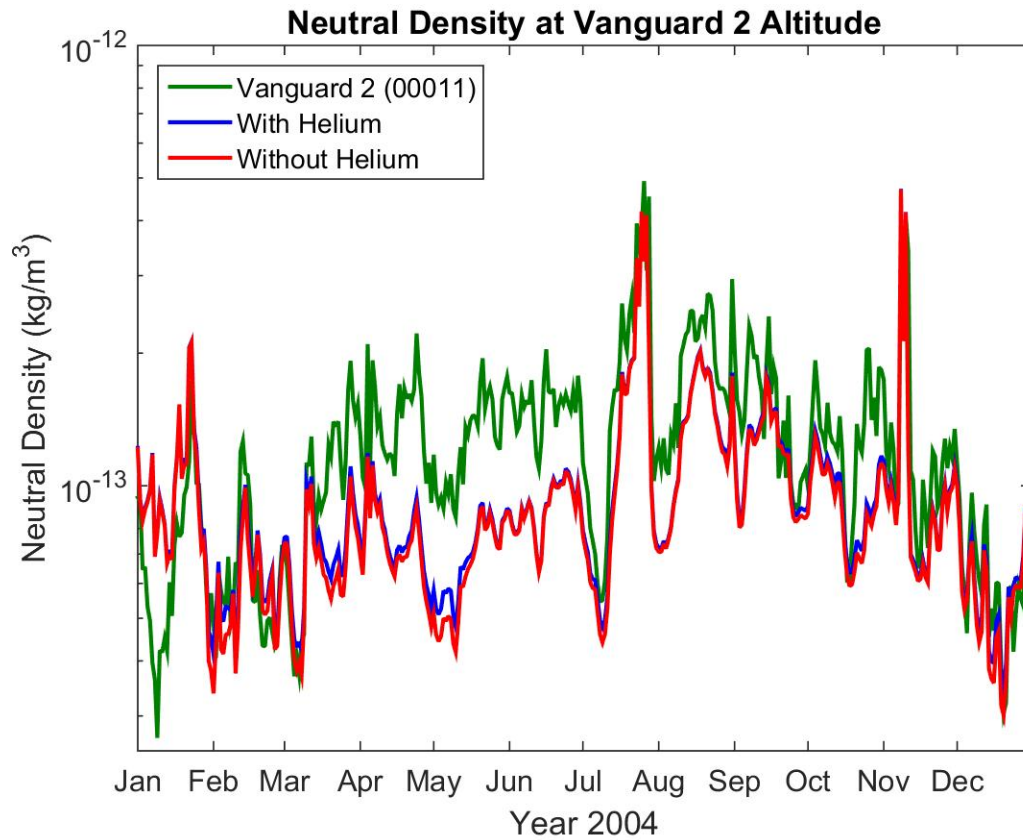


Figure 22. Neutral density at Vanguard 2 Altitude, 2004.

The Vanguard 2 analysis is a good case to verify the analysis of the GRACE B and Explorer 7 satellites because of its perigee height. However, the highly ecliptic orbit artificially lowers the neutral density for the majority of the daily data points. Aside from the anomaly revealed in 2004, the satellite data is almost exclusively above the two

model runs. The next three satellites provide a closer altitude and orbit type to compare and assist in determining whether the lower neutral density biases seen in the Explorer 7 and Vanguard 2 dataset are a product of the ecliptic orbit.

4.4 TIE-GCM Sampled at SURCAL 150B, SURCAL 160, and RIGIDSPHERE 2

Altitudes

The next three spherical satellites have perigee heights that average 750 km to 850 km. These three satellites provide the opportunity to sample the TIE-GCM at altitudes above the thermosphere. Despite the similarities in perigee, all three satellites have differences. Two of these satellites, SURCAL 150B and SURCAL 160, have slightly elliptical orbits with the difference between perigee and apogee averaging only 15 km. The RIGIDSPHERE 2 satellite has an elliptical orbit that is similar to the Explorer 7 satellite, but there is only a 100 km difference between the apogee and perigee height. As a result, its orbit decays at a lesser rate than the two SURCAL satellites. The decay in orbit that occurs due to the drag acceleration, equation (1), is important, because it will increase the overall neutral density when the orbiting altitude decreases which is seen in the density plots.

Another characteristic of these satellites is that their altitude is almost exclusively above the top boundary of the model. The diffusive equilibrium assumption is used for the values determined by the model. The inclusion of helium as a major species within the model still plays a significant role at lower altitudes as it determines a different scale height after the interactions are included in the initial calculations within the model. As altitude increases, the helium component of the neutral density composition becomes the

dominant species. The high solar activity in 2001 and 2002 is the only time when this does not occur and is the reason for the limited difference between the two model runs.

4.4.1 RIGIDSPHERE 2 Analysis

The first satellite analyzed in this section is the RIGIDSPHERE 2. Of the three satellites, this one has the lowest starting perigee height at 770 km. However, it is also has the most ecliptic orbit with a starting average apogee height of 870 km. As a result, the neutral density is influenced by both the perigee and apogee height of the satellite. A plot of the density profiles for the satellite and the two model runs is given in Figure 23.

The plot of the neutral density profiles over the seven year span is similar to the Explorer 7 and Vanguard 2 neutral density profiles shown in Figures 18 and 20, respectively. There is a steady increase in overall neutral density during the solar maximum timeframe and the neutral density is lower at the beginning and end of the data. The oscillatory features can be seen again in this dataset, but they are not as pronounced as the previous two spherical satellites. The biggest features that stand out are the clear difference that occurs between all three datasets across the entire timeframe. During lower solar activity, the ‘Without Helium’ run is clearly lower than the ‘With Helium’ run. This is most apparent in 1998 when almost an order of magnitude difference exists between the two model runs with the ‘With Helium’ plot being closer to the satellite data. Other deviations include vast differences during solar maximum between both model runs and the satellite data. This includes the satellite profile being both above and below the model data.

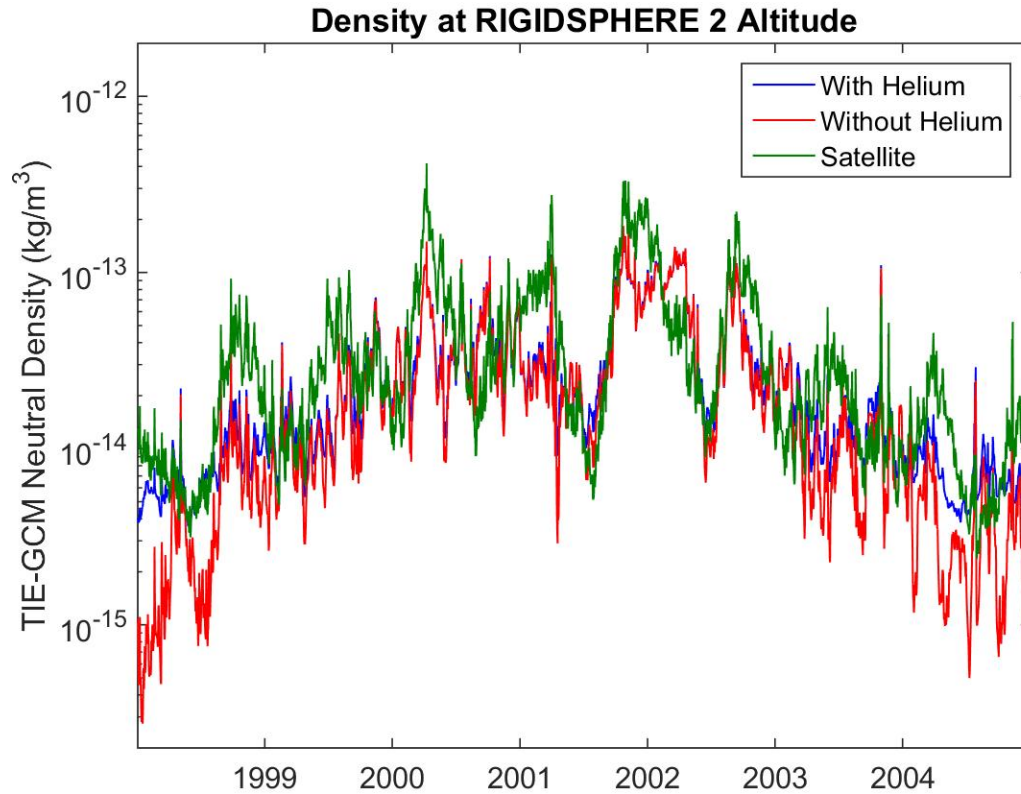


Figure 23. Neutral Density at RIGIDSPHERE 2 Altitude. The total neutral density at the RIGIDSPHERE 2 satellite (NORAD tracking ID: 05398) altitude is plotted for the satellite (green) and the both runs of the TIE-GCM (blue) and (red). The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 770 km and 870 km.

Figure 24 shows the difference in the three plots more clearly with overall higher error and a continued difference seen between the two model runs. The average error for the ‘With Helium’ and ‘Without Helium’ model runs is 49.27% and 57.31%, respectively. First, there is an improvement in the ‘With Helium’ run by almost 8%. This is magnified at the beginning and end of the data which was also obvious within the neutral density plots. During solar maximum, the difference in error is less apparent. The error lower in magnitude overall, but it is difficult to see with the extremely high spikes in the data from the beginning of 2000 to the beginning of 2003. These large spikes are a

product of the error equation and should not be used as a gauge of model performance. The error difference and the error during periods of lower solar activity are more indicative of the difference between the model runs. These spikes inflate the overall error that is trending lower for both model runs. A clearer look at the error tendencies can be seen in a yearly breakdown given in Table 3.

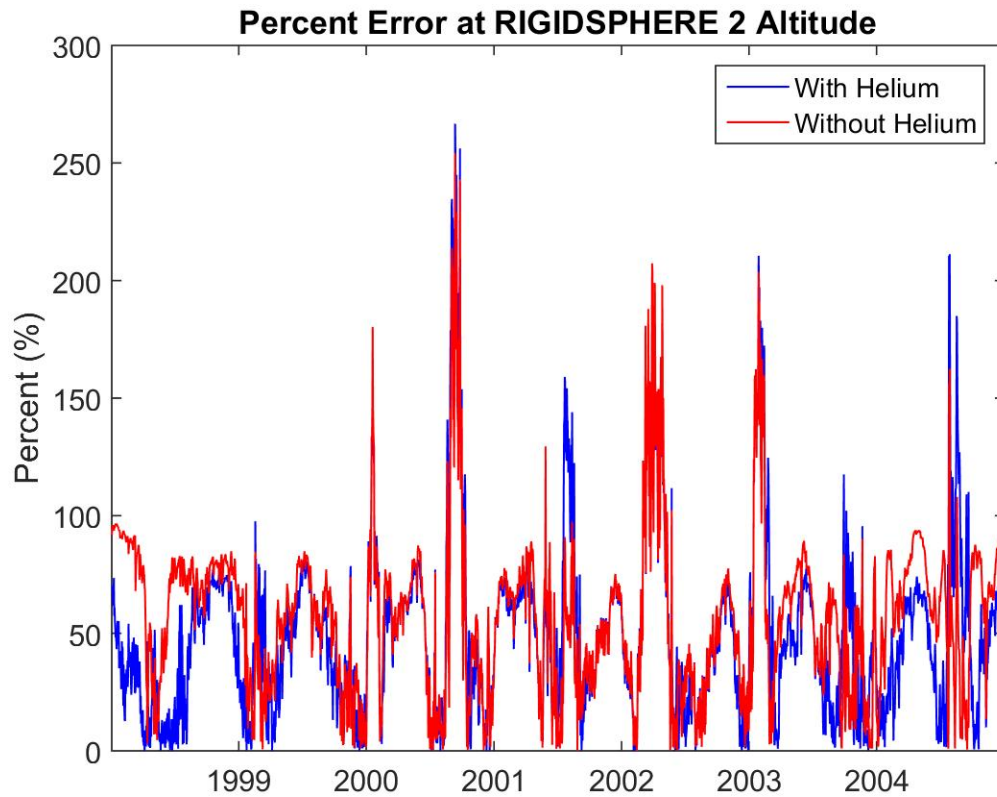


Figure 24. Percent Error at RIGIDSPHERE 2 Altitude. The percentage of error at the RIGIDSPHERE 2 (NORAD tracking ID: 05398) satellite altitude between the TIE-GCM ‘With Helium’ run (blue) and the ‘Without Helium’ run (red) are plotted. The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 770 km and 870 km.

Table 3. Error in TIE-GCM per Year for RIGIDSPHERE 2

	1998	1999	2000	2001	2002	2003	2004
Average Perigee Height	790.91 km	801.72 km	788.27 km	798.01 km	779.99 km	788.24 km	778.91 km
Solar Flux	123.18	156.37	179.37	187.41	171.21	125.53	105.26
Without Helium Error	70.75%	44.47%	59.89%	52.36%	53.00%	56.25%	64.42%
With Helium Error	39.26%	37.98%	60.78%	56.55%	49.63%	51.38%	49.27%
Error Difference	31.49%	6.49%	0.89%	4.19%	3.37%	4.87%	15.15%

According to the yearly averages in Table 3, the TIE-GCM ‘With Helium’ run is lower for five of the seven years (1999-2000, 2002-2004). When the ‘With Helium’ run is more erroneous, it is not by a large margin. This is in contrast to 1998 and 2004 where the difference is 31.49% and 15.15%, respectively. It is worth noting that during solar maximum, the error for both runs of the model is artificially high because the neutral density is a completely different profile during the times of the spikes in the error. The best example of this occurs during the 2001 and 2002 years where both runs are approximately 3-4% different in error, but the error profiles are very similar. A look at the neutral density of these two years can be seen in Figure 25.

As anticipated, the satellite data has a much different profile than the model data. The two model run profiles and the satellite data profiles are completely different at different periods within the two year timeframe. The difference described is not how far off in magnitude the plots were but rather how similar in shape the profiles were. For example, the largest magnitude difference was in January 2001 – March 2001. However, the profiles follow a similar shape. In contrast, from April 2001 – June 2001 and November 2001 – April 2002 the models profiles do not resemble the satellite data. Particularly during the November and December months of 2001, the profiles look to be

diverging. This discrepancy in the neutral density profiles does not account for all the difference in magnitude of the data. For example, the data in the beginning of 2001 shows a large difference in magnitude between the model and satellite data but all three density profiles are increasing and eventually account for a geomagnetic storm that is associated with the spike in the data.

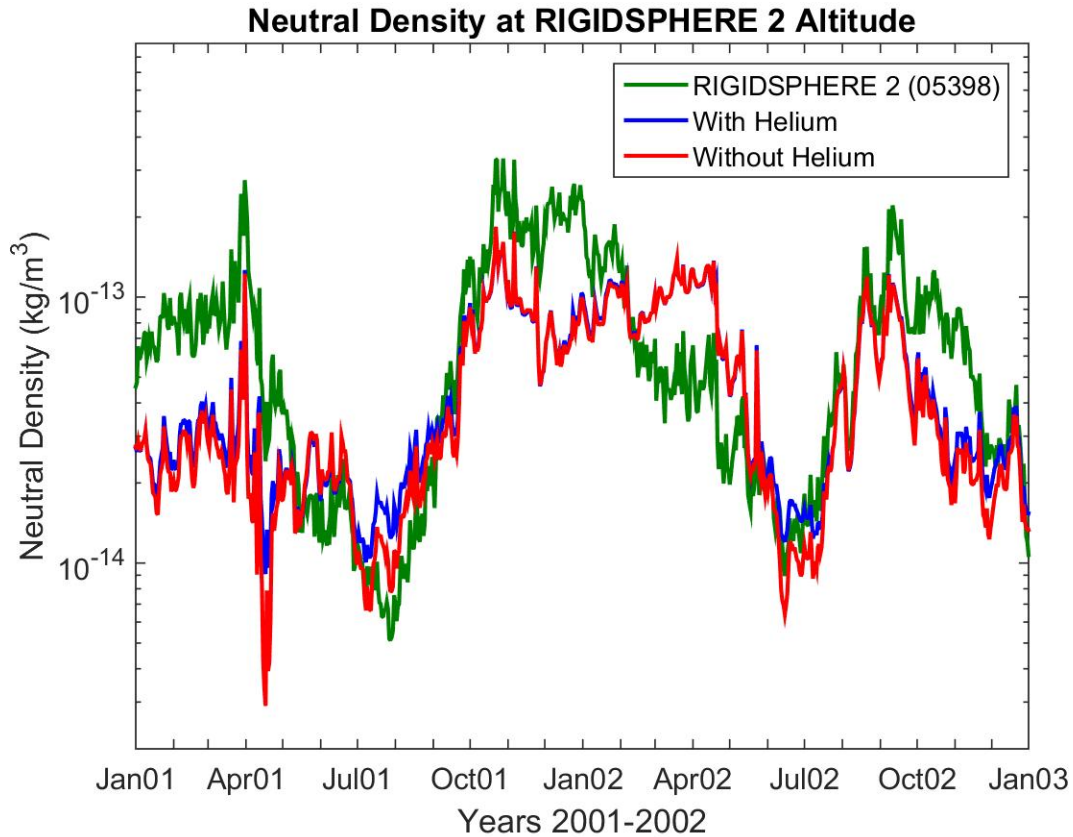


Figure 25. Neutral Density at RIGIDSPHERE Altitude, 2001-2002.

A closer look at the error during this timeframe shows the reason for increased error for both model runs. In Figure 26, the error is extremely similar between the two TIE-GCM runs. The maximum in error from July 2001 – August 2001 accounts for the

higher error in the ‘With Helium’ run for 2001. When compared to Figure 25, this is when the satellite data is lower in magnitude than the model data. At the RIGIDSPHERE 2 altitude, the addition of helium into the model has increased the overall total neutral density. This means that any time the satellite data is less than the model, the ‘Without Helium’ run will have less error than the ‘With Helium’ run. The majority of the rest of the error plot shows that the ‘With Helium’ run is less in magnitude than the ‘Without Helium’ run.

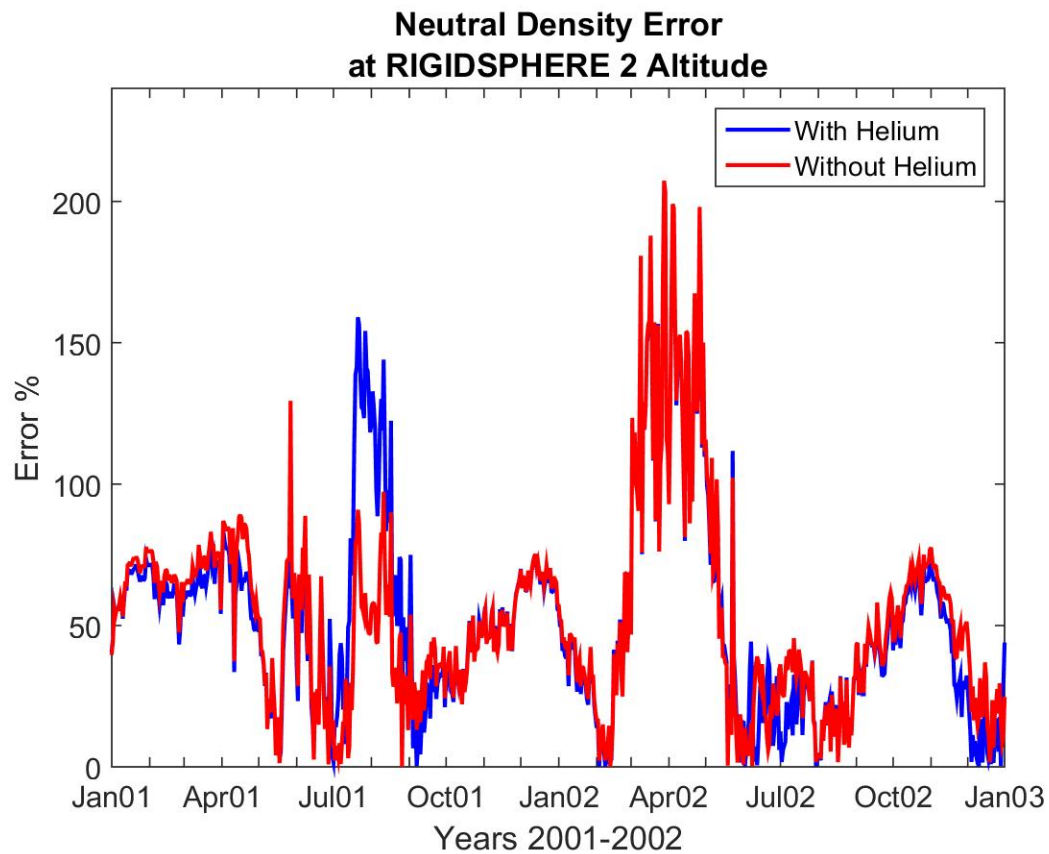


Figure 26. Percent Error at RIGIDSPHERE 2 Altitude, 2001-2002.

When looking at the solar activity for that timeframe, the model may have a weakness determining neutral density. Both solar indices are plotted in Figure 27. The first thing to note is there are two distinct timeframes when the error is consistently above 100% for either or both model runs. The first occurs in July - August of 2001. During this period of time the geomagnetic activity is at a minimum but the solar flux is increasing. While there is not a perfect alignment of error and the $F_{10.7}$ index, the 'With Helium' plot increases at nearly the same time. The increase in the $F_{10.7}$ index is more significant during this time than any during the plotted two year period. The 'With Helium' run of the TIE-GCM is accounting for this increase in solar flux more than the 'Without Helium' run. The large discrepancy in error does not continue through the entire increase in solar flux, but even during the end of August as the solar flux is reaching a peak, the 'With Helium' run is more erroneous than the 'Without Helium' run. This same discrepancy between the two model runs occurs again in June of 2002 when there is a minimum in geomagnetic activity and an increase in solar flux. It is during these conditions that the 'With Helium' run is inferior to the 'Without Helium' run.

The second major peak in error from Figure 26 occurs when the $F_{10.7}$ is decreasing and both model runs are not decreasing in neutral density as quickly as the satellite derived data. The difference in data is apparent in Figure 25 when the satellite data is consistently higher than the two, near identical runs of the TIE-GCM. There is not as obvious of a correlation between the solar activity and the neutral density for this example. As mentioned, the $F_{10.7}$ index is decreasing while there is only a slight to moderate increase in the A_p index. This is a possible example of the TIE-GCM over-

compensating in its calculation of neutral density whenever there is an increase in a solar index. Further evaluation is required to make this assertion.

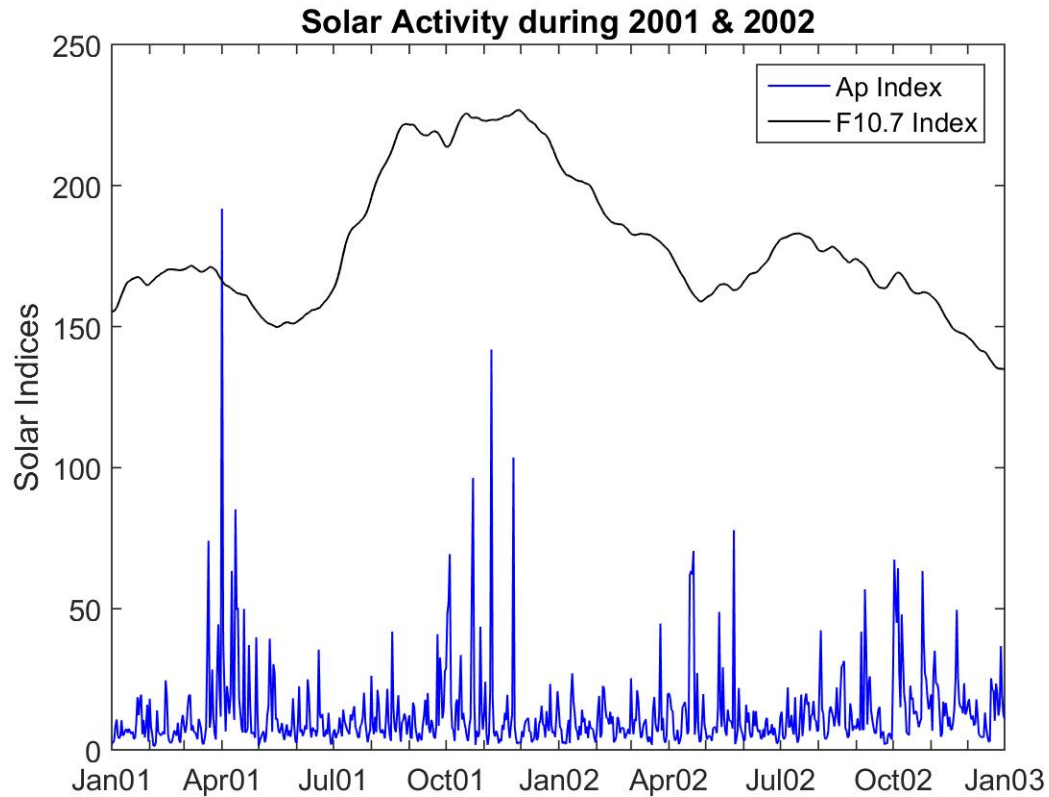


Figure 27. Solar Activity during 2001-2002. The geomagnetic activity and solar flux for 2004 displayed by the A_p and $F_{10.7}$ indices.

4.4.2 SURCAL 150B Analysis

The next satellite analyzed is the SURCAL 150B. The satellite is higher in perigee than the RIGIDSPHERE 2 with a starting average perigee height in 1998 of approximately 815 km. As previously mentioned, the satellite is in a slightly elliptical orbit with an average starting apogee height of 830 km. This small difference in altitude will lead to fewer extremes in the neutral density data. The weighted average

approximation is even closer to the true value at perigee and should provide a good comparison to the model. The neutral density plot of the SURCAL 150B satellite and the TIE-GCM runs can be seen in Figure 28.

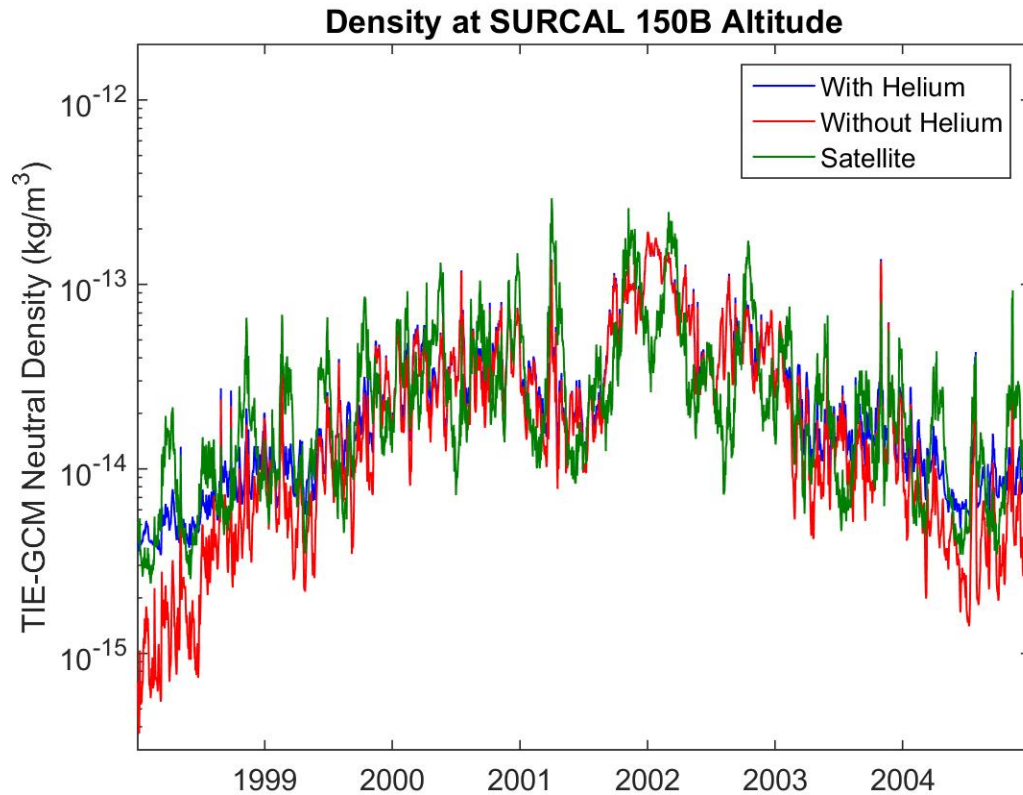


Figure 28. Neutral Density at SURCAL 150B Altitude. The total neutral density at the SURCAL 150B satellite (NORAD tracking ID: 02909) altitude is plotted for the satellite (green) and the both runs of the TIE-GCM (blue) and (red). The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 815 km and 830 km.

With a beginning and ending average altitude of 815 km and 755 km, there is a clear difference between the two model runs at these times. According to Figure 28, the difference is greater during 1998 than at any other point in the dataset. This was also observed in Figure 23 for RIGIDSPHERE 2 and is directly attributed to the higher

altitude dependence on helium as the primary neutral constituent. Figure 6 shows that the solar flux is slightly lower in 2004 than in 1998. However, the nearly 60 km drop in altitude is more significant for the contribution of helium which is why the ‘With Helium’ profile is much closer to the satellite profile in 1998 than 2004.

The difference in neutral density data during solar maximum is not as distinguishable between the two runs of the model. There is a deviation between the models and the satellite data that results in higher values of error. This is analyzed specifically considering the higher error that is found in the ‘With Helium’ run during that timeframe. The overall error plots for the SURCAL 150B satellite can be found in Figure 29.

There is high amount of error between the model and satellite data particularly during solar maximum. Over the entire dataset, the error for the ‘With Helium’ and ‘Without Helium’ runs average 58.28% and 61.19%, respectively. Both TIE-GCM runs have more error at the higher altitude than the previous satellites analyzed. The importance of helium in the lower exospheric altitudes is highlighted with over a 2.91% difference in error between the model runs. However, helium’s contribution to the total neutral density is still clearly dependent on solar activity. A breakdown of the year, altitude, solar flux, and error between the satellite and models runs is given in Table 4.

The yearly breakdown of SURCAL 150B shows a steady increase in error to a large maximum for both model runs in 2002. The yearly solar flux average is highest in 2001, but as Figure 6 shows, the peak occurs at the end of 2001. The high error occurs in conjunction with the higher solar activity but it is not a simple case of the TIE-GCM under or over prediction the neutral density. As Figure 30 shows, the model is simply

incorrect in the values of neutral density in comparison to the SURCAL 150B. In the next section, the SURCAL 160 is analyzed to see if this is unique to the satellite and/or altitude.

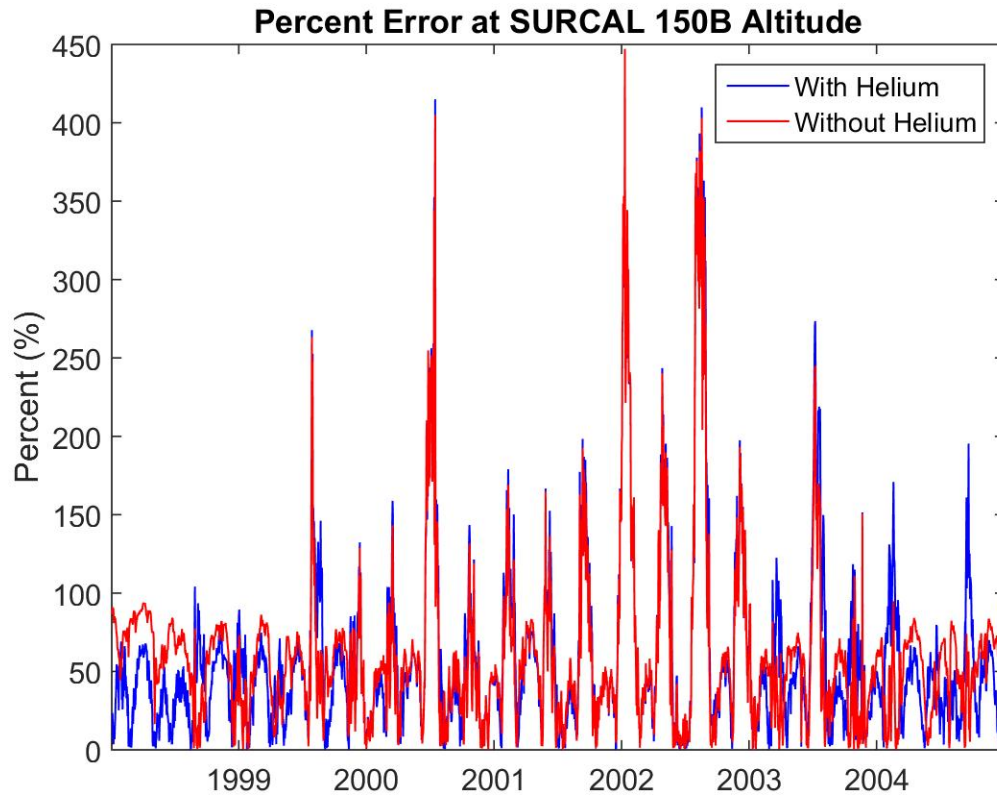


Figure 29. Percent Error at SURCAL 150B Altitude. The percentage of error at the SURCAL 150B (NORAD tracking ID: 02909) satellite altitude between the TIE-GCM ‘With Helium’ run (blue) and the ‘Without Helium’ run (red) are plotted. The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 815 km and 830 km.

The higher error occurs during the majority of years analyzed with the ‘With Helium’ iteration only performing better for three out of the seven years. With the exception of 1998, the error for both runs, regardless of which is higher, is within 4%

magnitude. Table 4 shows there is a 24.36% difference in error averaged in 1998 at an average perigee height of 811 km and average solar flux of 123. The solar flux average for 2004 is 105, but the difference in error is only 0.98%. This is a direct result of the altitude difference between these two years. Over the course of the seven years, the average perigee dropped 60 km to approximately 749 km. This quantifies that the contribution of helium is altitude dependent and is reflected in the model.

Table 4. Error in TIE-GCM per Year for SURCAL 150B

	1998	1999	2000	2001	2002	2003	2004
Average Perigee Height	811.18 km	807.12 km	797.01 km	785.01 km	765.68 km	755.27 km	749.55 km
Solar Flux	123.18	156.37	179.37	187.41	171.21	125.53	105.26
Without Helium Error	62.93%	52.89%	56.08%	57.43%	101.05%	48.69%	49.32%
With Helium Error	38.57%	49.26%	56.37%	59.14%	103.93%	52.40%	48.34%
Error Difference	24.36%	3.63%	0.29%	1.71%	2.88%	3.71%	0.98%

As mentioned, the extremely high error in 2002 is a result of almost completely different neutral density profiles. This can be observed in Figure 30. The TIE-GCM profiles follow the general trend of the satellite data with a general minimum in neutral density in the first half of 2001 and the overall maximum from the last few months of 2001 to the beginning of 2002. However, the satellite profile (green) crosses above and below the similar TIE-GCM plots several times during the two-year timeframe. The majority of the error comes from the model being higher in magnitude than the SURCAL 150B data. The error is given in Figure 31.

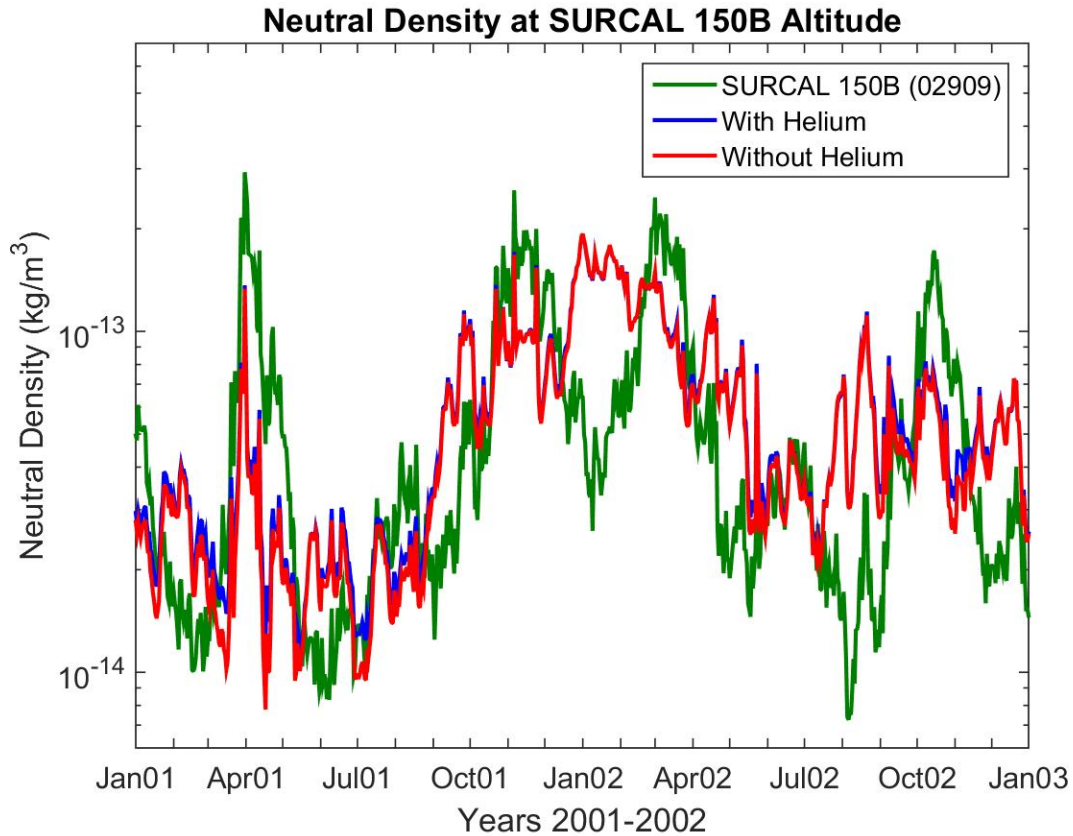


Figure 30. Neutral Density at SURCAL 150B Altitude, 2001-2002.

It should be noted that there is little difference between the two model runs error even at the two year scale. This confirms that the less than 4% difference in error between the model runs is apparent in the plotted profiles. In 2002, there were two large error maxima that correlate to a fairly significant decrease in the $F_{10.7}$ index. This decrease is sharper than other years as the sun was moving out of the solar maximum peak two years prior. It is possible the TIE-GCM has trouble compensating for the contraction in the atmosphere as the model neutral density decreased approximately a month later. This is supported by the fact that the model data is higher than the derived

satellite data. A comparison with the similar orbiting SURCAL 160 will help validate this observation.

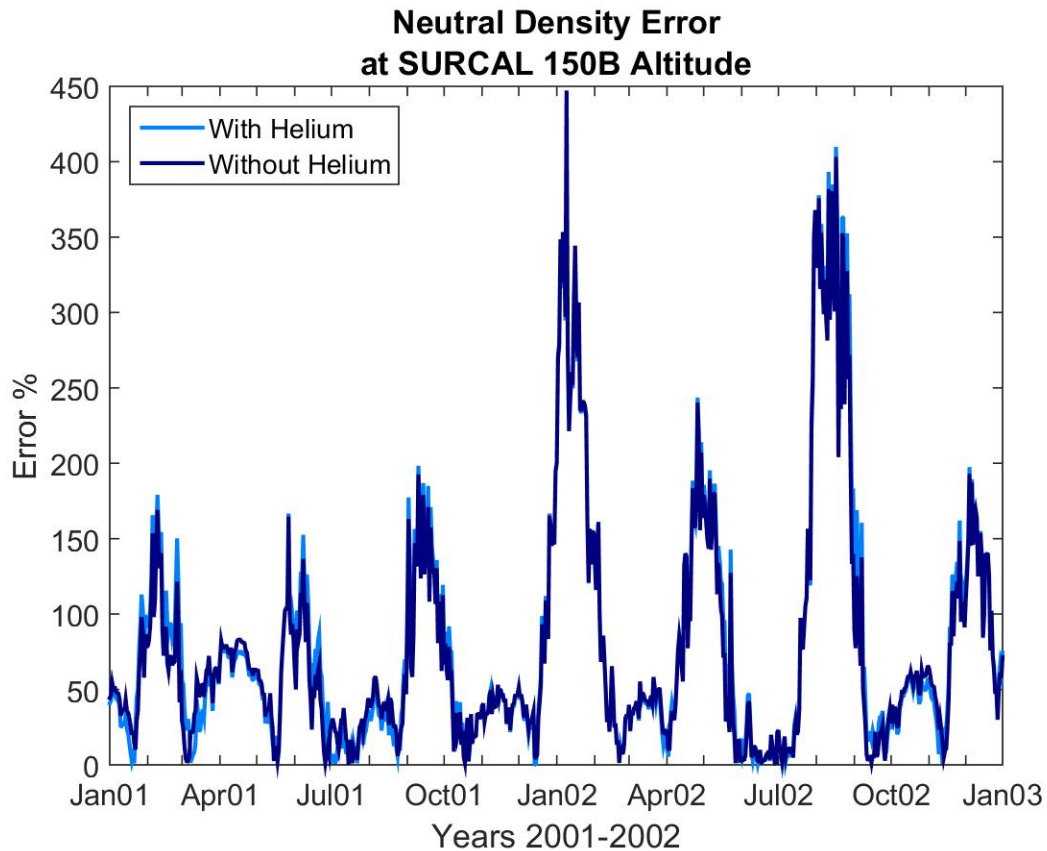


Figure 31. Percent Error at SURCAL 150B Altitude, 2001-2002.

4.4.3 SURCAL 160 Analysis

The SURCAL 160 shares a very similar, near-circular orbit to the SURCAL 150B that is a few kilometer higher in the atmosphere. These satellites were launched on the same date and part of the same mission and provide similar data from their orbits as a result. The neutral density profile for this satellite is given in Figure 32.

As expected, the profile is very similar to the SURCAL 150B satellite. Both model runs are consistently lower in magnitude than the satellite data at the beginning and end of the dataset. The biggest difference occurs in the beginning of 1998 with a near full order of magnitude difference between the two model runs. Also, the profile during the higher solar activity is inconsistent and follows the highly erroneous SURCAL 150B plot. The error for SURCAL 160 is given in Figure 33.

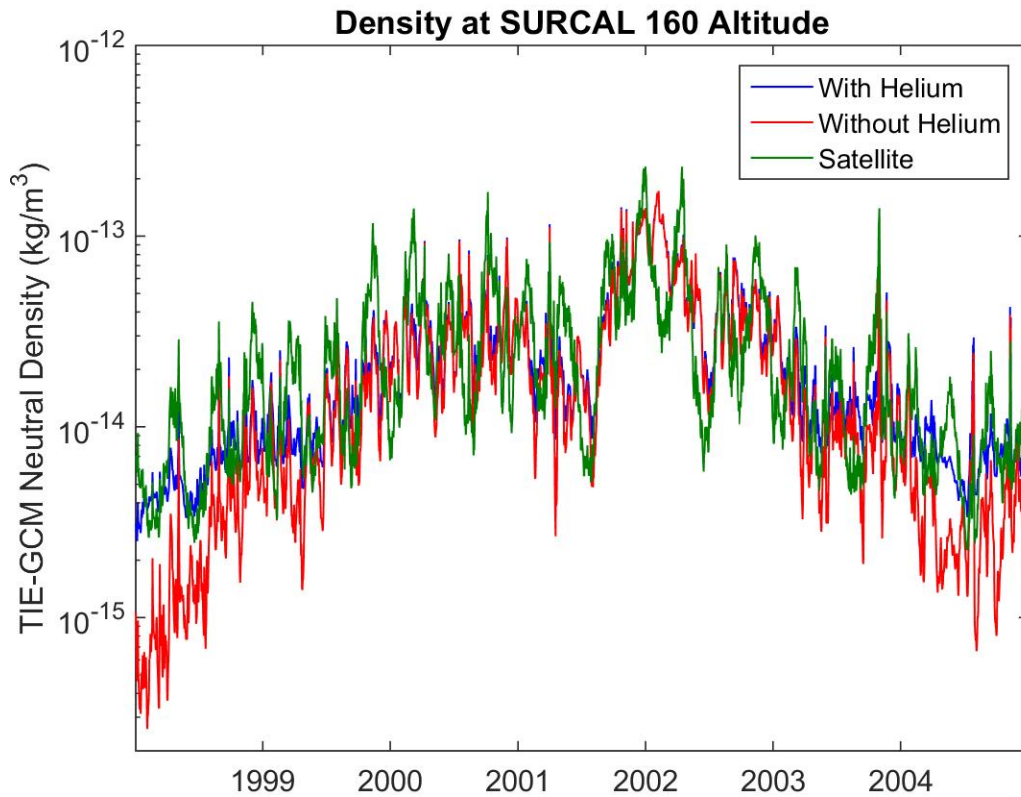


Figure 32. Neutral Density at SURCAL 160 Altitude. The total neutral density at the SURCAL 160 satellite (NORAD tracking ID: 02826) altitude is plotted for the satellite (green) and the both runs of the TIE-GCM (blue) and (red). The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 830 km and 845 km.

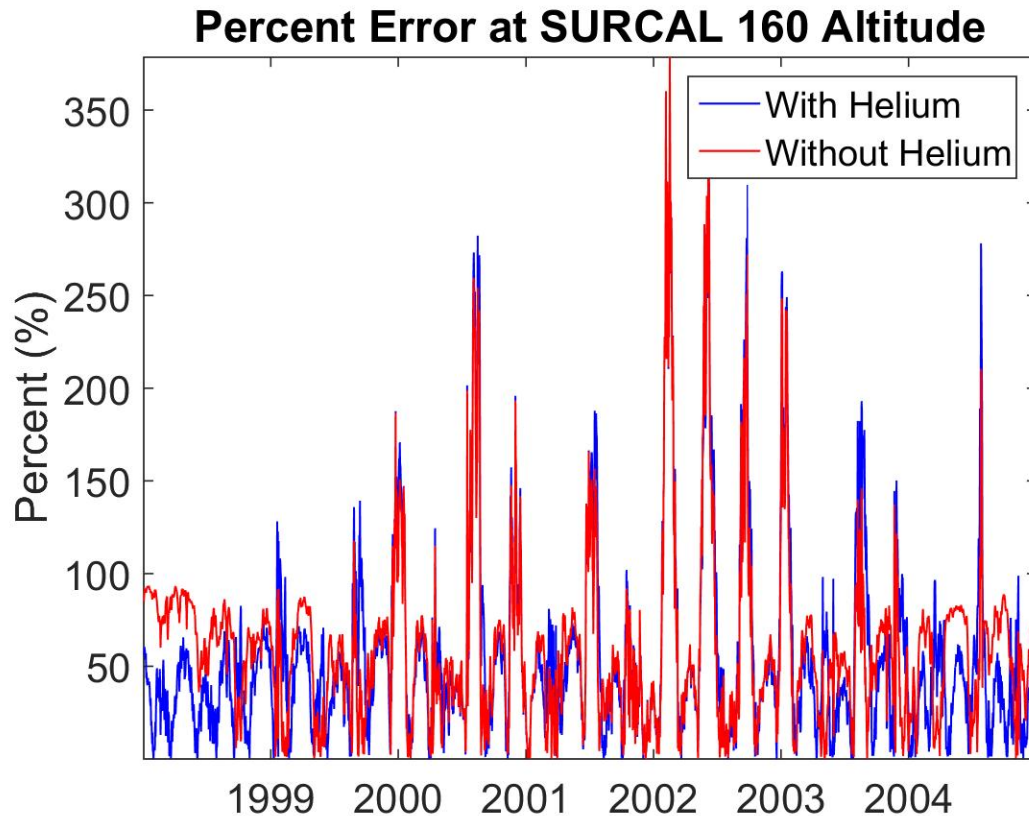


Figure 33. Percent Error at SURCAL 160 Altitude. The percentage of error at the SURCAL 160 (NORAD tracking ID: 02826) satellite altitude between the TIE-GCM ‘With Helium’ run (blue) and the ‘Without Helium’ run (red) are plotted. The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 830 km and 845 km.

Based upon the plot, the ‘With Helium’ run of the model is overall lower than the ‘Without Helium’ run. The ‘With Helium’ and ‘Without Helium’ TIE-GCM runs have average percentage error of 55.13% and 60.75%. This percentage is still relatively high but it is slightly lower than the SURCAL 150B satellite. This difference is noticeable during the beginning and ending timeframe of the data where a larger gap exists between the error plots. Also noticeable is the small difference between the two model runs around the higher solar flux index conditions in 2001 and 2002. Most of the He plot is not

distinguishable during this time period. Table 5 provides a closer look at the yearly averages of the altitude, solar flux, and error percentages of both model runs.

Table 5 is extremely similar to Table 4 with the ‘With Helium’ run of the TIE-GCM being more erroneous for five of the seven years. The biggest difference between the data comparison of the two SURCAL satellites is the difference in error magnitude at 1998 and 2004. These are the only two years that the ‘With Helium’ run has less averaged error, but for SURCAL 160 the difference in error is 33.85% and 18.34% for 1998 and 2004, respectively. This is much larger than the 24.36% and .98% of at the SURCAL 150B altitude. Even though there is only an average of 15 km difference in altitude between the two SURCAL satellites, this difference played a role in the improved difference in error.

Table 5. Error in TIE-GCM per Year for SURCAL 160

	1998	1999	2000	2001	2002	2003	2004
Average Perigee Height	826.28 km	821.67 km	814.38 km	801.98 km	785.59 km	778.96 km	774.29 km
Solar Flux	123.18	156.37	179.37	187.41	171.21	125.53	105.26
Without Helium Error	70.03%	50.12%	63.36%	47.23%	81.72%	56.74%	67.40%
With Helium Error	36.18%	50.75%	65.58%	47.51%	85.94%	60.90%	49.06%
Error Difference	33.85%	0.63%	2.22%	0.28%	4.22%	4.16%	18.34%

The ‘Without Helium’ run is performing worse at higher altitudes and in lower solar conditions. It should be noted that the average error of the ‘With Helium’ run for 1998 and 2004 has differed between 1998 and 2004 for both the SURCAL satellites. During 1998 the error decreased from 38.57% to 36.18% while the error increased in 2004 from 48.34% to 49.06%. These changes are subtle but also indicate that the higher

altitude and solar flux are not the sole components in determining error. There are other factors that may be unique to these particular satellite's data and other parameters beyond the scope of this research that may account for these opposite trends. However, an analysis of the altitude and solar flux relationship that exists between the six spherical satellites is explored in section 4.6.

For all three satellites within the 750-850 km altitude range, it was found that the error was highest for the 'With Helium' run during 2000-2003 when solar activity was greatest in magnitude. The 1998 and 2004 were consistently the best years for the 'With Helium' run. In the case of 2004, the error was not significantly lower than other years, but it was lower than the 'Without Helium' run for all three satellites. It also was the second largest difference in error overall when considering all three satellites in this section. The error in 1998 for all three satellites was not only lowest for the 'With Helium' run but for all years and each iteration of the TIE-GCM. Ultimately, this shows that a compressed atmosphere that is under lower solar activity conditions and is transitioning from a solar minimum to maximum leads to the major species of helium contributing positively to the TIE-GCM performance. Even though 2004 had a lower average value for solar flux, the atmosphere was expanded more due to the peak of the solar maximum only occurring a few years beforehand. The influence of helium as a major species was not as extreme for 2004 because the percentages of composition were not as heavily weighted toward helium. Higher in the atmosphere, the total neutral density and helium percentages approach unity. This will make helium even more important during solar minimum conditions; a characteristic that is explored with the next and final satellite.

4.5 TIE-GCM Sampled at CALSPHERE 1 Altitude Analysis

The most interesting satellite of the group is the CALSPHERE 1 for the sole reason that it is the highest in altitude of all the satellites in this study. It has already been shown that helium significantly influences the TIE-GCM during lower solar activity conditions when it is included as a major species at altitudes of 750-850 km. Based upon measurements of the exosphere, this remains the case until 1500 km when helium falls off and hydrogen becomes the dominant neutral species. The CALSPHERE 1 has a slightly elliptical orbit that ranges from 1010 km to 1045 km for the average starting perigee and apogee in 1998. This is well within the region of the atmosphere where helium is the sole dominant neutral species for both solar minimum and solar maximum conditions. As a result, this data will present a good example of the impact of helium as a major species in the TIE-GCM for the upper region of satellite orbits. The neutral density data at the CALSPHERE 1 satellite's altitude is plotted in Figure 34.

As Figure 34 shows, the modeled neutral density values at the CALSPHERE 1 satellite's altitude are the most distinguishable of all the satellites. The satellite neutral density averages an order of magnitude lower than the previous five satellites during solar maximum conditions. The magnitude between the two TIE-GCM runs is even more amplified with nearly a two-order of magnitude difference at the beginning of the data. There is such a drastic difference between the datasets that the plots are very distinct, a characteristic not shared by previous data sets. The satellite data and the 'With Helium' run data are extremely close during the early months of each year. They deviate towards the end of each year's data but are not consistent with a specific season. Despite this

deviation, the ‘With Helium’ and satellite plots are very close throughout the entire dataset. This is in contrast with the ‘Without Helium’ plot which is almost exclusively lower than the satellite data.

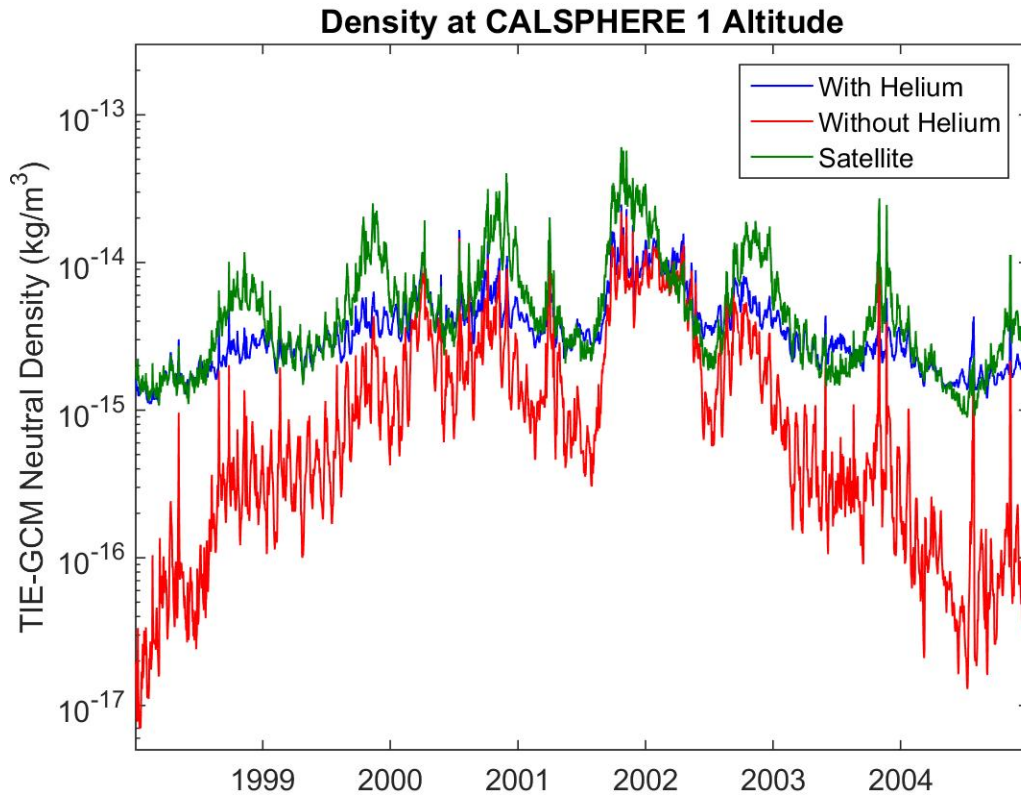


Figure 34. Neutral Density at CALSPHERE 1 Altitude. The total neutral density at the CALSPHERE 1 satellite (NORAD tracking ID: 00900) altitude is plotted for the satellite (green) and the both runs of the TIE-GCM (blue) and (red). The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 1010 km and 1045 km.

Figure 35 shows the error plots and it reflects the large difference in neutral density magnitude with the extremely high error within the ‘Without Helium’ plots during all years. The ‘With Helium’ error plot also reflects the difference shown in the neutral density plots in Figure 34. An oscillatory pattern exists within the ‘With Helium’

run error plot because the oscillations within the satellite neutral density data. The CALSPHERE 1 neutral density data has oscillations from the span of data collected around its entire orbit that shows up in the error plot. There are oscillations in the ‘Without Helium’ neutral density that makes it more uniform with the satellite data. This is function of what the daily satellite data is showing and not a feature identified in the ‘Without Helium’ run. The average of the ‘With Helium’ and ‘Without Helium’ error for the CALSPHERE 1 is 31.06% and 77.93%, respectively. The ‘Without Helium’ run is extremely large in comparison to the error that was recorded for the three satellites in section 4.4.

There are instances where the ‘Without Helium’ run has error that is less than the ‘With Helium’ run. This becomes apparent in the Figure 35 percentage error plot. Specifically in early 2002, the error plots become very busy, but the ‘Without Helium’ plots dips below the ‘With Helium’ plots. While it’s not easily seen in Figure 34 at first glance, this is a result of times when the satellite neutral density drops below the ‘With Helium’ run. The heightened solar activity of 2002 has resulted in higher average error for the ‘With Helium’ run in particular. Since the satellite data is plotted in between the two model runs and the ‘With Helium’ run is above the satellite data, the error actually decreases in 2002 for the ‘Without Helium’ run. This is an exact result of the ‘Without Helium’ plot being lower than the ‘With Helium’ plot and the satellite data decreasing as a result of the decreased $F_{10.7}$ index. This has already been detailed in section 4.4.1 with the RIGIDSPHERE 2 error values. In the case of the CALSPHERE 1 satellite, the ‘Without Helium’ plot is so much lower than the ‘With Helium’ plot that the overestimate of the ‘With Helium’ run is still closer in magnitude to the satellite data.

This is seen in the yearly breakdown of altitude, solar flux, and error from both model runs in Table 6.

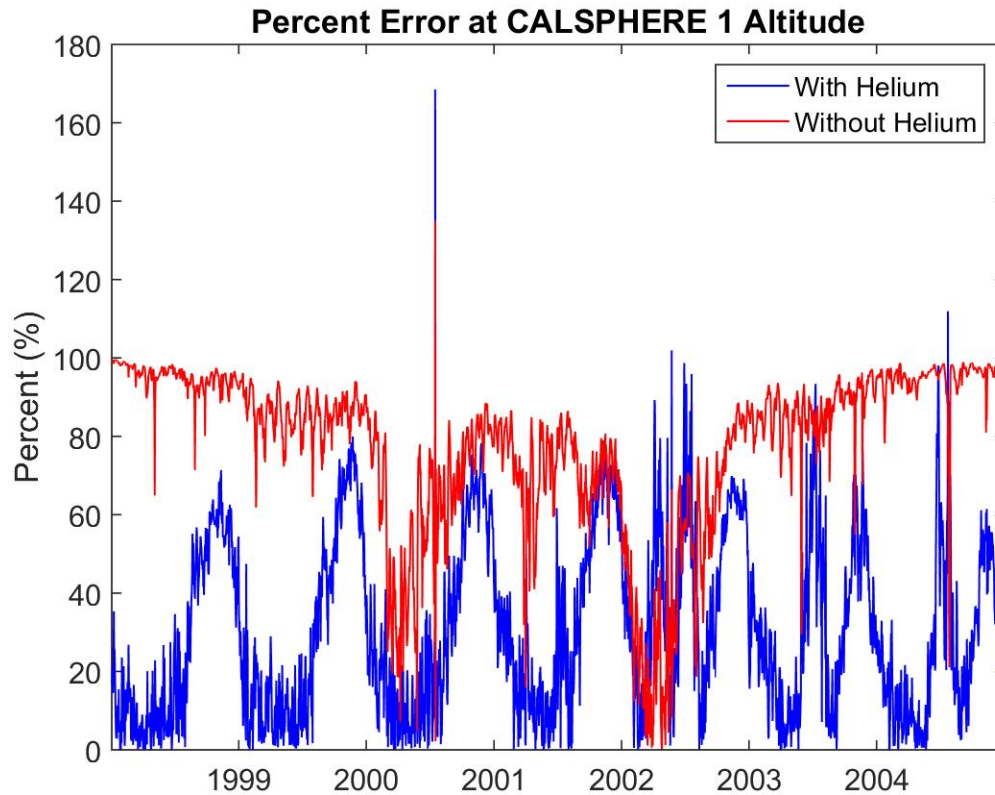


Figure 35. Percent Error at CALSPHERE 1 Altitude. The percentage of error at the CALSPHERE 1 (NORAD tracking ID: 00900) satellite altitude between the TIE-GCM ‘With Helium’ run (blue) and the ‘Without Helium’ run (red) are plotted. The satellite is in an elliptical orbit with a starting average perigee and apogee heights of 1010 km and 1045 km.

Based upon Table 6, it is clear the TIE-GCM is improved with the addition of helium as a major species at the CALSPHERE 1 altitude. This is highlighted in the 68.74% and 55.52% difference in error for 1998 and 2004, respectively. A common theme observed with the satellites above 750 km is the general increase in error for the

‘With Helium’ run and the general decrease in error for the ‘Without Helium’ run towards solar maximum. The primary reason for this tendency is the helium component to the TIE-GCM becomes less substantial during the expansion of the atmosphere. The model does improve as a result of the addition of helium, but there are weaknesses beyond the composition equations that may be improved upon.

Table 6. Error in TIE-GCM per Year for CALSPHERE 1

	1998	1999	2000	2001	2002	2003	2004
Average Perigee Height	1011.71 km	1012.64 km	1009.64 km	1006.69 km	1004.77 km	1003.83 km	1003.94 km
Solar Flux	123.18	156.37	179.37	187.41	171.21	125.53	105.26
Without Helium Error	95.21%	85.77%	62.92%	71.71%	48.99%	86.20%	91.60%
With Helium Error	26.47%	29.60%	30.45%	32.89%	40.86%	30.80%	36.08%
Error Difference	68.74%	56.17%	32.47%	38.82%	8.13%	55.40%	55.52%

One of these weaknesses can be seen more clearly with a closer look at year 2000, Figure 36. The assertion that the ‘With Helium’ plot is always higher than the ‘Without Helium’ plot holds true at the CALSPHERE 1 altitude as seen in Figure 36. This shows that the addition of helium into the TIE-GCM accounts for higher values of overall neutral density. However, as the data shows, this will cause it to be too high in magnitude at certain instances, leading to more error in the model.

Another specific example of the TIE-GCM requiring future improvement is how it handles solar storms at the higher altitudes. There are several spikes in the data that are seen throughout 2000. These spikes occur in both the model data and the satellite data. Two of the major peaks observed in May and July are the only times in 2000 that both model neutral density values exceed the magnitude of the satellite neutral density data.

Additionally, the spikes in the data indicate points where the ‘Without Helium’ run becomes extremely close in magnitude to the ‘With Helium’ run, but never exceeds it. The atmosphere in the ‘Without Helium’ TIE-GCM responds strongly to geomagnetic activity making it comparable to the ‘With Helium’ run. Figure 37 is a plot of the geomagnetic activity and the solar flux for the year 2000.

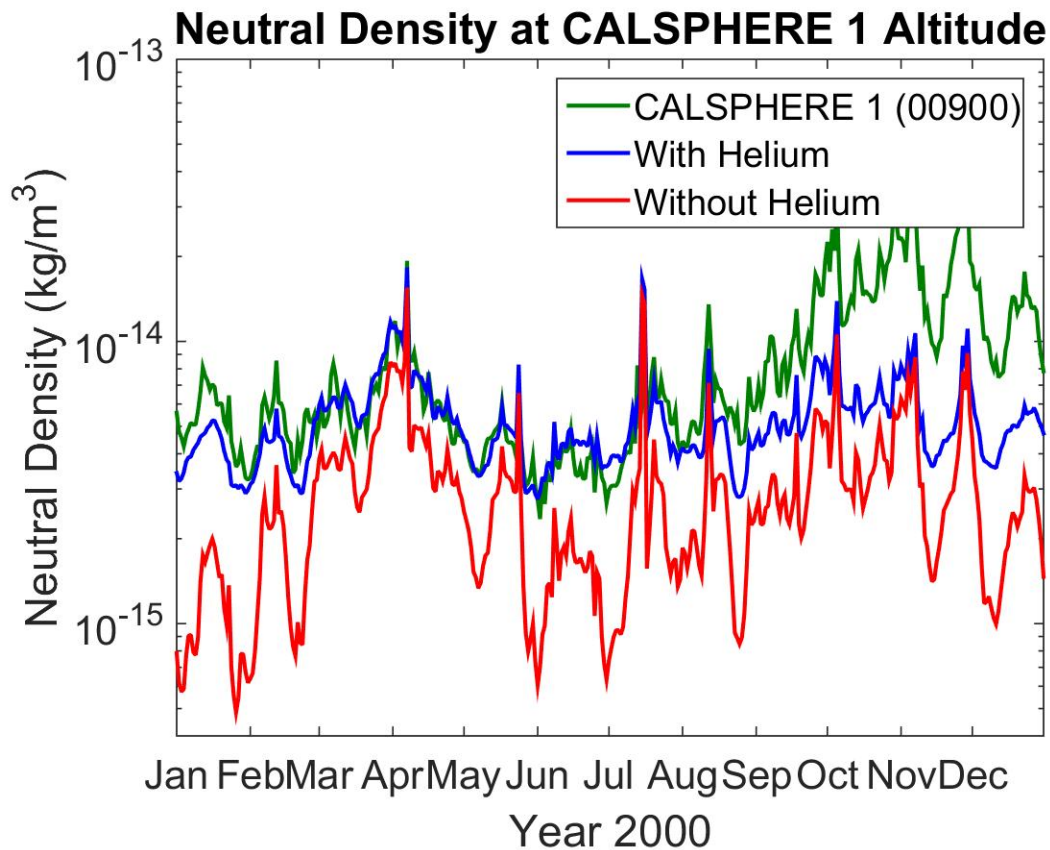


Figure 36. Neutral Density at CALSPHERE 1 Altitude, 2000.

In previous examples, the $F_{10.7}$ index has been a proxy that describes the changes in neutral density within the data. However, similar to the Explorer 7 example in section 4.3.1, the A_p index indicates the solar forcing mechanism for all the sharp spikes

observed in the neutral density data in Figure 36. There are several events that occur in 2000, but there are five that are focused on. The events in early April, May, July, August, and early October are all above 75 and are well represented in Figure 36. The first three events listed have comparable neutral density values between the both model runs and the satellite data. However, when a solar storm occurs, these values all increase as a result, but both model runs actually exceed the satellite data. The neutral density data increases for all the plots during the latter two events, but this time the model data does not exceed the satellite data. This is because there is already a large discrepancy between the both model runs and the satellite data. In summary, when the data is close during low geomagnetic activity, the model will increase the total neutral density over what is being observed.

Overall, the CALSPHERE 1 satellite provided insight on the extent to which helium can improve the TIE-GCM. This improvement also highlights the accuracy of the diffusive equilibrium assumption to extend the model vertically. Despite mixed results at the 750-850 km altitude range, the error in the TIE-GCM ‘With Helium’ run at 1000 km was closer to the low error values identified for the 500 km satellites where helium did not significantly contribute to the model. Additionally, the approximately two orders of magnitude difference at the beginning and end of the CALSPHERE 1 data shows that the original TIE-GCM lacks composition at these altitudes. The ‘Without Helium’ run is underestimating neutral density at higher altitudes as O continues to exponentially fall off. However, error in the ‘Without Helium’ model decreases during solar maximum and geomagnetic storms as the O composition expands and contributes more to the composition at the higher altitudes.

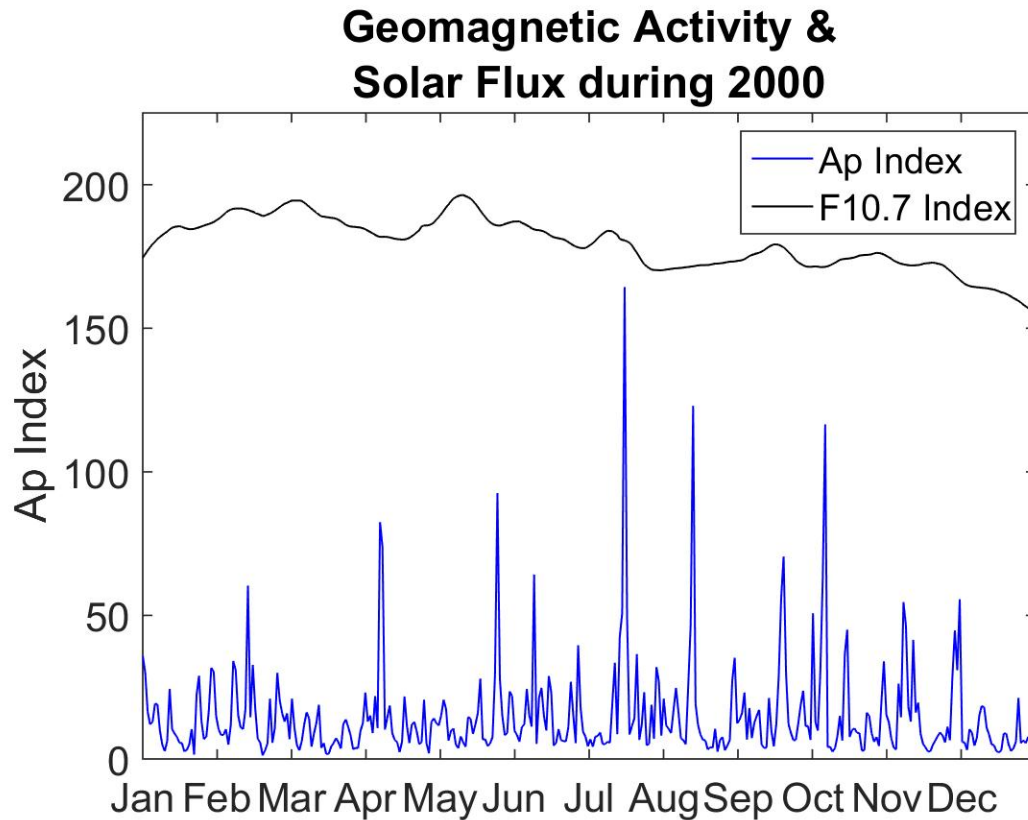


Figure 37. Solar Activity during 2000. The geomagnetic activity and solar flux for 2004 displayed by the A_p and $F_{10.7}$ indices.

4.6 Analysis of Error as a Function of Altitude and Solar Activity

The analysis from the previous four sections revealed that the performance of the TIE-GCM is dependent on the solar activity and altitude. The altitude dependence is not a simple linear progression through the atmosphere. For example, the average error for the TIE-GCM ‘With Helium’ run at the CALSPHERE 1 altitude is less than the all three satellites in section 4.4. This is independent of the type of orbit as the SURCAL satellites had near circular orbits and the RIGIDSPHERE 2 had a more elliptic orbit.

Unfortunately, a satellite that lies within the 850 km - 950 km range was not available for

analysis in this research. However, there is a clear difference of model performance at the highest altitude.

The best way to illustrate this feature is to break down the model into monthly averages. The yearly averages given in the previous two sections provided a good idea of the general performance of the model. There are several examples described throughout Chapter IV that show a seasonal and solar dependence in the data. Since the daily averages would be too much data to display individually in graphical format, a monthly average approach was taken.

The most extreme case is the CALSPHERE 1 satellite. In Figure 38, the monthly averaged percentage error for each run of the TIE-GCM is plotted against the monthly averaged value of the $F_{10.7}$ index. Although no correlation is made specifically in the figure, the same monthly plots of each model run align vertically for a specific $F_{10.7}$ index. Each data point is representative of a monthly average.

Figure 38 shows that there is a wide discrepancy among error plots at $F_{10.7}$ indices less than 150. The ‘With Helium’ run error ranges from 5% - 55% within this solar flux range while the ‘Without Helium’ run averages 80% - 90% during the same conditions. It is no coincidence that the error plots look like this during lower solar flux conditions as the helium dependence in the model and atmosphere is extremely amplified. As the solar flux increases over 150, there is no direct correlation between error and $F_{10.7}$ for either model run. However, as the yearly averages in Table 6 displayed, the ‘With Helium’ run plots are consistently lower than the ‘Without Helium’ run plots.

This wide separation in error was not as distinguished when analyzing the three satellites in section 4.4. During the higher solar activity conditions, it was determined that

the ‘Without Helium’ run produced less error than the ‘With Helium’, albeit a very small difference. However, the addition of helium into the TIE-GCM did not always improve the model at these mid-range altitudes. The years that the model improved were 1998 and 2004, which coincided with lower solar activity. The monthly averages and the associated $F_{10.7}$ index will generally show how distinguished the improvement is between the two TIE-GCM runs. This can be seen in Figure 39, which is a plot of the monthly averages of the SURCAL 160 satellite.

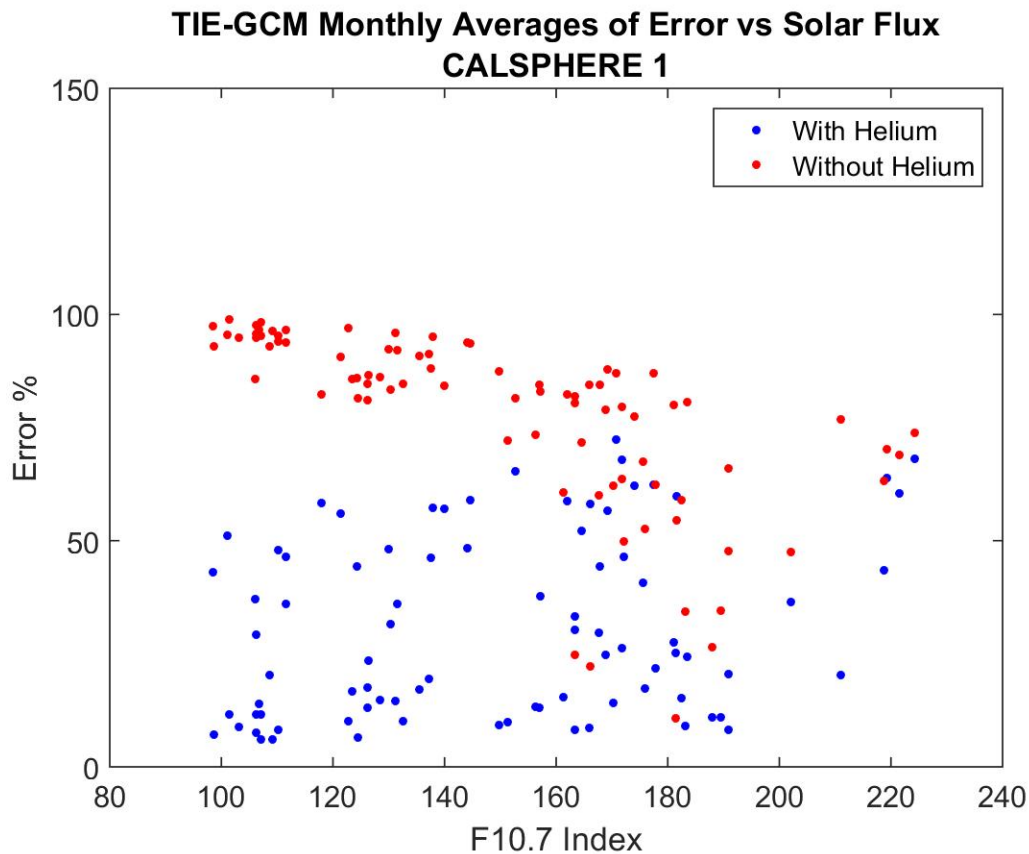


Figure 38. Error vs Solar Flux at CALSPHERE 1 Altitude. The monthly averages of the TIE-GCM error percentages for both runs at CALSPHERE 1 (NORAD tracking ID: 00900) altitude.

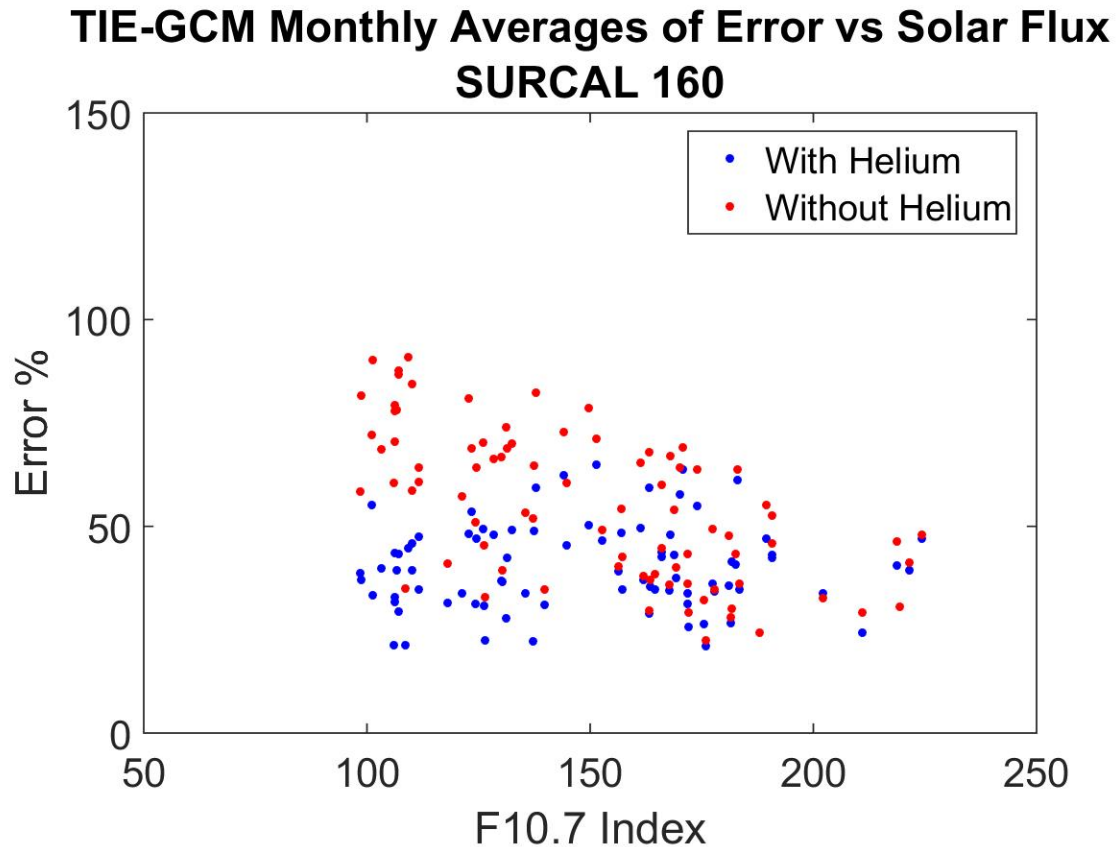


Figure 39. Error vs Solar Flux at SUCAL 160 Altitude. The monthly averages of the TIE-GCM error percentages for both runs at SURCAL 160 (NORAD tracking ID: 02826) altitude.

The difference between the error plots is not as wide as Figure 38, but there is a clear distinction of the ‘Without Helium’ red plots trending above the blue ‘With Helium’ plots. This is specifically the case for $F_{10.7}$ index values below 120. There are 19 months with average $F_{10.7}$ index values below 120, and 14 of them have average ‘With Helium’ run error below the ‘Without Helium’ run. This 73.6% average is much higher than the 58.3% of the collective 84 months that are within the seven year timeframe at the SURCAL 160 altitude. This is not as extreme as the CALSPHERE 1 altitude, but there is

a clear dependence on solar flux as to how well the addition of helium into the TIE-GCM improves the model.

The comparison between the $F_{10.7}$ index and the error does not consider the effect solar storms have on the error. As detailed several times in Chapter IV, the A_p index accounts for the spikes that are seen in all three datasets for the neutral density plots. These solar storms can occur during lower solar flux conditions and may account for the few monthly averages that have favored the ‘Without Helium’ run. However, further analysis into this will not be completed in this research.

The error differences of the SURCAL 150B and the RIGIDSPHERE 2 satellites are not as well-defined as in Figure 38 and 39 of the CALSPHERE 1 and SURCAL 160 satellites, respectively. This is partly due to the fact that at lower altitudes, the TIE-GCM has improved less with the inclusion of helium as a major species than at higher altitudes. The same applies to the Explorer 7 and Vanguard 2 satellites as both did not have significant differences between model runs at their altitude.

V. Conclusions and Recommendations

An analysis was completed for eight satellite datasets sampled in the TIE-GCM. The neutral density data associated with these satellites was considered highly accurate and provided a good comparison to the values sampled from the model. The analysis of the satellites went from the lowest altitude satellite (CHAMP) to the highest altitude (CALSPHERE 1) to show the increasing contribution of helium with altitude. A clear improvement in the total neutral density values was found in the TIE-GCM with helium included as a major species during solar minimum conditions. Very little change in the model's performance was found at lower altitudes where helium is not as dominant of a species. In the analysis of the mid-range altitudes, improvement was seen when the $F_{10.7}$ index was less than 125. Above this threshold, the TIE-GCM without helium as a major species performed slightly better at a yearly average. The model overcompensated for total neutral density for both runs during solar activity, as the neutral density did not decrease rapidly enough in conjunction with decreased solar flux values. The analysis of the highest altitude satellite at 1000 km perigee revealed an improved performance of the TIE-GCM during all seven years. The largest improvement in the model was observed in 1998 with a 68.47% error difference between the two model runs.

5.1 Methodology Improvements

This study used an error equation that inflated the values of error for model data larger in magnitude than the satellite data. Additionally, values below two orders of magnitude would start to sharply converge to 100% error. Fortunately, this difference was only recognized in the CALSPHERE 1 satellite when it was already clear the TIE-

GCM improved significantly. Future studies should look into different error calculations to consistently characterize the difference in the models. Despite the issue with the error calculation, the addition of helium into the TIE-GCM does improve the model and establishes a proof-of-concept for helium as a major species in physic-based models.

The difference in data described in Chapter III shows that there is possible improvement in this validation. In the time constraints of this research, utilizing the TLE and SGP4 propagator was the most efficient tool for acquiring tangible data to compare to the model. Other possible methods can be taken to improve the research. Two possible methods would either require access to Bruce Bowman's raw model data or access to his special perturbations model. The raw data could be used to apply the same weighted average used for the TIE-GCM. Another approach would be to run Bowman's model directly and sample the TIE-GCM with the entire orbits from his model. This would remove the use of the TLE data and SGP4 propagator.

5.2 Future Work

The spherical satellite data provided the opportunity to sample the model at the higher altitudes. The improvement that was determined in Chapter IV was afforded by the analysis of this alternate set of data. However, future studies would benefit from an increased altitude range and data that covered a full solar minimum. The CHAMP and GRACE data extended through the solar minimum in 2008-2009 and showed variability in the TIE-GCM during that timeframe. The higher-altitude spherical satellites had error differences of 10%-40% during the moderate solar conditions. The CALSPHERE 1 satellite specifically displayed a 68% difference in error during 1998 with an average

solar flux of 123. The neutral density data was two orders of magnitude different at the start of the 1998 year. The years 2008-2009 had solar flux values as low as 70. Increasing the set of data through 2010 would potentially show the most drastic change from the inclusion of helium in the TIE-GCM.

In addition to the expansion of the timeframe of data, the location and averaging of the two data sources can be improved in order to get a closer analysis. For example, the fact that the spherical satellite data was determined at the equatorial crossing was not explicitly known at the beginning of this research. Given more time to understand the nature of the data, two difference approaches to matching the data could have been taken.

At the time of this document, a validation study of the TIE-GCM with the inclusion of helium as a major species had not been completed. This is the first research on this validation and the results show the importance that helium has in the upper thermosphere and lower exosphere within the TIE-GCM. Despite potentially different approaches to future analysis and validation of the TIE-GCM's performance, this research shows that subsequent versions of the model should include helium.

Additionally, the proof-of-concept is established that a physics-based model handles the contribution of helium to the total neutral mass density well. As a result, this work paves the way for other physics-based models to include helium as a major species. Finally, this study is the next step for the TIE-GCM to become an operationally relevant model.

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14. ABSTRACT When considering the neutral constituents in the upper thermosphere and exosphere, helium needs to be accounted for as a major species. As detailed by Emmert [2015], most first-principle models do not consider helium a major species when solving for diffusion and collisions within the atmosphere. First-principle, physics-based models hold a distinct advantage of seasonal variations and spatial resolution over empirical models which leads to a more realistic depiction of the atmosphere. The National Center for Atmospheric Research's (NCAR) self-consistent, physics-based Thermosphere-Ionosphere-Electrodynamic General Circulation Model (TIE-GCM) has been updated to take into account this neutral constituent in its calculations. The major goal was to characterize this change to the TIE-GCM as a function of altitude as helium becomes a dominant species. A distinct improvement was found in the updated model during lower solar activity conditions and altitudes above 750 km altitudes.						
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