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Investigating the Weddell Sea Anomaly using TIE-GCM

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Abstract

The ionosphere is a region of Earth's upper atmosphere that is embedded in the thermosphere and parts of the exosphere and mesosphere. The ionosphere is a layer of electrons and electrically charged atoms and molecules that are created by atmospheric absorption of solar radiation. It is subdivided into many layers but for this report, only the F-layer will be of interest. In the F-layer, extreme ultraviolet (EUV) solar radiation ionizes atomic oxygen and in this layer, an intriguing feature occurs. This feature involves an anomalous evening phenomenon over a fixed geographic location, where the electron density during the nighttime is more than twice as large than at noon. This phenomenon takes place during the summer and is visible in the southern hemisphere. This intriguing phenomenon is known as the Weddell Sea Anomaly (WSA).

In an effort to understand this anomalous phenomenon, we investigated whether the Thermosphere-Ionosphere-Electrodynamic General Circulation Model (TIE-GCM) could successfully replicate the WSA observations. TIE-GCM is available for runs-on-request at the Community Coordinated Modeling Center (CCMC). Using the CCMC, we preformed TIE-GCM model runs for the conditions foreseeable for the development of the WSA. MATLAB was used to illustrate output data from TIE-GCM. The data obtained from TIE-GCM was also compared and contrasted to other empirical based model data such as: Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) and Mass-Spectrometer-Incoherent-Scatter (MSIS) E-90 for further investigation of TIE-GCM's ability to replicate the WSA.

Introduction

Earth's atmosphere is broken into layers based on its temperature gradient above the surface. The layers are: troposphere (0-12 km), stratosphere (12-50 km), mesosphere (50-80 km), thermosphere (80-700 km) and exosphere (700-10,000 km). Earth's ionosphere is the ionized portion of the upper atmosphere and is embedded in the thermosphere and parts of the mesosphere and exosphere.

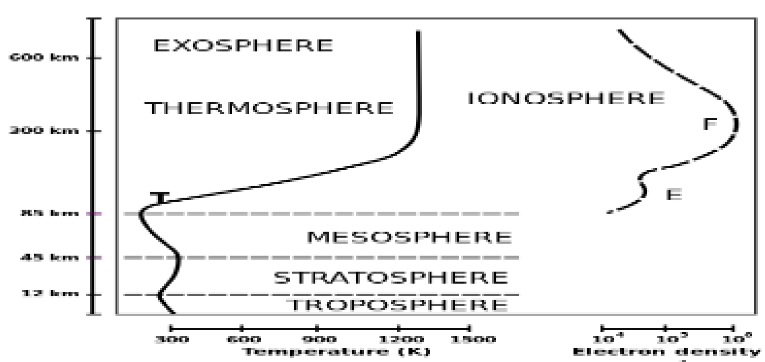

Figure 1: Temperature profile of Earth's atmosphere, also shown is the electron density profile of the ionosphere's E and F regions.

The ionosphere is the primary focal point for this report. It is broken into regions: D-Region, E-Region, and F-Region. The D-region only exist during the daytime and spans from 60-90 km. It also has the lowest electron density of the three (about $10^3\ cm^{-3}$). E-region spans from 90-150 km and has an electron density quantity of about $10^5\ cm^{-3}$. During the night, the D-region disappears and the E-region's electron density drops to D-region levels. Lastly, the F-region spans 150-800 km altitude and has the highest electron density which peaks at about $10^6\ cm^{-3}$. The F-region is subdivided into F1 (150-200 km) and F2 (200-800 km) region and in the F2 region of the ionosphere is where observations were made in the discovery of the Weddell Sea Anomaly.

For this project, we examined the behavior of the maximum F-region electron density (NmF2). NmF2 is the maximum value of electron density in its height distribution. As shown in Figure 1, the F-region of the ionosphere begins around 150 km, which is embedded in the thermosphere and reaches a maximum of 800 km, which is a part of the exosphere. The height maximum of the F2 layer, where the ionospheric electron density reaches a maximum is known as hmF2. At that altitude is where electron density is greatest.

The Weddell Sea Anomaly (WSA) was first discovered more than five decades ago by ionosonde observations near that Antarctic peninsula *(Chang et al, 2015).* The name was given because of its anomalous observations and proximity to the Weddell Sea region. It is an ionospheric phenomenon characterized by a larger than normal nighttime electron density compared to daytime electron density, which is a recurrent feature of the summertime Southern Hemisphere. This surprising phenomenon only occurs during the summer but disappears during the winter. Similar anomalous features have been observed in the northern hemisphere during local summer, but have shown smaller amplitudes *(Huang et al., 1989).* Satellite observations have shown that the WSA can extend from lower boundaries of South America and western Antarctic peninsula to the central Pacific. The area of this phenomenon that was studied for this paper will primarily focus on a fixed geographic location around 50°S latitude and 95°W longitude.

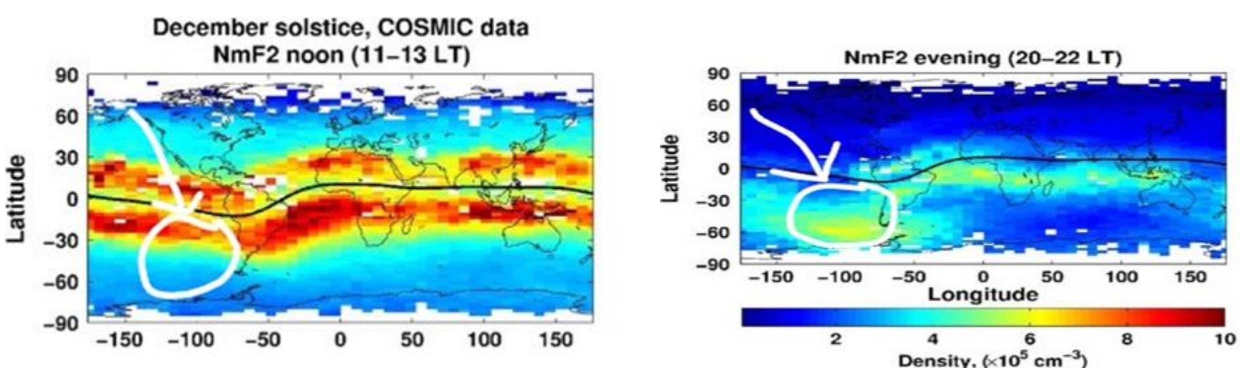

Figure 2: Global maps from COSMIC showing NmF2 for noon (left) and evening (right) during December solstice. The area where the Weddell Sea Anomaly occurs is circled.

Figure 2 shows the global peak electron density in the ionosphere at noon (left) and evening (right). The images were obtained from COSMIC data *(Lomidze et al., 2016)* that shows global distribution of NmF2 values. The solid black line in Figure 2 indicates the location of the magnetic equator. The location of the Weddell Sea Anomaly is circled in above Figure 2, which has a color scale showing the breakdown of electron density between noon and evening data. Based on the scale, the evening data shows a higher NmF2 value than its noontime counterpart at the WSA location.

The anomaly has baffled researchers since its discovery. It continues to be actively researched because of the unknown driving mechanism(s). A widely accepted explanation for the mechanism generating the WSA was described by *Dudeney and Piggott (1978),* who attributed the WSA to a combination of thermosphere neutral winds and magnetic declination effects *(Chang et al, 2015).* Dudeney and Piggott describe how the neutral winds transport plasma equatorward and upward along magnetic field lines from higher magnetic latitudes in the summer hemisphere, where the plasma persists for a longer period, due to the reduced loss rate at higher altitudes.

In an effort to investigate the WSA, we used the National Center for Atmospheric Research (NCAR)'s TIE-GCM. We accessed the model through the Community Coordinated Model Center (CCMC) website, to investigate the WSA. TIE-GCM is a comprehensive, first-principles, three-dimensional, non-linear numerical model of the coupled thermosphere and ionosphere system. The main objectives of this project were to investigate whether TIE-GCM could successfully replicate the Weddell Sea Anomaly. Model output from TIE-GCM include 3D density distribution predictions of the ionosphere as well as information about neutral winds, peak electron densities (NmF2), and temperatures.

Methodology and Approach

TIE-GCM is state of the art, physics-based model of the coupled thermosphere-ionosphere system. For this project, we investigated whether this model could replicate the Weddell Sea Anomaly. To request model runs for TIE-GCM, which was accessed through CCMC's website, the data runs needs input quantities for:

- Day of year (001-365)
- Month
- Year
- Duration (1-31 days)
- F10.7 index (solar activity)
- Kp index (geomagnetic activity)
- Spatial Resolution

For this project, all the run request of TIE-GCM were performed under solar quiet conditions (no solar storms were occurring). These runs were made from January 1-6, 2008, with a spatial resolution of 2.5°, and an output frequency of 20 minutes. What is meant by solar quiet conditions? During solar quiet conditions, there is quiet aurora forcing (low Kp index) and is at a solar cycle minimum (low F10.7 radio flux), which will be explained in further detail below. Runs were done for the December Solstice, which is summertime in the southern hemisphere, when the WSA is noticeable. The December solstice is a 60-day average of measuring ionospheric value parameters effects. Therefore, using these average values, the effects are minimized.

Quiet Aurora forcing is based on numerical values from the Kp index scale. Kp index, where 'K' come from the German word 'Kennziffer' meaning 'characteristic digit' and 'p' coming from the word planetary. Kp indices are used to characterize the magnitude of geomagnetic storms and are an excellent indicator of disturbances in the Earth's magnetic field. This disturbance in Earth's magnetic field is given an integer value the range 0-9 with 1 being calm and 5 or more indicating a geomagnetic storm *(swpc.noaa.gov)*.

Kp	0	0+	1-	1	1+	2-	2	2+	3-	3	3+	4-	4	4+
Kp (decimals)	0.00	0.33	0.67	1.00	1.33	1.67	2.00	2.33	2.67	3.00	3.33	3.67	4.00	4.33
Kp	5-	5	5+	6-	6	6+	7-	7	7+	8-	8	8+	9-	9
Kp (decimals)	4.67	5.00	5.33	5.67	6.00	6.33	6.67	7.00	7.33	7.67	8.00	8.33	8.67	9.00

Table 1: List of Kp indices. For this project, the Kp indices are highlighted.

What is solar cycle minimum? The solar cycle is the amount of magnetic flux that rises to the Sun's surface which varies with time in a cycle called the solar cycle. Solar cycles last 11 years on average. During solar cycle minimum, it is rare to see sunspots on the Sun. Sunspots indicate regions where the solar magnetic field is strong. High levels of sunspot activity lead to improved signal propagation on higher frequency bands, although they also increase the levels of solar noise and ionospheric disturbances *(Wikipedia).* From this, scientist have discovered the solar radio flux index, F10.7. F10.7 is a measure of the noise level generated by the sun at a wavelength of 10.7 cm (2800 MHz) at the earth's orbit. Historically, this index has been used as an input to ionospheric models as a surrogate for the solar output in wavelengths that produce photoionization in the earth's ionosphere (in the extreme ultraviolet bands) *[swpc.noaa.gov]*. For our research, we studied the WSA with a F10.7 value of 73 solar flux units (sfu).

The TIE-GCM results are stored in network common data format (NetCDF) files and include values for NmF2 and hmF2 as well as 3-dimension fields for the neutral and ion densities, temperatures, and winds. MATLAB was used to visualize the model output by producing 2-dimensional global color-contour maps for various model output parameters at a fixed universal time (UT). Examples of these maps can be seen below for selected output parameters from TIE-GCM.

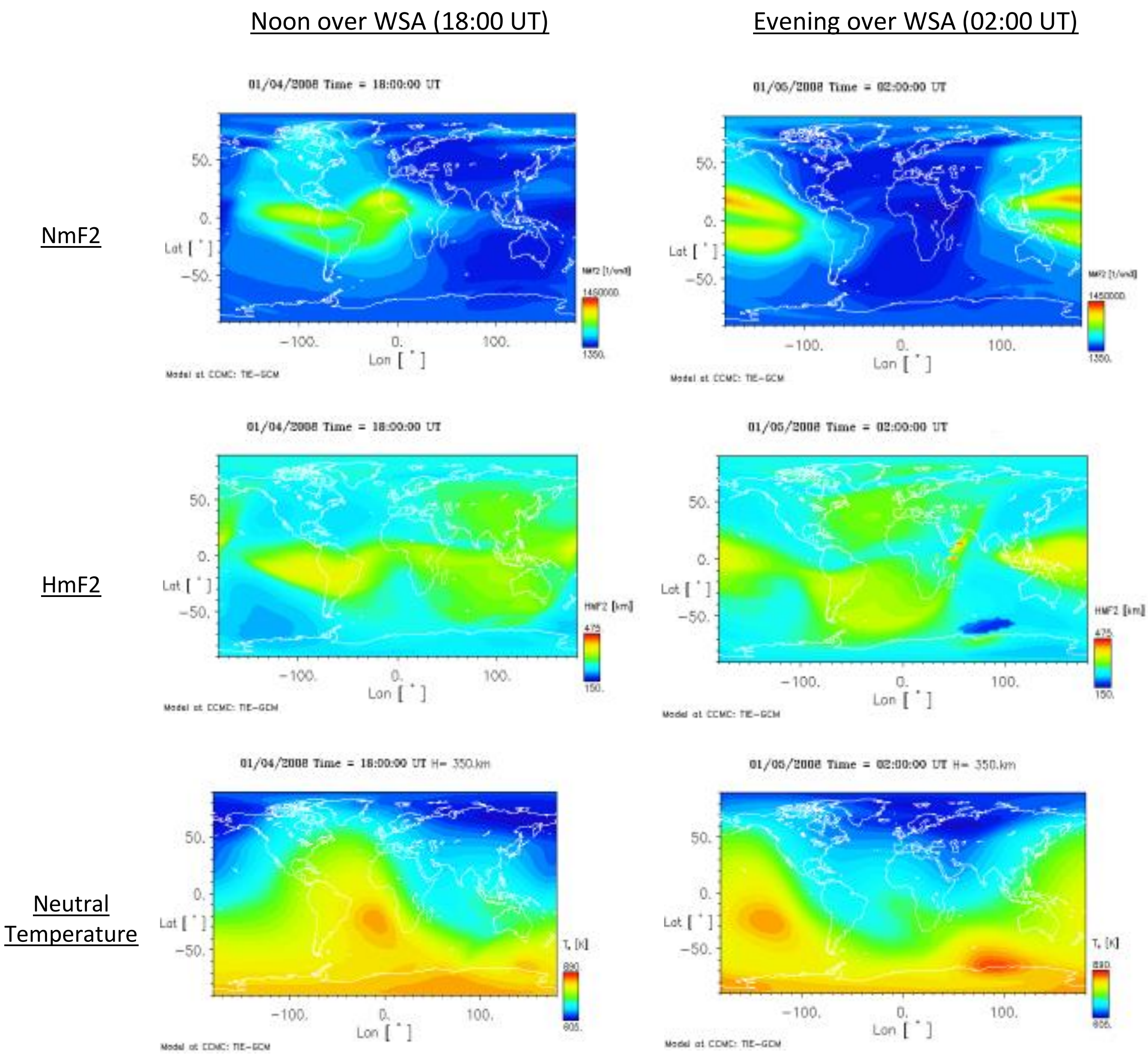

Figure 3: 2D representations of NmF2, HmF2, and neutral temperature (Tn) at local noon (18:00 UT) and nighttime (02:00 UT) values for global distribution.

Figure 3 shows a two-dimensional representation for global distribution of NmF2, HmF2, and Neutral Temperature (T_n) values for a fixed UT. The UT times were chosen so that they correspond to noon (1800 UT) and evening (0200 UT) local time over the WSA. The distribution is plotted latitude against longitude on a global scale. Shown later, will be 1-Dimensional line plots of NmF2 and T_n at a fixed time and increasing altitude (HmF2) profile. This representation will show how those values vary with altitude.

As mentioned previously, output information from TIE-GCM was illustrated with the computing program MATLAB. Using MATLAB, we created a fixed local time-plot of the peak electron density (NmF2) at noon and evening (20:00) LT. This would help to show the Weddell Sea Anomaly at the fix local times.

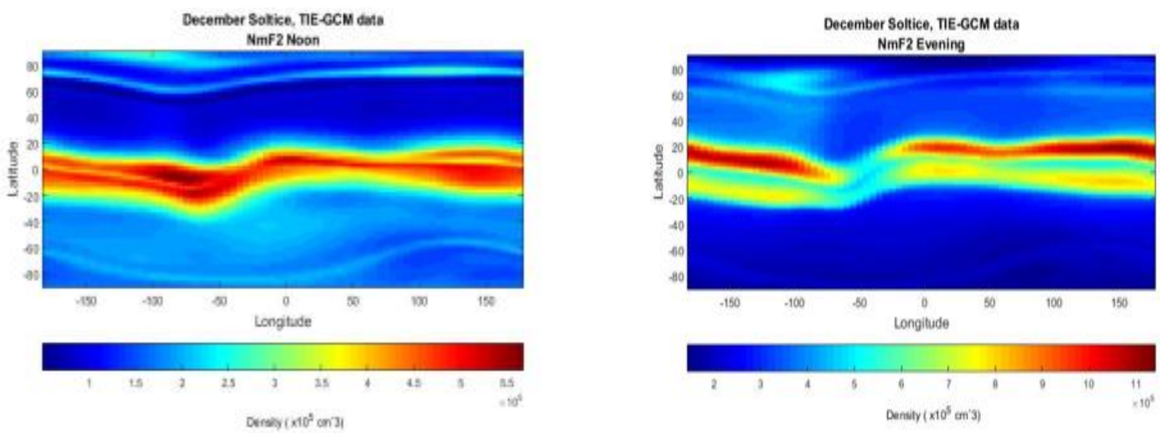

Figure 4: NmF2 from TIE-GCM at fixed noon (left) and evening (right) local time plot of TIE-GCM.

Figure 4 shows global peak electron density in the ionosphere at noon (left) and evening (right) from output data from TIE-GCM using MATLAB. The figures show global distribution of NmF2 values at a fixed constant local time. The color scale provides insight into these increasing values from blue (low density) to red (high density). The MATLAB plots were created as a comparison to Figure 2 to see if TIE-GCM can replicate the Weddell Sea Anomaly. Unlike Figure 2, there is no evidence of the WSA in Figure 4 when comparing the fixed local noon and evening time NmF2 results in that region. Results obtained from TIE-GCM were further compared and contrasted against data from COSMIC *[Lomidze et al, 2015].* The two models were plotted in a 1D line plot at a fixed geographic location over the Weddell Sea region. This plot shows a 24-hour time-period showing peak electron density values for COSMIC and TIE-GCM.

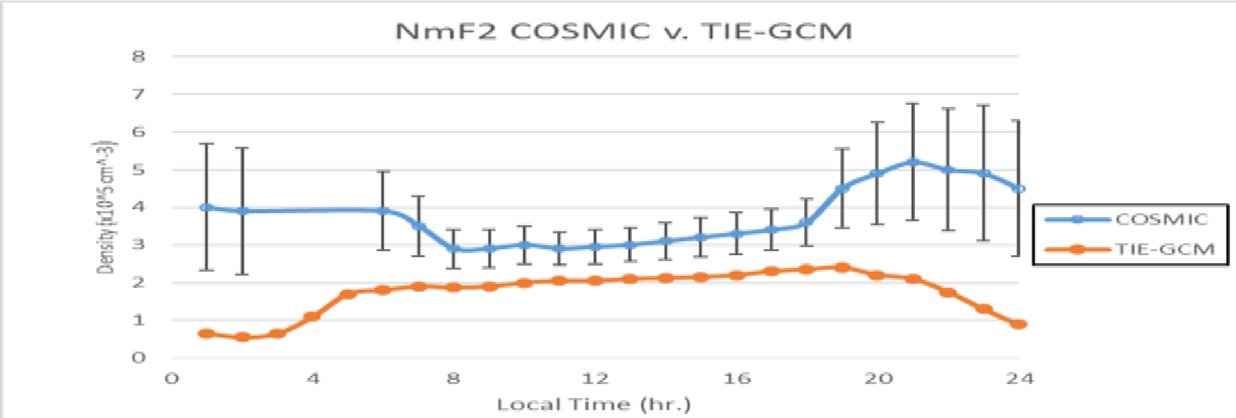

Figure 5: Comparison of NmF2 values from COSMIC & TIE-GCM for a 24-hour local time at global coordinates, 93.75°W 53.75°S

First observations show that TIE-GCM has suspiciously low values of NmF2 at all local times when compared to COSMIC. The peak electron density maximum for COSMIC has a value around $5 * 10^5\ cm^{-3}$, whereas TIE-GCM has a value of roughly $2 * 10^5\ cm^{-3}$. Even though TIE-GCM does show a slightly higher nighttime electron density than noontime, TIE-GCM does not replicate the results shown in Figure 2.

In an effort to understand the surprisingly low NmF2 values from TIE-GCM, we did another comparison of TIE-GCM, but this time with an empirical-based model. The Mass-Spectrometer-Incoherent-Scatter (MSIS) E-90 model was used as a comparison. MSIS E-90 model describes the neutral temperature and densities in the upper atmosphere (100+ km). The densities we looked at for this project were the number densities for atomic oxygen (ionizing factor) and molecular nitrogen (reducing factor), as well as neutral temperature. In the F2 layer of the ionosphere, O2 molecules are ionized into atomic oxygen ions (O+). We wanted to see if the atomic oxygen ion quantities being produced was greater than the loss by molecular nitrogen. Figure 6 shows a side by side comparison of TIE-GCM with MSIS-E-90 Atmosphere Model for atomic oxygen, nitrogen and neutral temperature against altitude to compare and contrast the data.

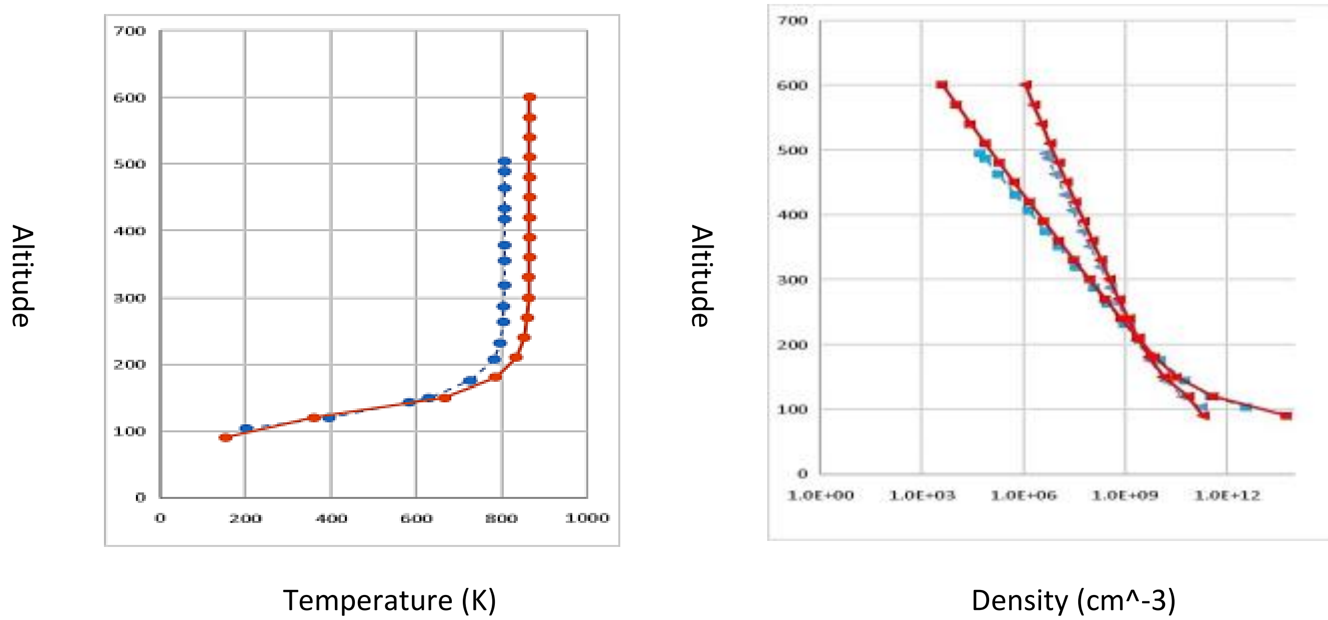

Figure 6: 1D line plots comparing MSIS & TIE-GCM data. MSIS data points are solid red lines whereas TIE-GCM data points are dashed blue lines. Atomic Oxygen data points (right) are shown as triangles and Molecular Nitrogen points (right) are squares. The neutral temperature points are circles (left).

Figure 6 shows line plots comparing MSIS and TIE-GCM results. Neutral temperature (left) results show a temperature profile for both models with increasing altitude. The plots were set at noon local time Both plots show similarities in Atomic Oxygen (O), Molecular Nitrogen (N2) and Neutral Temperature. The table below, shows differences in the two models based on results from Figure 6.

Altitude	Atomic Oxygen (O) (production) (cm^{-3})	Molecular Nitrogen (N2) (loss) (cm^{-3})	Production/loss O/N2 (%)	Neutral Temperature (K)
100 km	$1.92 * 10^{11}$ $1.76 * 10^{11}$	$5.60 * 10^{13}$ $3.85 * 10^{12}$	0.34 4.57	154.2 202.42
300 km	$3.48 * 10^{8}$ $3.61 * 10^{8}$	$8.75 * 10^{7}$ $1.16 * 10^{8}$	397.7 311.2	862.8 804.59
500 km	$5.92 * 10^{6}$ $4.41 * 10^{6}$	$7.22 * 10^{4}$ $5.23 * 10^{4}$	8199.5 8432.12	865.0 805.09

Table 2: comparison of values for MSIS and TIE-GCM data at fixed altitudes. MSIS values are highlighted

At lower altitudes, TIE-GCM has: a higher neutral temperature, and low atomic oxygen and molecular nitrogen values than MSIS does. As the altitude profile increases, however, TIE-GCM has: a lower neutral temperature

Results and Conclusion

For this report, we were investigating whether TIE-GCM could replicate observations of the Weddell Sea Anomaly as shown in Figure 2 from data received from COSMIC. We requested runs of TIE-GCM through CCMC's website using input data quantities such as time of day and year, duration of runs, and F10.7 index. CCMC provided output files as 2D visual representations of global distribution for parameter such as NmF2, HMF2, and neutral temperature (T_n) [Figure 3]. For this project, we focused on NmF2 observations, which is the maximum electron density in the F2 layer of the ionosphere (Figure 1). Output results from CCMC, we plotted fixed local time-plots for noon and evening NmF2 values using MATLAB (Figure 4). Analyzing the MATLAB results to compare to data from COSMIC observations revealed that the Weddell Sea Anomaly did not exist in the TIE-GCM results. We plotted a local, 24-hour, 1-D NmF2 time-series comparing results from TIE-GCM and data from COSMIC (Figure 5). In Figure 5, it reveals that TIE-GCM results are relatively low compared to COSMIC. However, both graphs revealed a maximum during local evening.

The suspicious results from TIE-GCM prompted us to investigate whether the atomic oxygen and molecular nitrogen values were major players in the results. In the F2 layer of the ionosphere, O2 molecules are ionized into atomic oxygen ions (O+). Production of O+ in the F2 layer, causes losses in molecular nitrogen (N2) density (Figure 6). We plotted a 1-D plots comparing atomic oxygen and molecular nitrogen against increasing altitude in the low to mid latitude ionosphere from empirical based model, MSIS. Shown in Figure 6 and Table 2, TIE-GCM and MSIS results for atomic oxygen and molecular nitrogen are roughly identical. This caused us to rule out the possibility of atomic oxygen being the driving force behind the suspiciously low TIE-GCM electron density results.

The reasons underlying why TIE-GCM underestimates the observed NmF2 are still unknown at this time. Future studies of investigating the Weddell Sea Anomaly involve studying: photoionization of the neutrals in the upper atmosphere and transport processes of plasma. Photoionization of the neutrals (e.g. atomic O, etc.) is the primary source of ionization in the ionosphere, which is caused by solar radiation in the EUV range. It is known that some transport processes cause the net production of ions to increase over the net loss. When the production is greater than the loss, this can cause the electron density to increase. Further examining photoionization and plasma transport process during the evening hours can provide insight into the development of the WSA.

References and Acknowledgements

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5. Huang, Y.-N., K. Cheng, S.-W. Chen, On the equatorial anomaly of the ionospheric total electron content near the northern anomaly crest region, *J. Geophys. Res.*, **94**, 13515, 1989.
6. Simulation results have been provided by the Community Coordinated Modeling Center (CCMC) at Goddard Space Flight Center through their public Runs on Request system
7. (http://ccmc.gsfc.nasa.gov). The CCMC is a multi-agency partnership between NASA, AFMC, AFOSR, AFRL, AFWA, NOAA, NSF and ONR. The TIE-GCM was developed by *R.G. Roble et al.* at HAO NCAR.
8. http://www.swpc.noaa.gov/products/planetary-k-index
9. https://starchild.gsfc.nasa.gov/docs/StarChild/questions/question17.html
10. https://en.wikipedia.org/wiki/Ionosphere

Special thanks to my faculty advisors, Maura and Ludger, and Ivana Molina

Appendix

MATLAB code

```
list = dir('C:\Users\DaeSean\Desktop\OUTPUT FILES
111316\DaeSean_Jones_111316_IT_1\out\s*.nc')

s = length(list);
```

```
NMF2 = NaN(144,72,24*s);
Noon_NMF2 = NaN(72,72);
Eight_NMF2 = NaN(72,72);


for i=1:s %s
    time=(24*(i-1)+1):(24*i);


    filename = list(i).name;
    ncid = netcdf.open(filename,'NC_NOWRITE');

    varid0 = netcdf.inqVarID(ncid,'NMF2');
    NMF2(:,:,time) = netcdf.getVar(ncid,varid0);

    varid0 = netcdf.inqVarID(ncid,'time');
    timemodel(time) = netcdf.getVar(ncid,varid0);

    varid0 = netcdf.inqVarID(ncid,'lon');
    lon = netcdf.getVar(ncid,varid0);

    varid0 = netcdf.inqVarID(ncid,'lat');
    lat = netcdf.getVar(ncid,varid0);


 end
lon_new=-180:5:175;

for t=1:72
    Noon_NMF2(72-t+1,:)=NMF2(145-(2*t),:,t);

end
for t=1:24
    Eight_NMF2(24-t+1,:)=NMF2(49-2*t,:,t);
end

for t=25:72
    Eight_NMF2(72-t+25,:)=NMF2(145-(2*t)+48,:,t);

End

imagesc(lon_new,lat,Noon_NMF2')
figure(2)
imagesc(lon_new,lat,Eight_NMF2')
```