FINAL REPORT FOR NASA PROJECT - NNG04GN04G

LWS: Effect of EUV and High Latitude Forcing on Thermospheric Densities

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1.0 EXECUTIVE SUMMARY

The focus of this project was to understand the variability of the neutral density in the Earth's thermosphere. This is important for practical purposes related to satellite drag. It is also important from a fundamental scientific point of view because there are many gaps in our understanding of thermospheric density. Although thermospheric density has been studied for many years, there remain many fundamental mysteries relating to its behavior. The number of papers published (12) and conference presentations made during this project is a testimony to the level of interest in this topic and its importance. We managed to address all of the science questions posed in our proposal, in addition to some new ones that emerged during the project. We first list the stated goals of the project, then provide a bulleted list of highlights from our work, including the list of 11 papers published and submitted. Finally, we provide Annual Reports by year, including the 1-yr no-cost extension, with publications and presentations for each year. In addition to the 12 papers, we made 50 presentations during the project.

1.1 Objectives of Proposed Work

The LWS TR&T Report of July 2003 identified two key objectives for addressing space weather hazards related to thermospheric neutral density:

> *Objective 1: Determine the effects of long and short-term variability of the Sun on the mass density of the atmosphere between 120 and 600 km altitude and describe these effects with accuracy better than 5%.*
>
> *Objective 2: Understand and predict satellite drag variations during geomagnetic storms and during the solar activity cycle.*

In turn, the Report led to a single priority for the neutral density community:
Priority: Develop more advanced thermospheric density and composition models.

We proposed to use existing density data from the GRACE, CHAMP and TIMED satellites, together with solar EUV drivers from TIMED, and various high latitude data to address these two objectives and the single priority - by answering the following science questions:

> ***1) What is magnitude of thermospheric density changes in response to variability of the Sun on different temporal scales?***
>
> ***2) How does density in upper thermosphere respond to Joule heating?***
>
> ***3) What are the key drivers of density perturbations in upper thermosphere?***
>
> ***4) How valid are the assumptions behind the determination of neutral densities from satellite drag data?***

The products of the proposed research will include scientific understanding, presentations at conferences, and scientific publications. Specifically, we will test our understanding and modeling of the effects of solar EUV, Joule and particle heating, and momentum forcing on thermospheric densities in the 120 - 600 km region. The proposed work will lead to improvements in our ability to understand and predict satellite drag variations during geomagnetic storms and during the solar activity cycle. We will also provide improvements in the TIMEGCM that can be used by the developers of the fully coupled models, and some simple validations of these products. The PI, Dr. Crowley, is associated with the CISM project for Space Weather Modeling. He is also involved in the internal validation efforts of the NCAR team (see letter of support from Dr. Stan Solomon). The proposed work will also have operational benefits, as Dr. Crowley also has access to the HASDM team, through collaboration with Space Command (Bruce Bowman), and he is a member of the DMSP SSUSI (ultraviolet imager) Cal-Val teams for the dayside ionosphere and neutral density. Eventually, this work will lead to first principles models (probably with data assimilation) that describe density (and associated composition) effects with accuracy better than 5%. In turn, the proposed work will lead to better predictions of satellite orbits.

1.2 Summary of Project Achievements

In this section, we list some of the highlights of the project results. More detail is provided below, broken out by year, including papers and presentations listed by year.

The project has been very successful, with the publication of 12 papers, and several more that will be completed in the future. A total of 50 presentations were made at conferences (Year 1:2:3:4 = 10:8:20:12). While we did not answer all of the science questions posed, we did answer some of them. We also are left with a new set of questions to answer in the future (not listed here).

The highlights of the research are:

- The thermospheric densities derived from the accelerometers on NASA's GRACE satellite have undergone validation, and the data analysis techniques have been improved. We now have much greater understanding of the various effects such as solar radiation on the spacecraft and the accelerometer measurements.
- The TIMEGCM global first-principles model has been pushed to extremes of storm behavior by simulations of some of the largest storms of the past 10 years. We have used the high latitude electrodynamic inputs provided by AMIE for all of these runs, representing the most extensive use of AMIE to drive first principles models. The model simulations are generally improved substantially by using the AMIE fields to drive the model.
- Comparison of the GRACE density data with the TIMEGCM output has revealed that the model is capable of simulating the density perturbations rather well in many cases. We claim this is a result of the fidelity of the high latitude inputs from AMIE. These high fidelity model simulations are now waiting to be analyzed further to interpret the observed density variations in more detail. The model does not simulate features with wavelengths on the order of 10º, which is expected due to the model resolution.
- We have produced the first analysis of the response of thermospheric density to Joule heating. This has been something of a "holy grail" for density scientists. Using data alone, it has been very difficult to separate the competing effects of tides, high latitude variability and solar variability. We have used the TIMEGCM as a numerical laboratory, simulating the response to the same high latitude inputs for solar maximum, minimum and different seasons. We have analyzed these simulations to provide a look-up table describing the density response to Joule Heating as a function of season and solar cycle. The uniformity of the response from event to event is remarkable.
- We have used GRACE and CHAMP data to validate our numerical experiments describing the relationship between Joule heating and thermospheric density. We performed numerical simulations of the density response for some of the largest storms of the past decade, and compared them with our previous controlled numerical experiments. We found that the results are comparable. Again, the uniformity of the response from event to event is remarkable. However, we have density data for the actual storm periods, and we have been able to validate the numerical models, showing that they match the data reasonably well.
- We developed a simple technique to subtract the effects of solar forcing from the numerical experiments, and applied it to the data also. We used this technique to isolate the density response as a function of F107 for different solar fluxes and seasons. We have analyzed these simulations to provide a look-up table describing the density response to F107 variations as a function of season and solar cycle. In principle it could also be applied for different solar wavelengths when the spectral data are available.
- We helped to investigate the response of the thermospheric composition and density to High Speed streams. It is clear that the response is different during these events, although more work is needed to clarify the drivers.
- We have studied the density cell structure. We showed for the first time that there is a strong relationship between the sign of the IMF BY component and the orientation of the cell structure with local time. Specifically, the cell pattern rotates to earlier local times as the BY changes from negative to positive. We also showed that the same rotation applies to the composition of the high latitude thermosphere.
- The result describing the variation of composition as a function of BY was used to question a conclusion reached previously by other scientists. We showed that their observational result was exactly the opposite of what is actually observed. And we provided a new explanation of their observations, simulating their event with TIMEGCM to confirm our ideas.
- We studied the density cells at high latitude to investigate how high they remain visible. We used CHAMP data to confirm the model result that the cell structures grow weak by 400 km altitudes.

- We used the model to show for the first time that Joule heating is relatively unimportant in driving the cell structure. Instead, it is almost completely driven by momentum forcing. This is a dramatic departure from previous thinking.
- We have used GUVI data to produce the first systematic study of the solar cycle and seasonal effects on density and composition.
- We used cross-track winds from CHAMP to investigate the effect of winds on the density analysis of GRACE data. We showed that the effect is generally small, but can be large, as expected. The study confirmed that most of the large density fluctuations observed by GRACE at high latitudes are probably real, rather than artifacts introduced by in-track winds.
- We used the model to investigate how the high latitude wind pattern is established. The model provided the relative contribution of different forcing terms in the momentum equation.
- We had the unexpected opportunity to study cross-track winds and densities on Mars, using aerobraking data from MGS and Mars Odyssey. Using our model of the Martian thermosphere, we validated a new wind-derivation technique based on the satellite accelerometers. We also showed that the aerobraking passes are often subject to very large wind-shears. This wind derivation will be used by the SwRI Mars Scout mission if it is selected by NASA.
- A cross-track wind analysis has been developed at UTAustin based on GRACE data. An intial comparison of the GRACE winds with the TIMEGCM wind predictions shows that many similar features are present in the data and the model, although time sis not permit detailed comparisons to be made on an event-by-event basis.
- We have collaborated with an exceptional group of scientists distributed around the country to produce these results and we are grateful for the opportunity to work with them. We are particularly grateful for the invitations to work with the LWS Density Focused Science Team led by Art Richmond, and the Air Force NADIR MURI team led by Jeff Forbes and Tim Fuller-Rowell.

List of 11 Papers Resulting from this Project

1) Schlegel, K., H. Luhr, J. P. ST. Maurice, G. Crowley and C. Hackert, Thermospheric Density Structures Over the Polar Regions Observed With CHAMP, Ann. Geophys., 23, 1659-1672, 2005

2) Meier, R. R., G. Crowley, D. J. Strickland, A. B. Christensen, L. J. Paxton, and D. Morrison, First look at the November 20, 2003 super storm with TIMED/GUVI, J. Geophys. Res., Vol. 110, A09S41, doi:10.1029/2004JA010990, 2005.

3) **Crowley, G.**, T. J. Immel, C. L. Hackert, J. Craven, and R. G. Roble (2006), Effect of IMF BY on thermospheric composition at high and middle latitudes: 1. Numerical experiments, J. Geophys. Res., 111, A10311, doi:10.1029/2005JA011371.

4) Immel, T. J., **G. Crowley**, C. L. Hackert, J. D. Craven, and R. G. Roble (2006), Effect of IMF By on thermospheric composition at high and middle latitudes: 2. Data comparisons, J. Geophys. Res., 111, A10312, doi:10.1029/2005JA011372.

5) Goncharenko, L., J. Salah, G. Crowley, L. J. Paxton, Y. Zhang, A. Coster, W. Rideout, C. Huang, S. Zhang, B. Reinisch, and V. Taran (2006), Large variations in the thermosphere and ionosphere during minor geomagnetic disturbances in April 2002 and their association with IMF By, J. Geophys. Res., 111, A03303, doi:10.1029/2004JA010683

6) J.U. Kozyra, G. Crowley, B. A. Emery, X. H. Fang, G. Maris, M. G. Mlynczak, R. J. Nieciejewski, S. E. Palo, L. J. Paxton, C. E. Randall, P.-P. Rong, J. M. Russell III, W. Skinner, S. C. Solomon, E. R. Talaat, Q. Wu, J.-H.Yee, Response of the Upper/Middle Atmosphere to Coronal Holes and Powerful High Speed Solar Wind Streams in 2003, submitted to AGU Monograph on High Speed Streams and their Effects (Editor: Bruce Tsurutani), February 2006.

7) G. Crowley et al., Solar Cycle and Seasonal effects on the Density and Composition Measured by GUVI, manuscript in preparation for J. Geophys. Res.

8) M. Cheng, J. Ries, B. Tapley, S. Bettadpur, G. Crowley, Satellite Accelerometer Measurements for Study of Atmospheric Density and Winds, submitted to JGR.

9) Crowley, G., and R.H. Tolson, (2007), Mars Thermospheric Winds from MGS and Odyssey Accelerometers, J. Spacecraft and Rockets, 44(6), doi:10.2514/1.28625

10) B. Tapley, J. Ries, S. Bettadpur, and M. Cheng, Neutral Density Measurements from the GRACE Accelerometers, J. Spacecraft and Rockets, 44(6) November-December, 1220-1225, 2007

11) Crowley, G., and R. R. Meier, Disturbed O/N_2 Ratios and Their Transport to Middle and Low Latitudes, submitted to AGU Chapman Conference Monograph, October 2007.

12) Crowley, G., B. Tapley, N. Curtis, C. Hackert, G. Bust, R. Frahm and R.G. Roble, Effects of Large Storms On Thermospheric Density, submitted to J. Geophys. Res., March 2008.

2. SUMMARY OF ACHIEVEMENTS BY YEAR

2.1 YEAR 1

2.1.1 What is magnitude of thermospheric density changes in response to variability of the Sun on different temporal scales?

1) We have run the AMIE assimilation code for the Superstorm interval around November 20, 2003, for both hemispheres. The inputs collected for these runs include about 150 magnetometers, SuperDARN and DMSP E-fields for both the Northern and Southern hemispheres.

2) We have run several versions of the ASPEN-TIMEGCM for the same Superstorm interval. The first run used simplified high latitude inputs driven by potential patterns from the Heelis model, and the Roble and Ridley (1987) auroral specification. The run turned out to reproduce many of the global composition changes observed by the GUVI instrument on TIMED. The GUVI data provide a first direct look at the corresponding variation in the vertical density and composition profiles.

We also performed an ASPEN simulation using AMIE to specify the high latitude convection pattern and auroral particle precipitation. This improved the temporal response of the global thermosphere, but underestimated the magnitude of the global response. We are therefore analyzing the existing model runs, which predict many of the observed features. We are also investigating the reasons for the underestimate, and expect to improve it in the 2nd year.

We have written a paper on the Nov simulations with Dr. Meier (see below).

3) Our Co-I Dr. Tapley analyzed GRACE densities for the Superstorm interval around November 20, 2003, and provided them to Dr. Crowley. These data were used for three components of the proposed research: (a) validation and improvement of the GRACE density retrievals; (b) comparison of GRACE densities with those derived from limb profiles from the Global Ultra-Violet Imager (GUVI) on the TIMED satellite; (c) validation and interpretation of the ASPEN-TIMEGCM simulations.

We determined that the GRACE density retrievals had numerous problems, including corrections for solar radiation effects, and the use of a variable ballistic coefficient. The radiation correction was improved and a revised data set was provided to SwRI. The varying ballistic coefficient was replaced with a constant value, which improved the density estimates. However, the GRACE densities are still larger than the TIMED-GUVI and ASPEN-TIMEGCM densities by about a factor of 2, suggesting improvements may still be possible in the GRACE ballistic coefficient. These may partly be due to the neglect of neutral winds in the standard GRACE analysis, and will be studied further in year 2.

4) The entire CHAMP density data for 4 years from 200-2004 has been compiled and provided to Dr. Crowley by Dr. Bruinsma of CNRS. We have begun to compare the CHAMP densities to the ASPEN simulations for the Superstorm interval around November 20, 2003. We have written a paper on CHAMP-ASPEN comparisons with Dr. Schlegel (see below).

5) We have performed detailed AMIE calculations for the April 2002 storm period.

6) We have simulated the April 2002 storm period using two sets of high latitude inputs to the model. The first employed the simplistic Heelis (1982) convection model, and the Roble and Ridley (1987) auroral oval specification. The second simulation used AMIE potential and auroral parameters.

We have performed some detailed analysis of the TIMEGCM density and composition simulations in support of work with the TIMED-GUVI data. In particular, we have begun to analyze the April 2002 simulations in terms of periodic response functions, to see whether this mathematical approach is useful for global empirical density and temperature specifications.

We have written a paper on the April storm period with Dr. Goncharenko (See below).

7) We are in the process of comparing the ASPEN-TIMEGCM simulations for April 2002 with the corresponding GRACE and CHAMP density data.

2.1.2 How does density in upper thermosphere respond to Joule heating?

We have run the ASPEN-TIMEGCM for different seasonal and solar cycle cases, and have begun to examine how the neutral density responds at different altitudes, and at different locations. We have obtained CHAMP data for 4 years, and will use this to validate our model runs. We will also obtain more GRACE data to contribute to the validation.

2.1.3 What are key drivers of density perturbations in the upper thermosphere?

We have begun to explore and evaluate the terms causing density perturbations in the model. We have begun to develop a new post-processor to isolate the different forcing terms contributing to the density changes.

We have shown, in the past, that a first principles model driven by appropriate inputs can simulate high latitude density features (Crowley et al., 1989a,b; 1995; 1996a,b) observed by satellites flying near 200 km altitudes. We have never previously tried to observe the cells at altitudes near 400 or 500 km, where GRACE and CHAMP make their measurements. This year, we have found that the model does not predict density cells at the CHAMP altitudes, whereas they do appear to observed by the CHAMP satellite. We have written a paper on this effect with Dr. Schlegel (See below).

Of particular interest is what the compositional variation looks like in the cells. The ASPEN model predicts that the O and N2 will not have the same horizontal distribution. We have performed a numerical experiment to investigate the effect of the IMF By component on high latitude density structures. We find a significant effect. In particular, the pattern of high and low densities is rotated to earlier local times as the By component increases from -7 nT to + 7nT. We have also produced realistic simulations of the DE-1 imager data from 1981, to investigate the IMF By effect. We find in both studies that the IMF effect on composition is opposite from that postulated by Immel et al., (1997).

Two papers are in the process of being submitted with Dr. Immel (See below).

2.1.4 What are the uncertainties in the GRACE (and CHAMP) density estimates?

The calculation of the density from the accelerometer and standard drag models is based on a number of assumptions that can be examined more carefully by reference to ASPEN simulations. This task is not part of the primary GRACE or CHAMP missions, and is therefore not funded by their other efforts.

This year, we determined that the GRACE density retrievals had numerous problems, including corrections for solar radiation effects, and the use of a variable ballistic coefficient. The radiation correction was improved and a revised data set was provided to SwRI. The varying ballistic coefficient was replaced with a constant value, which improved the density estimates. However, the GRACE densities are still larger than the TIMED-GUVI and ASPEN-TIMEGCM densities by about a factor of 2, suggesting improvements may still be possible in the GRACE ballistic coefficient. These may partly be due to the neglect of neutral winds in the standard GRACE analysis, and will be studied further in year 2.

Year 1 Publications

1) Schlegel, K., H. Luhr, J. P. ST. Maurice, and G. Crowley, Thermospheric Density Structures Over the Polar Regions Observed With CHAMP, Ann. Geophys., in press, 2005.

2) Meier, R. R., G. Crowley, D. J. Strickland, A. B. Christensen, L. J. Paxton, and D. Morrison, First look at the November 20, 2003 super storm with TIMED/GUVI, J. Geophys. Res., in press, 2005.

3) Crowley, G., T. J. Immel, C. L. Hackert, J. Craven and R. G. Roble, The Effect of IMF BY on Thermospheric Composition at High and Middle Latitudes, 1: Numerical Experiments, Submitted to J. Geophys. Res., 2005

4) Immel, T. J., G. Crowley, C. L. Hackert, J. Craven and R. G. Roble, The Effect of IMF BY on Thermospheric Composition at High and Middle Latitudes, 2: Data Comparisons, Submitted to J. Geophys. Res., 2005

5) Goncharenko, L., J. Salah, G. Crowley, L. Paxton, , et al., Variability in the thermosphere and ionosphere during minor geomagnetic disturbances in April 2002 and its association with IMF By orientation, Submitted to J. Geophys. Res., July 2004

Year 1 Presentations

1) Crowley, G., C. Hackert, R. R. Meier, L. Paxton, D. Strickland, Y. Zhang, X. Pi, A. Manucci, A, Christensen, D. Morrison, Global Thermosphere-Ionosphere Response To Storms, Spring AGU, New Orleans, LA, 2005

2) Kozyra, J. U., G. Crowley, B.A. Emery, X. H. Fang , M. Hagan, G. Lu, M. G. Mlynczak, R. J. Niciejewski, S. E. Palo, L. J. Paxton, J. M. Russell III, W. Skinner, S. C. Solomon, Q. Wu, J-H Yee, Atmospheric Effects of Coronal Holes and Powerful High-Speed Solar Wind Streams in 2003 Observed by the TIMED Spacecraft, Spring AGU, New Orleans, LA, 2005.

3) Crowley, G., C. Hackert, R. R. Meier, L. Paxton, D. Strickland, Y. Zhang, X. Pi, A. Manucci, A, Christensen, D. Morrison, Global Thermosphere-Ionosphere Response To Storms, Ionospheric Effects Symposium, Alexandria, VA, May 2005

4) Kozyra, J. U., G. Crowley, L. P. Goncharenko, M. E. Hagan, G. Lu, M. G. Mlynczak, L. J. Paxton, J. M. Russell, S. C. Solomon, E. R. Talaat, J. Yee, First Three Years of TIMED: New Results in Sun-Earth Connections, Fall AGU, San Francisco, CA, 2004.

5) Meier, R., G. Crowley, D. J. Strickland, A. B. Christensen, L. J. Paxton, and D. Morrison, Looking at the November 20, 2003 super storm with TIMED/GUVI: comparison with the TIMEGCM, Fall AGU, San Francisco, CA, 2004.

6) Crowley, G., B. Tapley, S. Bettadpur, M. Cheng, L. Paxton, Y. Zhang, D. Morrison, A. Christensen, R. Meier, D. Strickland, *Effect of the October – November 2003 Super-storm on Thermospheric Density and Composition*, Fall AGU, San Francisco, CA, 2004.

7) Kozyra, J. U., C. R. Clauer, D. DeZeeuw, X. H. Fang, T. I. Gombosi, M. W. Liemohn, A. J. Ridley, T. H. Zurbuchen, B. J. Anderson, P. C. Brandt, H. Korth, D. G. Mitchell, L. J. Paxton, L.J. Zanetti, Y. Zhang, C. A. Cattell, J. P. Dombeck, G. Crowley, R. A. Frahm, C. J. Pollock, J. R. Sharber, J. D. Winningham, D. S. Evans, S. Greer, M. R. Hairston, R. A. Heelis, C. Y. Huang, A. Korth, A. J. Mannucci, B. T. Tsurutani, M. J. Mendillo, T. E. Moore, K. Shiokawa, M. F. Thomsen, *Superstorm Observations and Insights: Observers Perspective*, Huntsville Modeling Workshop, AL, 10/04.

8) Curtis, N., G. Crowley, C. Hackert, J. Kozyra, R.G. Roble, *Quantifying the Periodic Thermospheric Response for the April 14-24, 2002 Storm Period*, CEDAR Working Group, Santa Fe, NM, June 2004.

9) Bronn, J., G. Crowley, C. Hackert, R. Meier, L. Paxton, D. Strickland, A. Christensen, D. Morrison, Y Zhang, P. Straus, R. Walterscheid, J. Craven, C. Meng, S. Avery, Global *Thermosphere – Ionosphere Response to the October – November 2003 Storms,* Spring Meeting of the AGU, Montreal, Canada, May 2004.

10) B. Tapley, *GRACE Accelerometers and Their Impact on Density Determination,* Atmospheric Neutral Density and Solar Indices Workshop, Colorado Springs, CO,May 25, 2004

2.2 YEAR 2

We have successfully completed publication of several papers that were in various stages of preparation last year (see list below). We were invited to join the new LWS Density Team, led by Dr. Art Richmond (based on the LWS TR&T winners announced in April 2005) and we participated in their first meeting in Boulder. In addition, we have made progress on the four different study areas identified for the project using the GRACE, CHAMP and GUVI data sets together with the TIMEGCM fully coupled thermosphere-ionosphere model.

Dr. Crowley has started a small business (ASTRA), and has modified his relationship with SwRI from that of employee to subcontractor. As a result, he has asked Dr. Rudy Frahm to take over as PI, while Dr. Crowley acts as Project Manager via a subcontract to ASTRA.

ASTRA employs a Masters student from UT San Antonio to work on the GRACE, CHAMP and GUVI data. We also hired two undergraduates as summer interns to develop algorithms for plotting and analysis of the GUVI, GRACE and CHAMP data. We now have a part-time undergraduate learning about computer programming and data analysis through working with the CHAMP data

2.1.1 What is magnitude of thermospheric density changes in response to variability of the Sun on different temporal scales?

a) We have begun the process of examining the GRACE, CHAMP and GUVI data sets as a function of solar cycle and F107. We have shown that the GUVI data undergoes a well-defined variation with solar cycle and season, and this work will be submitted for publication shortly.

b) We have worked with Dr. Janet Kozyra on the effects of Corotating Interaction Regions and High Speed Streams on the Earths thermosphere and ionosphere. The study has led to an exciting development that shows an interesting variation in the GUVI composition with F107. We are in the process of simulating this period with the TIMEGCM. We have submitted one paper with Dr. Kozyra on this topic (see below).

2.1.2 How does density in upper thermosphere respond to Joule heating?

We have developed plotting codes for the CHAMP data sets that allow us to examine the entire data set and to bin it in different ways. The data clearly show the effects of Joule heating events, and we have focused on the November 2003 storm period. We are in the process of completing a paper on this topic, which compares for the first time the detailed measurements of density from GRACE with those deduced from GUVI data.

We will have enough data and model simulations to make some important comments about the effects of Joule heating during our 3rd year.

2.1.3 What are key drivers of density perturbations in the upper thermosphere?

a) We have completed publication of 2 papers with Dr. Immel that explore for the first time the composition variations that underlie the density changes at high latitudes. Any theory to explain the density perturbations must also explain the composition variations. We are working on this topic through another grant, in which we examine density changes in terms of instability theory.

b) The low-latitude densities measured by GRACE and CHAMP undergo complex variations during magnetic storms. However, there is an overall pattern of increases at some latitudes and decreases at other latitudes. We are using the TIMEGCM and GUVI limb data to explain some of the density variations observed by GRACE and CHAMP during storms at low and middle latitudes. This work would not be possible without the independent measurements of density and composition, together with the model. It is expected to lead to a paper in Year 3.

2.1.4 What are the uncertainties in the GRACE (and CHAMP) density estimates?

We have continued effort directed at the improvement of the GRACE accelerometer data analysis for recovering the atmospheric neutral density. This is a complicated problem because of the extreme sensitivity of the GRACE accelerometer, and lack of accurate models for the interaction of the satellite surface with atmosphere and the knowledge of the atmosphere rotation and winds The correct interpretation of the accelerometer data also requires detailed knowledge of the direct and earth-reflected solar radiation pressure as well as the magnitude and temporal location of any translational accelerations from the attitude control actions. There are remaining issues with the GRACE data, but the improvement in the quality of the grace derived density allows cross-validation against the GUVI data and the TIMEGCM model results. The comparisons have been illuminating. These comparisons are possible with the improved GRACE data product.

During the contract period:

a) In a major advance, we have implemented an improved model for removing form the GRACE accelerometer data the effects of direct and earth reflected solar radiation on the satellite . As a part of the overall error assessment, the effects of the error in the solar radiation model on the GRACE accelerometer derived density have been analysed to provide an upper bound on the density recovery error.

b) We have also developed a smoothing technique to account for 'twangs" from the data. These signals result from thermal induced mass redistribution on the satellites. These effects usually occur during entry and exit of the earth's shadow.

c) We have examined the effect of the ballistic coefficient model on the derive the densities, and and evaluated the characteristics of three contemporary models. The effects of the adopted model on the overall accuracy of the estimate uncertainty of the GRACE density results has been assessed

d) We have developed an improved algorithm for a more accurate determination of the density using the GRACE acceleromater data.

d) We have identified six 4-week intervals when GRACE makes measurements in exactly the same place as GUVI on the dayside, so that we can reliably compare the two density datasets without having to resort to interpolation via a model. In Year 3, we will complete the comparison, which is expected to help improve the GRACE analysis algorithms.

e) Dr. Tapley and the UT group are writing a paper to describe the GRACE data analysis and the complexities of the analysis algorithm that will next year form the basis of a paper for publication.

Year 2 Publications Update (includes Year-1 papers)

1) Schlegel, K., H. Luhr, J. P. ST. Maurice, G. Crowley and C. Hackert, Thermospheric Density Structures Over the Polar Regions Observed With CHAMP, Ann. Geophys., 23, 1659-1672, 2005

2) Meier, R. R., G. Crowley, D. J. Strickland, A. B. Christensen, L. J. Paxton, and D. Morrison, First look at the November 20, 2003 super storm with TIMED/GUVI, J. Geophys. Res., Vol. 110, A09S41, doi:10.1029/2004JA010990, 2005.

3) Crowley, G., T. J. Immel, C. L. Hackert, J. Craven and R. G. Roble, The Effect of IMF BY on Thermospheric Composition at High and Middle Latitudes, 1: Numerical Experiments, in press J. Geophys. Res., 2006

4) Immel, T. J., G. Crowley, C. L. Hackert, J. Craven and R. G. Roble, The Effect of IMF BY on Thermospheric Composition at High and Middle Latitudes, 2: Data Comparisons, in press J. Geophys. Res., 2006

5) Goncharenko, L., J. Salah, G. Crowley, L. J. Paxton, Y. Zhang, A. Coster, W. Rideout, C. Huang, S. Zhang, B. Reinisch, and V. Taran (2006), Large variations in the thermosphere and ionosphere during minor geomagnetic disturbances in April 2002 and their association with IMF By, J. Geophys. Res., 111, A03303, doi:10.1029/2004JA010683

6) J.U. Kozyra, G. Crowley, B. A. Emery, X. H. Fang, G. Maris, M. G. Mlynczak, R. J. Nieciejewski, S. E. Palo, L. J. Paxton, C. E. Randall, P.-P. Rong, J. M. Russell III, W. Skinner, S. C. Solomon, E. R. Talaat, Q. Wu, J.-H.Yee, Response of the Upper/Middle Atmosphere to Coronal Holes and Powerful High Speed Solar Wind Streams in 2003, submitted to AGU Monograph on High Speed Streams and their Effects (Editor: Bruce Tsurutani), February 2006.

7) G. Crowley et al., Solar Cycle and Seasonal effects on the Density and Composition Measured by GUVI, manuscript in preparation for J. Geophys. Res.

Year 2 Presentations (see above for list of Year 1 presentations)

1) Immel, T. J., S. B. Mende, H. U. Frey and G. Crowley, *FUV Imaging for the LWS Program*, Spring AGU, New Orleans, LA, May 2005

2) G. Crowley, B. Tapley and S. Solomon, *Upper Atmosphere Neutral Density Response to the Changing Sun: Project Outline*, Density Working Group meeting, Boulder, CO, September 2005

3) G. Crowley, and B. Tapley, *Density and compositional responses from GUVI and the GRACE satellite*, GUVI Team Meeting, St. George, UT, October 2005

4) G. Crowley, S. Solomon, A. Burns, W. Wang, M.J. Wiltberger, *Status of Ionosphere-Thermosphere Modeling: What's Missing?*, Fall AGU, San Francisco, December 2005

5) Cheng, M., S. Bettapur, J, Ries, and B. Tapley et al., *Atmospheric neutral density from accelerometer data of the GRACE*, Fall AGU, San Francisco, December 2005

6. Cheng, M., S. Bettadpur, J. Ries, B. Tapley, Atmospheric Neutral Density From Accelerometer Data of GRACE, Eos Trans. AGU, 86(52), 2005 Fall Meet. Suppl., Abstract SA51A-1127

7) B. Tapley, The GRACE Mission: Status and Density Determination, Atmospheric Neutral Density and Solar Indices Workshop, Colorado Springs, CO,Oct. 12-13, 2005

8) B. Tapley, G. Crowley, S. Bettadpur, M. Cheng, J. Ries ,Satellite Accelerometer Measurements for Study of Atmospheric Density and Winds, Atmospheric Neutral Density Forecast Workshop**,** Colorado Springs, CO, 20-21 Apr 2006

2.3 YEAR 3

Our work this year has been directed towards answering the following:

1) What is magnitude of thermospheric density changes in response to variability of the Sun on different temporal scales?
We have analyzed GRACE and GUVI data from seven one-month periods, and interpreted the density variations from GRACE in terms of multiple mechanisms and time-frames, including: season, latitude, local time, UT, solar flux, and geomagnetic magnetic activity. This work was presented at the 2006 Fall AGU meeting, and is being written up.

2) How does density in upper thermosphere respond to Joule heating? What are the key drivers of density perturbations in upper thermosphere?

We have simulated the atmospheric response to the seven intervals above, and we are in the process of quantifying the Joule heating response. We have also examined the response of high latitude neutral density cells to Joule heating and momentum forcing.

4) How valid are the assumptions behind the determination of neutral densities from satellite drag data?
We have pursued a detailed analysis of the factors affecting the reliability of the density estimates from the accelerometer technique. We have improved the analysis significantly, and the results have been presented and are being written up.

Some highlights of the year have been:
1) Attended a 3-day technical interchange meeting with Bruce Bowman (Air Force Space Command), and the GRACE team at UTAustin. We explored the status of our LWS research, and how it applies to Air Force problems.

2) Invited to present a paper at the AGU Chapman Conference on Mid-Latitude Ionospheric Disturbances (Yosemite, January 2007). The title of the paper was: "Disturbed O/N2 Ratios and Their Transport to Middle and Low Latitudes", by G. Crowley and R.R. Meier. We have been invited to write up the presentation for a special AGU Monograph.

3) Dr. Crowley started a new company (ASTRA). He has been very busy with the move and the start-up, and consequently we did not get as much work done as we had expected. A 1-year no-cost extension has been requested.

Year 3 Publications Update (includes Year-1 and Year-2 papers)

1) Schlegel, K., H. Luhr, J. P. ST. Maurice, G. Crowley and C. Hackert, Thermospheric Density Structures Over the Polar Regions Observed With CHAMP, Ann. Geophys., 23, 1659-1672, 2005

2) Meier, R. R., G. Crowley, D. J. Strickland, A. B. Christensen, L. J. Paxton, and D. Morrison, First look at the November 20, 2003 super storm with TIMED/GUVI, J. Geophys. Res., Vol. 110, A09S41, doi:10.1029/2004JA010990, 2005.

3) Crowley, G., T. J. Immel, C. L. Hackert, J. Craven and R. G. Roble, The Effect of IMF BY on Thermospheric Composition at High and Middle Latitudes, 1: Numerical Experiments, in press J. Geophys. Res., 2006

4) Immel, T. J., G. Crowley, C. L. Hackert, J. Craven and R. G. Roble, The Effect of IMF BY on Thermospheric Composition at High and Middle Latitudes, 2: Data Comparisons, in press J. Geophys. Res., 2006

5) Goncharenko, L., J. Salah, G. Crowley, L. J. Paxton, Y. Zhang, A. Coster, W. Rideout, C. Huang, S. Zhang, B. Reinisch, and V. Taran (2006), Large variations in the thermosphere and ionosphere during minor geomagnetic disturbances in April 2002 and their association with IMF By, J. Geophys. Res., 111, A03303, doi:10.1029/2004JA010683

6) J.U. Kozyra, G. Crowley, B. A. Emery, X. H. Fang, G. Maris, M. G. Mlynczak, R. J. Nieciejewski, S. E. Palo, L. J. Paxton, C. E. Randall, P.-P. Rong, J. M. Russell III, W. Skinner, S. C. Solomon, E. R. Talaat, Q. Wu, J.-H.Yee, Response of the Upper/Middle Atmosphere to Coronal Holes and Powerful High Speed Solar Wind Streams in 2003, submitted to AGU Monograph on High Speed Streams and their Effects (Editor: Bruce Tsurutani), February 2006.

7) G. Crowley et al., Solar Cycle and Seasonal effects on the Density and Composition Measured by GUVI, manuscript in preparation for J. Geophys. Res.

8) M. Cheng, J. Ries, B. Tapley, S. Bettadpur, G. Crowley, Satellite Accelerometer Measurements for Study of Atmospheric Density and Winds, submitted to JGR.

Year 3 Presentations (see above for list of Year 1 and Year 2 presentations)

1. Mannucci, A.J., Tsurutani, B.T., Crowley, G., Verkhoglyadova, O.P., **Ionospheric Response During Four Intense Geomagnetic Storms,** Spring AGU, Acapulco, MX, 2007

2. Clemmons, J.H., G. Crowley, G., Heelis, R.A., Manucci, A.J., Paxton, L.J., Pfaff, R.J., Spann, J.F., **Space-based research into the ionosphere-thermosphere system: The need for greater organization and a plan for achieving it**, Spring AGU, Acapulco, MX, 2007

3. Crowley, G., Meier, B., Tapley, B., Bettadpur, S., Cheng, M., Ries, J., Abusali, P., Paxton, L., Christensen, A., **Effect of 27-day Solar Rotation of Thermospheric Density and Composition,** GUVI Science Team Meeting, Logan, Utah, Feb 2007.

4. Crowley, G., **Comparing GRACE density to GUVI density**, GUVI Science Team Meeting, Logan, Utah, Feb 2007

5. Crowley. G., and R.R. Meier, **Disturbed O/N2 Ratios and Their Transport to Middle and Low Latitudes,** AGU Chapman Conference on Mid-Latitude Ionospheric Disturbances, in Yosemite, CA, January 2007

6. Crowley, G., **Contrasting Thermospheric Behavior at Solar Maximum and Solar Minimum,** Fall AGU, San Francisco, CA, 2006

7. Talaat, E.R., Yee, J., Crowley, G., Roble, R., **Energetics of the solar maximum ionosphere, thermosphere and mesosphere,** Fall AGU, San Francisco, CA, 2006

8. 10. Pallamraju, D., Chakrabarti, S., Solomon, S., Crowley, G., **Compositional changes in thermosphere during a geomagnetic storm inferred using ground- based daytime OI 630.0nm optical airglow emissions,** Fall AGU, San Francisco, CA, 2006

9. Smith, D.C., Talaat, E.R., Yee, J., Woods, T., Roble, R.G., Crowley, G., **Examination of Cadence of Solar Soft X-ray Flux on the Ionosphere and Thermosphere,** Fall AGU, San Francisco, CA, 2006

10. Crowley, G., Meier, B., Tapley, B., Bettadpur, S., Cheng, M., Ries, J., Abusali, P., Paxton, L., Christensen, A., **Effect of 27-day Solar Rotation of Thermospheric Density and Composition,** Fall AGU, San Francisco, CA, 2006

11. Richmond, A.D., Akmaev, R., Anderson, P.C., Crowley, G., Drop, D.P., Lummerzheim, D., Solomon, S.C., Tobiska, W., **Thermospheric Density and Composition: an Integrated Research Approach,** Fall AGU, San Francisco, CA, 2006

12. Crowley, G., **Why Study Science? (or How to Get a Job!),** Presented at O'Connor High School Physics Colloquium, September 2006

13. Crowley, G., B. Tapley, S. Solomon, R. Meier, **LWS: Effect of EUV and High Latitude Forcing On Thermospheric Densities,** Presented at Living With A Star Density and Winds Focused Science Team Meeting, HAO-NCAR, Boulder, CO, September 2006

14. Crowley, G., T. Immel, C. Hackert, R. Roble, J. Craven, **Effect of IMF BY on Thermospheric Composition at High and Middle Latitudes**, Invited Seminar, High Altitude Observatory, NCAR, Boulder, Sept 20, 2006

15. Crowley, G., and R.H. Tolson, **Mars Thermospheric Winds from MGS and Odyssey Accelerometers**, Presented at AIAA Conference, Keystone, CO, August 2006

16. Tapley, B., S. Bettadpur, M. Cheng, and J. Ries, Neutral Density Measurements from the GRACE Accelerometers, Proc. AIAA/AAS Astrodynamics Specialist Conference, 21-26 August 2006, Keystone, Colorado, paper AIAA-2006-6171

17. Cheng, M., S. Bettadpur, J. Ries, and B. Tapley).Atmospheric Neutral Density from GRACE Accelerometer Data, COSPAR2006-A-02111, 36th COSPAR Scientific Assembly, Beijing, China, July 16-23, 2006

18. Crowley, G., and B. Tapley, **Update on the GRACE-GUVI comparisons,** Presented at NSF CEDAR Meeting, Santa Fe, NM, June 2006.

19. Crowley, G., C. Hackert, R. R. Meier, D. J. Strickland, L. J. Paxton, A. Christensen, D. Morrison, G. Bust, A.D. Richmond, R. G. Roble, ***How Do High Latitude Inputs Modify The Global I-T Structure?***, Presented at NSF CEDAR Meeting, Santa Fe, NM, June 2006.

20. Tapley, B., S. Bettadpur, M. Cheng, J. Ries, and G. Crowley, Satellite Accelerometer Measurements for Study of Atmospheric Density and Winds, Atmospheric Neutral Density Forecast Workshop Colorado Springs, CO 20-21 April 2006

2. 4. YEAR 4

Year 4 was a 1-year no-cost extension. In Year 4, we planned to bring to a conclusion various aspects of the project, and expected to publish several additional papers. We continued to participate in the LWS Density team led by Dr. Richmond, including a meeting that coincided with the CEDAR conference in June 2006. Another Density team meeting took place in September 2007 in Boulder.

We were invited to join a team funded by the Air Force to study thermospheric density variability. The team is led by Jeff Forbes and Tim Fuller-Rowell.

Dr. Crowley has visited the GRACE team at UT Austin several times during the year for program reviews and updates.

In the previous years of the project we have developed several powerful tools for the analysis and interpretation of data and model output. For example, we now have model runs, data analyzed and validated, and tools to analyze the models for several storm periods. This final year of the project was an opportunity to use the tools to gain more scientific understanding. We describe our progress in several areas below.

3.1 What is magnitude of thermospheric density changes in response to variability of the Sun on different temporal scales?

We have used the six 4-week periods where GRACE and GUVI orbits overlap, and examined the response of the thermosphere to solar EUV variations. Compared with TIMEGCM simulations of same periods, so that we can examine the detailed mechanisms behind the density variations. There are clear responses of the desnity to F107 changes. We have quantified how the thermosphere responds to this variability of solar EUV inputs using the F107 index. We find some interesting patterns that we will publish in a paper. The response varies from season to season and with solar cycle. We have used this variation to remove the effect of solar variability, so that we can study the effect of Joule heating in isolation from solar effects.

Closure - The deliverables from this set of tasks is a series of look-up tables quantifying the density response to solar variations as a function of altitude for different seasons, solar activity and geomagnetic activity levels. These tables will be made available to anyone who needs them, upon request. We would also expect to publish them in manuscript form. We also anticipate that there will be at least one paper resulting from the work.

3.2 How does density in upper thermosphere respond to Joule heating?

We have enough data and model simulations to make some important comments about the effects of Joule heating on density. We have analyzed the ASPEN-TIMEGCM for different seasonal and solar cycle cases, and examine how the neutral density responds at different altitudes, and at different locations. Simulations from a model are of limited use when considered in isolation, therefore we validated our simulations by comparing the results with GRACE, CHAMP and GUVI density data for specific time intervals. The measurements act as a kind of calibration for the model predictions.

We have also done a series of model runs using a fixed set of storm inputs for different seasonal and solar cycle conditions to examine how the density response varies with season and solar cycle in a "numerical laboratory". We are currently completing the comparison of these numerical experiments with the 'realistic" runs for the actual 1-month intervals where we have good GRACE data.

Closure - The deliverables from this set of tasks will be a series of look-up tables quantifying the density response to Joule heating variations as a function of altitude for different seasons, solar activity and geomagnetic activity levels. These tables will be made available to anyone who needs them, upon request. We would also expect to publish them in manuscript form. We anticipate that there will be at least one paper resulting from the work (likely two).

3.3 What are key drivers of density perturbations in the upper thermosphere?

Density cells: We have shown, in the past, that a first principles model driven by appropriate inputs can simulate high latitude density cells (Crowley et al., 1989a,b; 1995; 1996a,b) observed by satellites flying near 200 km altitudes. In Year 1, we showed for a single event that these cells do not appear to be present in the CHAMP data near 500 km.

During Year 4 we have examined the driving forces of the winds and density cells. In particular, we have compared the effects of Joule heating and momentum forcing on the cell structure. Our results contradict the "common lore" that the cells are driven mainly by Joule heating. In fact we find that the effect of Joule heating is small compared with the momentum forcing.

We have performed a study of the forcing terms in the momentum equation.

Closure - The deliverables from this set of tasks will mainly be scientific understanding that will be valuable when trying to understand high latitude density perturbations that are not explained by empirical models. We anticipate that there will be at least one paper resulting from the work.

3.4 What are the uncertainties in the GRACE (and CHAMP) density estimates?

1) We have continued calibration of accelerometer data from GRACE via comparison with GUVI data and TIMEGCM simulations of specific storm and quiet intervals mentioned above..
2) We have improved our understanding and separation of the atmospheric winds and rotation in determination of atmospheric density from accelerometer data.
3) We used the simulated winds and density from the TIMEGCM to predict the likely influence of winds on the in-track accelerometer measurements on GRACE. These winds can cause both under-estimates and over-estimates of the density from the GRACE satellite measurements.
4) We examine in-track wind data from CHAMP, comparing it with the TIMEGCM winds. We will found a series of examples where the CHAMP and GRACE orbits are orthogonal at high latitudes, so that the CHAMP cross-track winds (near 350 km) approximately represent in-track winds for the GRACE satellite (near 400 km). This provided the first experimental investigation of how much the in-track winds may affect the estimated density from GRACE.

Closure - The deliverables from this task will be a reliable set of density measurements from the GRACE accelerometer that can be used by the broader community for further density studies, together with a detailed report describing the GRACE data analysis. We expect to publish several papers from this work over the next few months.

3.5 Can we measure cross-track winds using accelerometers and gyros on Mars aerobraking missions?

Dr. Robert Tolson and Darren Baird have used MGS and Mars Odyssey accelerometers and gyro data to estimate cross-track winds during aerobraking maneuvers. We have validated their wind estimates using our first-principles Mars thermosphere model. We found that the unusual shears in their wind measurements reflect the presence of large wind shears in the Mars thermosphere, and their technique appears to provide the first wind data from Mars. While not part of the proposed work, we took the opportunity to work with the Mars data. It required only a small amount of effort on our part.

Year 4 Publications Update (includes Year-1, Year-2 and Year-3 papers)

1) Schlegel, K., H. Luhr, J. P. ST. Maurice, G. Crowley and C. Hackert, Thermospheric Density Structures Over the Polar Regions Observed With CHAMP, Ann. Geophys., 23, 1659-1672, 2005

2) Meier, R. R., G. Crowley, D. J. Strickland, A. B. Christensen, L. J. Paxton, and D. Morrison, First look at the November 20, 2003 super storm with TIMED/GUVI, J. Geophys. Res., Vol. 110, A09S41, doi:10.1029/2004JA010990, 2005.

3) **Crowley, G.**, T. J. Immel, C. L. Hackert, J. Craven, and R. G. Roble (2006), Effect of IMF BY on thermospheric composition at high and middle latitudes: 1. Numerical experiments, J. Geophys. Res., 111, A10311, doi:10.1029/2005JA011371.

4) Immel, T. J., **G. Crowley**, C. L. Hackert, J. D. Craven, and R. G. Roble (2006), Effect of IMF By on thermospheric composition at high and middle latitudes: 2. Data comparisons, J. Geophys. Res., 111, A10312, doi:10.1029/2005JA011372.

5) Goncharenko, L., J. Salah, G. Crowley, L. J. Paxton, Y. Zhang, A. Coster, W. Rideout, C. Huang, S. Zhang, B. Reinisch, and V. Taran (2006), Large variations in the thermosphere and ionosphere during minor geomagnetic disturbances in April 2002 and their association with IMF By, J. Geophys. Res., 111, A03303, doi:10.1029/2004JA010683

6) J.U. Kozyra, G. Crowley, B. A. Emery, X. H. Fang, G. Maris, M. G. Mlynczak, R. J. Nieciejewski, S. E. Palo, L. J. Paxton, C. E. Randall, P.-P. Rong, J. M. Russell III, W. Skinner, S. C. Solomon, E. R. Talaat, Q. Wu, J.-H.Yee, Response of the Upper/Middle Atmosphere to Coronal Holes and Powerful High Speed Solar Wind Streams in 2003, submitted to AGU Monograph on High Speed Streams and their Effects (Editor: Bruce Tsurutani), February 2006.

7) G. Crowley et al., Solar Cycle and Seasonal effects on the Density and Composition Measured by GUVI, manuscript in preparation for J. Geophys. Res.

8) M. Cheng, J. Ries, B. Tapley, S. Bettadpur, G. Crowley, Satellite Accelerometer Measurements for Study of Atmospheric Density and Winds, submitted to JGR.

9) **Crowley, G.,** and R.H. Tolson, (2007), Mars Thermospheric Winds from MGS and Odyssey Accelerometers, J. Spacecraft and Rockets, 44(6), doi:10.2514/1.28625

10) B. Tapley, J. Ries, S. Bettadpur, and M. Cheng, Neutral Density Measurements from the GRACE Accelerometers, J. Spacecraft and Rockets, 44(6) November-December, 1220-1225, 2007

11) Crowley, G., and R. R. Meier, Disturbed O/N_2 Ratios and Their Transport to Middle and Low Latitudes, submitted to AGU Chapman Conference Monograph, October 2007.

12) Crowley, G., B. Tapley, N. Curtis, C. Hackert, G. Bust, R. Frahm and R.G. Roble, Effects of Large Storms On Thermospheric Density, submitted to J. Geophys. Res., March 2008.

Year 4 Presentations (see above for list of Year 1,2 and 3 presentations)

1. Kozyra, J U., Crowley, G, Doe, R A., Mlynczak, M G., Paxton, L J., Skinner, W R., Solomon, S C., Talaat, E., Woods, T N., Wu, Q., Yee, J, **Overview of TIMED CEDAR observations showing the MLTI system response to changing drivers from solar maximum to solar minimum,** presented at the Fall AGU Meeting, San Francisco, CA, December 2007

2. Erickson, P J., Goncharenko, L P., Nicolls, M J., Crowley, G., Kelley, M C., **Dynamics of American Sector Mid and Low Latitude Ionospheric and Thermospheric Response During the November 2004 Superstorm,** presented at the Fall AGU Meeting, San Francisco, CA, December 2007

3. Crowley, G, **Thermospheric Response to Energy and Momentum Inputs from the Magnetosphere,** presented at the Fall AGU Meeting, San Francisco, CA, December 2007

4. Crowley G., **Relationship Between Thermospheric Density and Nitric Oxide,** presented at the Air Force MURI Kick-off Meeting, Boulder, CO, November 2007

5. Crowley G., **Thermospheric Density Cells at High Latitudes,** presented at the Air Force MURI Kick-off Meeting, Boulder, CO, November 2007

6. Crowley G., **Relationship Between Density and Joule Heating: A Numerical Experiment Using the TIMEGCM Model,** presented at the Air Force MURI Kick-off Meeting, Boulder, CO, November 2007

7. Crowley G., B. Tapley, M. Cheng, J. Ries, and S. Solomon, **LWS: Effect of EUV and High Latitude Forcing on Thermospheric Densities,** presented at the LWS Focused Science Team Meeting, Boulder, CO, September 2007

8. Crowley G., B. Tapley, M. Cheng, J. Ries, J. Forbes, E. Sutton, and S. Bruinsma, **LWS: Effect of Neutral Winds on CHAMP and GRACE Density Measurements,** presented at the LWS Focused Science Team Meeting, Boulder, CO, September 2007

9. Crowley G., N. Curtis, and A. Reynolds, **November 2004 Storm Study using TIMEGCM and GUVI,** presented at the NSF CEDAR Workshop, Santa Fe, NM, June 2007

10. Erickson, P J., Goncharenko, L P., Nicolls, M J., Crowley, G., Kelley, M C., **Dynamics of American Sector Mid and Low Latitude Ionospheric and Thermospheric Response During the November 2004 Superstorm,** presented at the NSF CEDAR Workshop, Santa Fe, NM, June 2007

11. Cheng, M., J. Ries, and B. Tapley, Assessment of the Solar Radiation Model for GRACE Orbit Determination, Proc. AAS/AIAA Astrodynamics Specialist Conference, 19-23 August 2007, Mackinac Island, Michigan, paper AAS 07-283

12. Cheng, M., B. Tapley, S. Bettadpur, and J. Ries, Determination of Thermospheric Winds from GRACE Accelerometer Data, Proc. AAS/AIAA Space Flight Mechanics Winter Meeting, 27-31 January 2008, Galveston, Texas, paper AAS 08-176