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Final Report **March 2009**

Title: "Estimating the Neutral Atmosphere Drivers using a Physical Model"

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In the initial phase of this study, research focused on implementing a physical model into an ensemble Kalman filter to estimate the location and magnitude of the upper atmospheric heating. Since the neutral atmosphere is strongly externally driven during geomagnetic storms, specifying the upper atmospheric heating is necessary when describing the time-dependent evolution of the neutral density. Challenges arise when only a portion of the upper atmosphere is observable. Because the upper atmospheric dynamics is nonlinear and incompletely observed, determining the heating location from the observed atmospheric response is not straightforward, as shown in the example Figure 1. The nonlinear system of equations can provide numerous possible solutions, only one of which is correct. Although the response of the neutral density to the heating is initially linear at storm onset, the system becomes increasingly nonlinear with time as illustrated in Figure 1. The true heating source (blue circles) becomes increasingly more difficult to predict (red crosses) as the storm progresses.

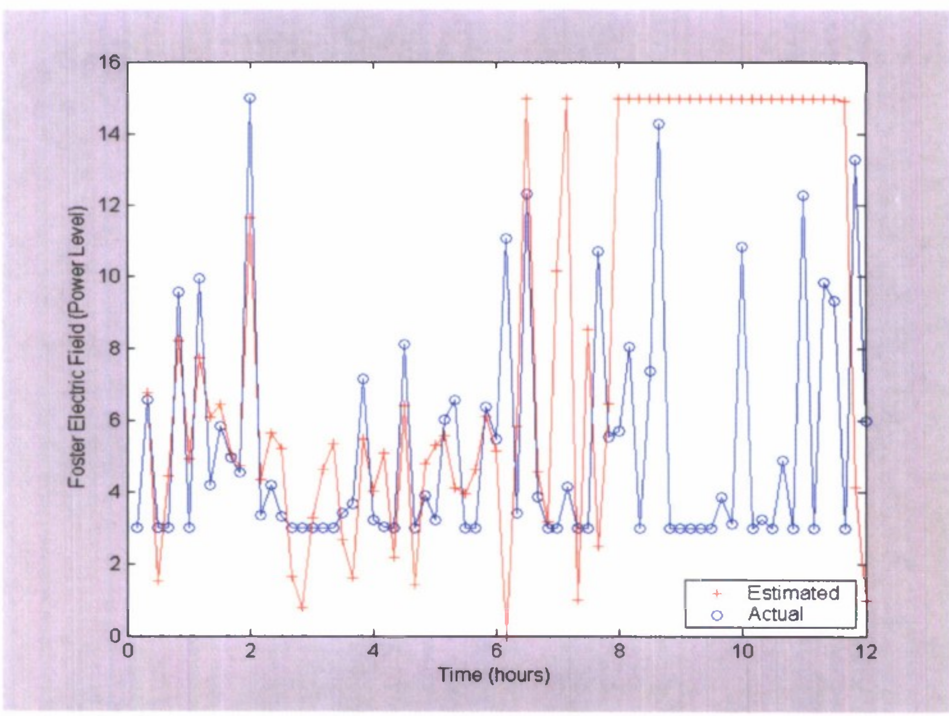

Figure 1: The increasingly nonlinear response to the upper atmospheric drivers as the geomagnetic storm progresses.

The physical model was incorporated into the Kalman filter system in two phases to better tackle the challenges in dealing with the nonlinear heating/response system. The first phase used a simplified model that numerically solves the differential equations that describe the gravity wave propagation of the upper atmosphere at a single altitude. Using the simpler model to solve the complex nonlinear dynamics of the neutral atmosphere provides the groundwork for building the full system. The simpler model and associated enKF solution allows one to more easily tackle the challenges in estimating a nonlinear system. The capability of this system using the simple model is illustrated in Figures 2 below.

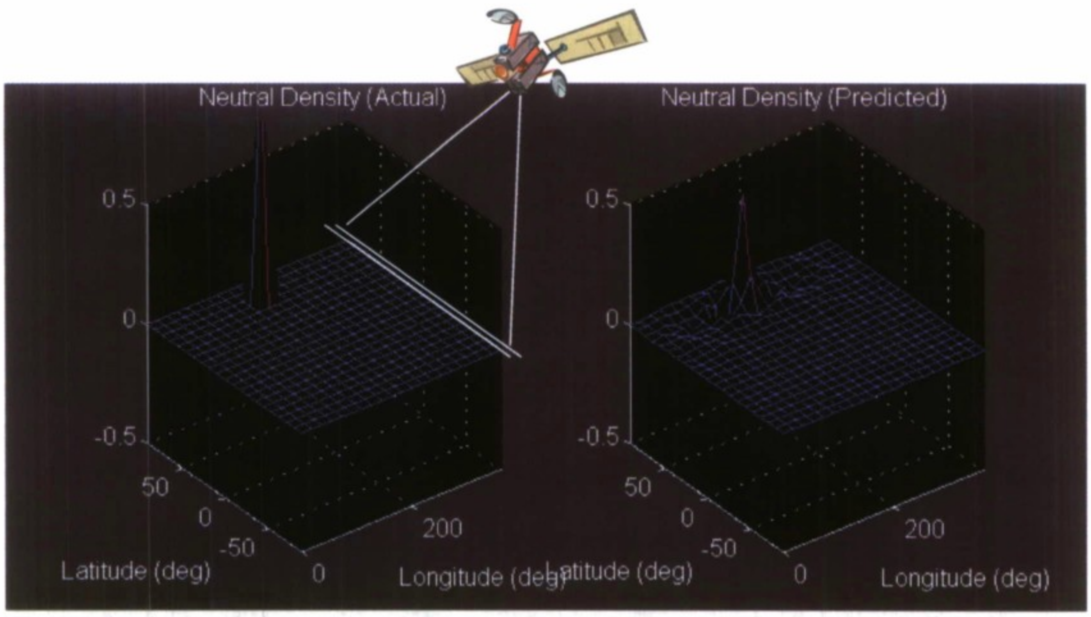

Figure 2: A simulation of an unobserved heating source (right) and the enKF solution of the unobserved heating (left).

In Figure 2, a heating source is shown by a simulated density spike at 80 degrees latitude and 180 degrees longitude in the left panel of the figure. The satellite is observing a region (the outlined white satellite track covering all latitudes at 360 degrees in the left panel) far from the heating source. The enKF estimates the amount of heating at the unobserved location (at 180 degrees longitude) by comparing the observed response (at 360 degrees longitude) with the physical model prediction. The enKF is able to iteratively estimate (right panel) what the heating would have been at 180 degrees longitude based on the observed neutral atmospheric response and the model prediction. The ability to solve these types of problems is important because they resemble the actual complexity of the system as well as the inability to completely observe these systems due to limited satellite coverage. The combination of the nonlinear dynamics and limited observation coverage makes this type of problem very difficult to solve. The system presented here, even with the simplified physical model, is so challenging that the field of nonlinear optimization and other related fields are dedicated to solving these types of problems. The ability of the enKF to obtain a solution for this nonlinear system indicates the feasibility of the solution method used in this study and provides a framework for the full physical model to be applied.

The second phase involved replacing the simple model with a significantly more advanced numerical model, the Coupled Thermosphere-Ionosphere Model, CTIM (Fuller-Rowell, *et al.* 1996b). CTIM simulates the time-dependent structure of the wind vector, temperature and density of the neutral thermosphere by numerically solving the non-linear primitive equations of momentum, energy and continuity. The global atmosphere is divided into a series of elements in geographic latitude, longitude and pressure. The time dependent variables of southward and eastward wind, total energy density, and neutral temperature are evaluated at each grid point by an explicit time-stepping numerical technique. After each iteration, the vertical wind is derived, together with temperature, density, and heights of pressure surfaces. The parameters can be interpolated to fixed heights for comparison with the Challenging Minisatellite Payload (CHAMP) or the Gravity Recovery and Climate Experiment (GRACE) density data.

The implementation of the physical model required reformulation to operate optimally in a recursive data assimilation system and required the design of a Kalman smoother to take advantage of this version of CTIM. This improved system overcame the major challenges associated with solving an externally forced, nonlinear and incompletely observed neutral density.

Reformulating CTIM to optimally run in a data assimilation system has been a considerable and important undertaking. CTIM was originally designed for investigative research into the upper atmospheric dynamics - as opposed to recursive use in a data assimilation system. Although CTIM is regarded as an advanced model in the field of upper atmospheric research and has proven itself for operation in a data assimilation system, its forward-time-only solution inhibited its operation in a recursive system. The data assimilation's recursive ability is a necessity for solving incompletely observed, nonlinear systems where the external forcing is not entirely known.

This recently completed recursive data assimilation system has been named the Global Recursive Neutral Density Estimator and Locator (GReNDEL). This system is the first of its kind in that it applies an advanced physical model in a time-forward and -reverse recursive system. The system's recursive ability accomplishes several goals that have not been possible with prior systems, which includes: (1) a complete description of the location, duration, and spatial distribution of the upper atmospheric heating through observing the heating response; (2) a correct nonlinear description of the upper atmosphere response once the heating has been specified – even during greatly varying storm conditions; (3) the ability to calculate conditions in unobserved regions through CTIM's nonlinear dynamics; and (4) the ability to specify heating anywhere on the globe – not just limited to the electric field distribution. This system is a major step in resolving the upper atmospheric heating and response as compared with traditional empirical model-based systems, which must rely on scalar solar and geomagnetic indices. The results of this progress will provide an improved specification of the neutral density heating distribution beyond the previous level of resolution.

Solution Method of GReNDEL

Until now, data assimilation systems have been limited by the empirical model description of the upper atmospheric nonlinear dynamics and the scalar index description of the varied forcing. Empirical models cannot completely describe the complex chain of events that connect the heating and the complex atmospheric response – especially if the storm continues beyond several hours. Furthermore, the use of scalar geomagnetic indices to describe the greatly varying heating distributions is insufficient. Small inconsistencies in the heating location and magnitude can lead to vastly different conclusions since the upper atmosphere is strongly, externally driven. Furthermore, these difficulties are exacerbated by the inability to observe all parts of the globe at any given time with many of the new single-satellite in situ and remote observation sources. Even global ballistic coefficient estimation does not have a sufficient time resolution (several hours) to capture rapidly varying storm conditions (minute-to-minute).

The recursive physical model data assimilation system, GReNDEL, overcomes the limitations in scalar indices and empirical modeling. GReNDL improves upon the solar and geomagnetic scalar indices by instead describing the location, shape, and magnitude of the heating source. Once this more complete description of the heating is obtained, the physical model, CTIM, numerically solves the complex, nonlinear response of the neutral atmosphere. Recursive iteration of this system provides a global map of the heating sources – even in regions far from the heating source and in unobservable regions.

GReNDEL accomplishes these tasks by recursively solving CTIM's response to a particular heating source (see Figure 3). Since CTIM can now operate in reverse-time, CTIM can estimate possible heating source distributions based on the observed response. Because of the nonlinear nature of the system, slight differences in the observed response can indicate greatly varying possible heating conditions. Because of the sensitivity and instability of the nonlinear system, recursive iterations are required so that the Kalman filter can gradually build a picture of the heating location, distribution shape, and magnitude. The result is a picture that is much more descriptive and realistic as compared with scalar indices or non-iterative solution methods.

There are other advantages to solving the system in this recursive manner. Heating locations at other locations, beyond the observed response region, can be solved. This capability is necessary since the response, due to the propagation of gravity waves, is often not in the same region as where the heating occurred. The recursive method in GReNDEL allows one to accomplish these propagated heating/response solutions.

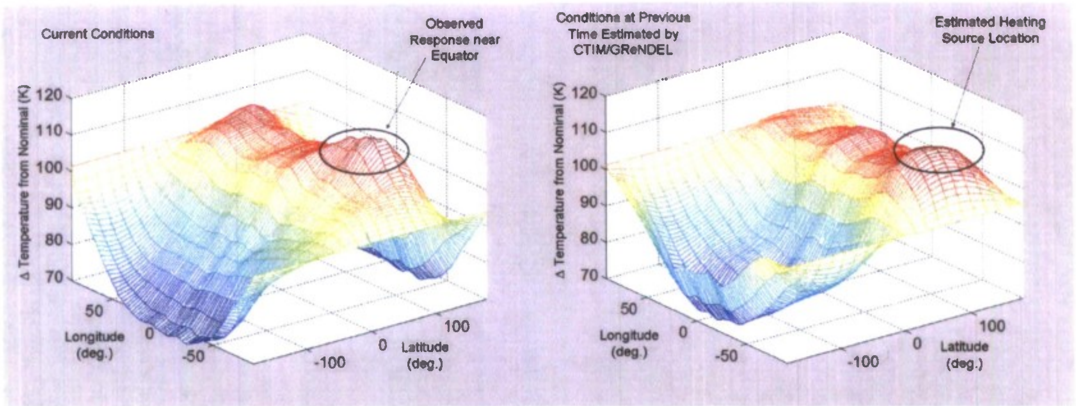

Figure 3: Running CTIM in reverse time and recursively correcting heating/response to estimate density as well as heating source location, distribution, and maginitude.

CTIP Validation against Multiple Data Sources

Having established a data assimilation infrastructure using CTIM, the next phase was to improve the physical model by incorporating a more realistic global ionosphere-plasmasphere, remove biases, and improve the code to follow the response and recovery time-scales to geomagnetic activity. CTIM used a simplified ionosphere limiting the use of plasma observables within the data assimilation scheme. Detailed comparison of the more advanced code that includes a global ionosphere plasmasphere, the Coupled Thermosphere Ionosphere Plasmasphere electrodynamics model (CTIPe), enable the physical model to be validated against neutral and plasma data sources. In the current tests, the data sources include the CHAMP neutral density data, the European incoherent scatter radar facility (EISCAT) ionospheric data, and total electron content from the operational US-TEC data assimilation model. Detailed comparison enabled design of some significant improvements in the code to remove model/data biases and model time constants.

Figure 4 shows a comparison of CTIPe with eight days of a year-long operation of the EISCAT facility. The model is able to follow the day-to-day changes during April 2005 reasonably well with minimal biases. However, the model predicted a winter anomaly at high latitudes, which was not observed by EISCAT, which introduced a seasonal bias. This bias was removed by introducing more realistic seasonal/latitude dependence in solar dissociation rates.

Detailed comparison of CTIPe with CHAMP during six months in 2005 also revealed that the recovery to geomagnetic storms was too slow in the numerical simulations. The physical process affecting the recovery times is largely due to the radiative cooling by nitric oxide. If the recovery rate is too slow the magnetospheric energy input required to maintain the observed density was also correspondingly too small. The NO cooling rate during a geomagnetic storm is controlled by too processes. Firstly, the increase in temperature in the presence of the background solar produced NO increases the cooling rate. Secondly, the NO production at mid to high latitudes during a geomagnetic storm is controlled by auroral electron precipitation, which further increases the cooling rate. The latter process was underestimated in CTIPe and in CTIM.

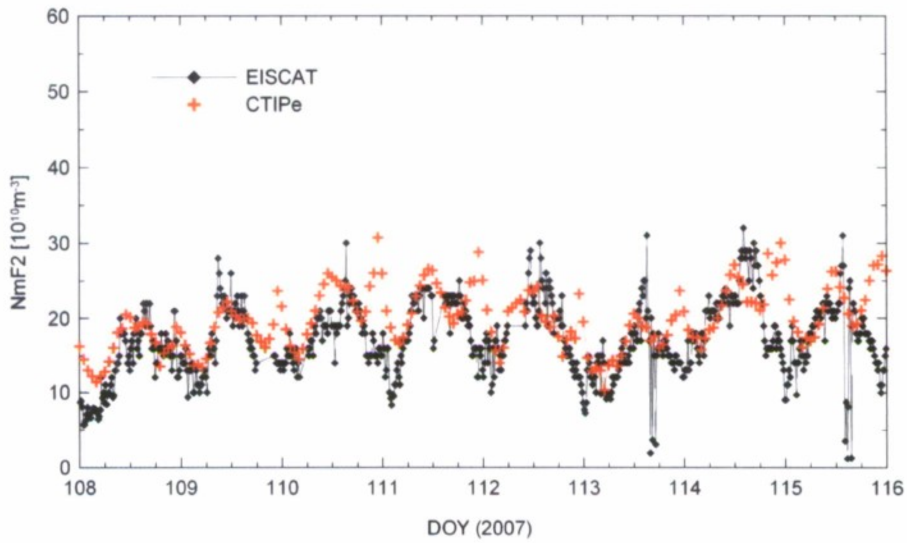

Figure 4. Comparison of EISCAT plasma density (black) with a physics-based model

To capture the recovery times more accurately an empirical NO model from Marsh et al., based on SNOE observations, was included as a module in order to simulate the observed height/latitude storm time changes in NO more realistically. The model is able to improve the storm-time changes in NO and radiative cooling during the response and recovery phase of a geomagnetic storm. The added advantage is that the empirical model is computationally fast and robust under all forcing conditions.

Figure 5 shows a comparison of CTIPe neutral mass density with the CHAMP satellite data for the first fifteen days of 2005. Model biases are not present for this period and the response and recovery time scales are realistic. This more accurate physics-based model can be used as the forward model in the data-assimilation scheme and for subsequently forecasting the system. The specific state of the thermosphere-ionosphere is dependent on the energy sources: particularly solar radiation and magnetospheric Joule and particle heating, together with internal mixing processes from turbulence and global circulation (the thermospheric "spoon").

Extensive comparison of CTIPe has also been done with the total electron content (TEC) over the CONUS from the US-TEC operational model. Validation of US-TEC itself has revealed an accuracy of less than 2 TEC units for vertical TEC, so providing an excellent data source to validate the physics based model. CTIPe has been running in a real-time mode for about a year to enable comprehensive comparison with the data to establish the baseline accuracy through the seasons.

The structure of the code was also modularized and the code was made more robust to enable stronger forcing terms to be applied. With the increase in radiative cooling it was necessary to include much larger geomagnetic sources, particularly Joule heating, in order to follow the time history of neutral density during a geomagnetic event. Modularizing the code enable the physical processes in the more sophisticated CTIPe code to be ported to CTIM if required, which is a simpler faster code suitable for data assimilation. In addition, modules that are not required to be self-consistent can be replaced by empirical algorithms. Validating and estimating drives for one parameter in a physical model (e.g. N_e) provides a means to specify and forecast another parameter, such as neutral density for satellite drag.

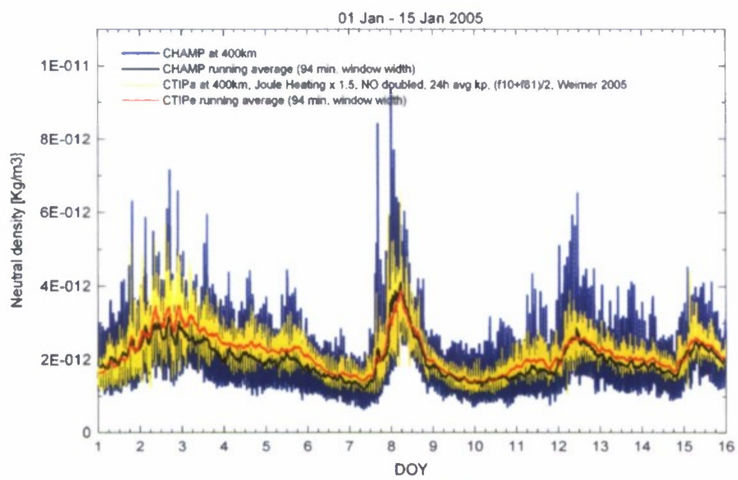

Figure 5. Comparison of CHAMP satellite orbit-averaged neutral density (black) with a physics-based prediction.

The next step, which will be continued under the new NADIR MURI initiative, will be to incorporate the more sophisticated and validated physical model into the ensemble Kalman filter data-assimilation scheme.

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