GDC-AO-SYNATMUG

Geospace Dynamics Constellation (GDC) Project

Synthetic Atmospheres: A User's Guide

Goddard Space Flight Center
Greenbelt, Maryland

National Aeronautics and
Space Administration

Table of Contents

List of Figures

List of Tables

1 INTRODUCTION

1.1 Purpose

This guide provides a primer on using four Global Ionosphere-Thermosphere Model (GITM) simulations (*Ridley et al. [2006]).* While they are driven by realistic data inputs, the synthetic atmospheres outlined in this document are designed to be "hypothetical representations" of Earth's atmosphere during different activity levels. Four geomagnetic activity types represented in these simulations are: (1) A Quiet Time, (2) An Isolated Substorm, (3) A Steady Magnetospheric Convection (SMC) Event, and (4) A Strong Storm Time. Each simulation archive consists of six hours of model output, produced at one-minute time resolution.

Section 2 outlines key aspects of the global circulation model that was used to generate these synthetic atmosphere files, highlighting the main parameters, such as grid size and physics packages included in the model. **Section 3** outlines each of the four synthetic simulations individually, outlining all of the key input parameters. Finally, **Section 4** provides a guide for how to access the model outputs.

We note that the GITM code was used to generate all of the output in this manual, in order to maintain consistency between the simulations. However, GITM represents only one of the many ionosphere-thermosphere models housed at NASA Goddard Space Flight Center's Community Coordinated Modeling Center (GSFC/CCMC). The user is encouraged to explore the outputs from several models through GSFC/CCMC as these simulations may not be sufficient to fully capture processes or features of interest. The user can use the inputs and settings in this document to recreate similar outputs using any desired model available at https://ccmc.gsfc.nasa.gov/.

1.2 Scope

This document is provided for planning purposes on NASA's Science Office for Mission Assessment website for Geospace Dynamics Constellation at: https://lws.larc.nasa.gov/GDC.

This document only describes the GITM simulations provided for planning purposes. It is not intended to state or imply any information about or requirements for a GDC project or solicitation. In the case of contradiction between this document and any document containing information about or requirements for a GDC project or solicitation, those documents supersede this document.

1.3 Related Documentation

1.3.1 Reference Documents

(1) NASA Science and Technology Definition Team for the Geospace Dynamics Constellation Final Report
(2) Proposal Information Package for the Geospace Dynamics Constellation Announcement of Opportunity

2 THE GLOBAL IONOSPHERE-THERMOSPHERE MODEL

The Global Ionosphere-Thermosphere Model (GITM) produced the four simulations provided in this archive. GITM was developed at the University of Michigan and has become a widely used and publicly available model for the upper atmosphere. The source code can be obtained from Github using the following link: https://github.com/aaronjridley/GITM/tree/master. All of the simulations in this archive were produced by a version of GITM obtained from this repository on November 1, 2019. However, because GITM is a community code undergoing constant development, newer versions of the code may produce results that differ from those provided here.

GITM is a non-hydrostatic global circulation model for the upper atmosphere of the Earth (*Ridley et al. [2006]*) and planetary atmospheres (*Bell et al. [2014], Bougher et al. [2015]*). This model simulates the energy balance, chemistry, and dynamics of the mutually coupled ionosphere and thermosphere from 100 km to ~600 km. Moreover, GITM is an altitude-based model capable of non-uniform grid resolution in both altitude and latitude. More details of the GITM framework can be found in a series of key papers: *Ridley et al. [2006], Deng et al. [2019], Vichare et al. [2012],* and *Zhu et al. [2016].*

2.1 Inputs and Settings Common to All GITM Simulations

The GITM archive consists of four simulations representing the Earth's upper atmosphere during a quiet time, an isolated substorm, a steady magnetospheric convection event, and a strong storm. However, some key aspects are shared by all of the simulations. First, each simulation consists of six hours of simulation time with an output file produced every minute. This results in 360 individual GITM "data cubes" for each of the four event types. These files can be viewed as a four-dimensional (4-D) dataset, wherein a physical parameter, such as neutral temperature, is produced in latitude (geographic), longitude (geographic), and altitude for each 1-minute interval over the entire six-hour event time.

Key settings for the numerical grids were held constant for all of the simulations. **Table 1** outlines the general grid characteristics common to all of the archived simulations. GITM is a three-dimensional model formulated in spherical polar coordinates (r,θ,ϕ), where r is the radial distance from the center of the planet (or equivalently altitude), θ is the latitude, and ϕ is the East longitude that increases from 0 to 360.0 degrees. For altitudes, GITM uses a non-uniform grid with a resolution that is a fraction of the local scale height, H_{atm}, meaning that the grid spacing is finer at low altitudes and becomes coarser at higher altitudes. The altitude grid is set at the initialization of a simulation, using the neutral atmosphere scale heights determined by the empirical Naval Research Laboratory Mass Spectrometer Incoherent Scatter Radar (NRL-MSISE-00, *Picone et al. [2002]*). This method results in altitude grids that can vary with each simulation, where the topmost altitudes typically vary from ~500 km (near solar minimum) up to ~750 km (near solar maximum).

Table 1. Global grid settings for all simulations.

	Resolution	range
Latitude	Uniform 1.0^0	-90.0º S to 90.0^0 N
Longitude	Uniform 3.3^0	0.0º E to 360.0º E
Altitude	Non-Uniform: 0.2 Hatm	50 altitude levels Model Bottom: 98 km Model Top (varies): 500 km – 700 km

GITM incorporates several well-documented physics packages to calculate the ion electrodynamics, Solar Extreme Ultraviolet/Ultraviolet (EUV/UV) inputs, and auroral particle precipitation during geomagnetic events. These physics models are listed in **Table 2**, along with their most primary inputs. For high-latitude electrodynamics, the *Weimer et al. [2005]* potential model is used to specify the magnetospheric E-field that drives the ion dynamics. In order to properly drive this module, the upstream solar wind conditions ($\mathbf{V}_{sw}$ and $\mathbf{B}_{imf}$) are read in as a function of time from an external data file obtained from OMNIWeb, allowing these drivers to change over time. Alternatively, GITM can be set to run with fixed values for these upstream drivers, and each event in **Section 3** will indicate (1) what data is being used and (2) how it is implemented (i.e., static or time-dependent).

The Dynamo calculation methods of *Vichare et al. [2012]* are used to simulate the low-latitude electrodynamics and the primary inputs for the dynamo solver are provided by GITM self-consistently (that is, they are not directly forced by a specified data file). Moreover, the low-latitude electrodynamics are solved using the modified APEX coordinates of *Richmond [1995].* For the auroral particle precipitation and the associated ionization/heating, GITM utilizes a modified version of the *Fuller-Rowell and Evans [1987]* model that is driven by the Hemispheric Power Index (HPI) as a function of time. Like the upstream solar wind drivers for the *Weimer [2005]* potential model, the HPI data can either be (1) an input from a data file obtained from the National Oceanic and Atmospheric Administration Space Weather Prediction Center (NOAA/SWPC) or (2) specified by the user at the start of the run and held fixed.

GITM can employ either the Flare Irradiance Spectral Model (FISM) (*Chamberlain et al. [2008]*) or the EUV flux model for Aeronomic Calculations (EUVAC) (*Richards [1994])* to calculate solar irradiances. For the simulations in this archive, the EUVAC model was used, which uses the $F_{10.7\text{-cm}}$ proxy in solar flux units (1 sfu = 10^{-22} J/m^2/Hz). Finally, the lower boundary temperatures, winds, and neutral densities are specified by the NRL-MSISE-00 model (*Picone et al. [2002]*) and these vary as a function of time according to that model. This time-varying lower boundary allows the simulation to approximate the effects of upward propagating waves and tides on the thermosphere, providing a more realistic simulation for planning purposes. For this lower boundary, the only input for the NRL-MSIS00 module is the date and the time (UT) of the simulation.

Table 2. Key Processes & Models Driving GITM Simulations.

	Model Used	Primary Input
High-Latitude Electrodynamics	*Weimer [2005]*	Upstream Solar Wind conditions ($\mathbf{V}_{sw}$, $\mathbf{B}_{imf}$)
Low-Latitude Electrodynamics	GITM Dynamo solver (*Vichare et al. [2012]*)	Self-consistent within GITM
Auroral Particle Precipitation	*Fuller-Rowell and Evans [1987]*	HPI Inputs
Lower Boundary	NRL-MSISE-00	Date and time
Solar EUV/UV	EUVAC	$F_{10.7\text{-cm}}$

2.2 Special Cases: The Isolated Substorm and the SMC Event

For the Substorm and SMC event types, we applied the methods outlined in *DeJong et al. [2018]*. For these events, we sought to provide the user with the best estimate of the rapid variations due to auroral driving by including two significant updates: (1) specify the electron precipitation fluxes in the auroral zone using imaging data taken from the Polar Ultraviolet Imager (Polar/UVI) and (2) specifying the electrodynamic potentials using Assimilative Mapping for Ionosphere Electrodynamics (AMIE). These two changes allowed us to simulate finer structure at high latitudes and to provide the best estimate for the auroral and thermosphere changes during these types of events.

3 THE GLOBAL IONOSPHERE-THERMOSPHERE MODEL

In this section, we outline the major features of the four simulated events. These event types are intended to span the most likely range of geomagnetic activity conditions that could be experienced during the planned Geospace Dynamics Constellation mission lifetime, spanning geomagnetic activity levels from extreme quiet to storm time conditions. Each event is broken out separately in the following sections, where we highlight the input parameters used, the upstream conditions, and a sample of the GITM outputs.

3.1 Quiet Time Simulation

This simulation is meant to approximate the extreme quiet time conditions that occurred during the January 2, 2010 between 00:00 - 06:00 time frame. **Figure 1** highlights key observations found in the OMNI database (https://omniweb.gsfc.nasa.gov/ow_min.html). The left-hand panel of this figure depicts the upstream solar wind conditions and the right panel contains the geomagnetic indices.

In an effort to approximate the conditions for this quiet time, the parameters in **Table 3** were used as inputs for the GITM simulation. Moreover, we chose to fix the input parameters over the six-hour simulation, providing a very steady quiet time simulation to serve as a baseline calibration for the user. Thus, the Hemispheric Power Index (HPI) and upstream solar wind drivers ($\mathbf{V}_{sw}$ and $\mathbf{B}_{imf}$) were held at the constant values listed in **Table 3**; the solar wind parameters are specified in the Geocentric Solar Magnetosphere (GSM) coordinate system.

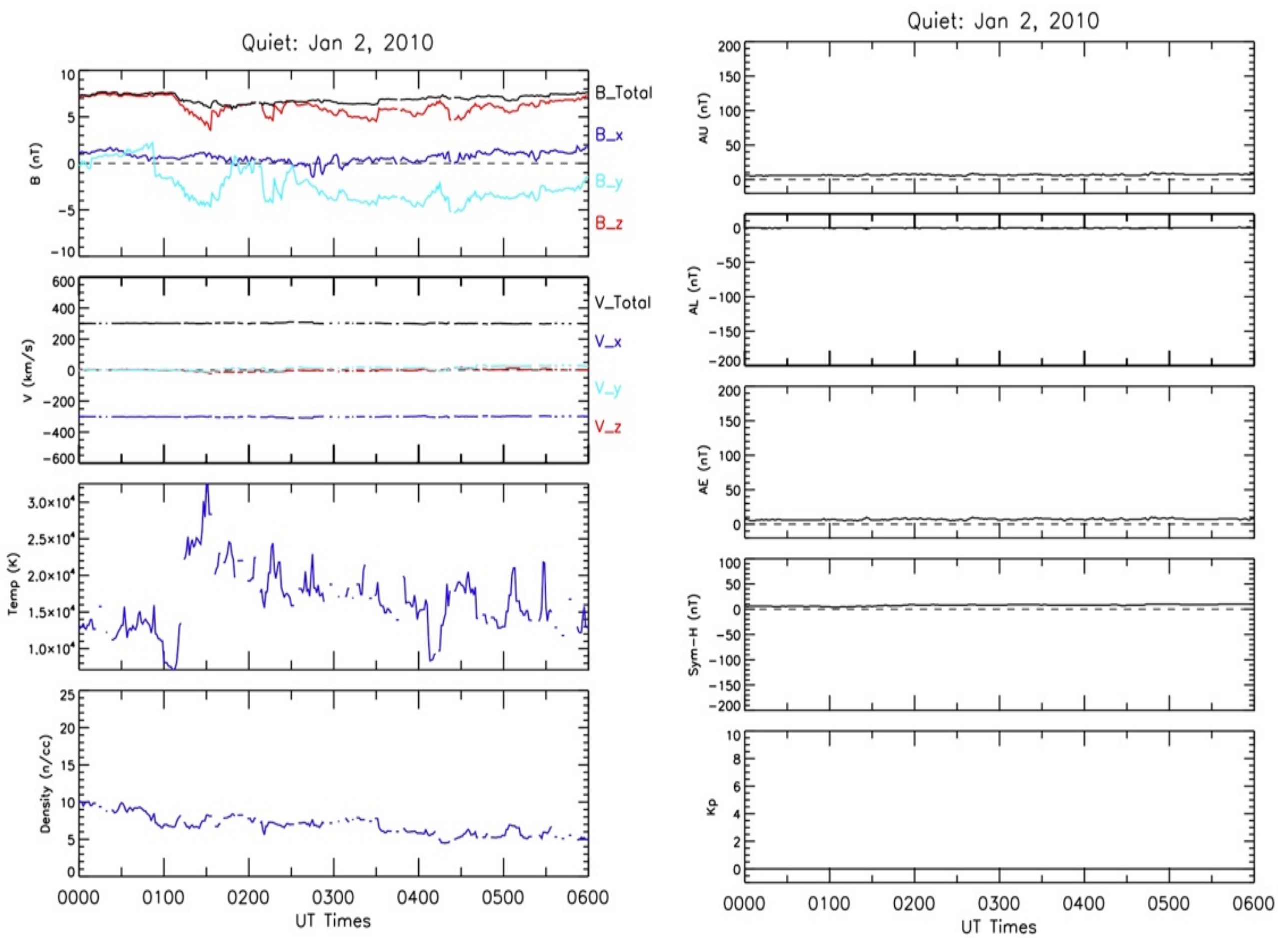

Figure 1. Upstream conditions during the quiet time of Jan 2, 2010 (left panel) and geomagnetic indices during the same period (right panel).

Table 3. Input parameters for the GITM quiet time simulation. Note that the inputs are held fixed over time. **V** and **B** are given in the GSM coordinate system.

	Index/Parameter	**Data Source**
Solar Activity	F10.7-cm = 75 sfu	OMNI Web
Solar Wind Conditions	$\mathbf{V}_{sw}$ = (Vx,Vy,Vz) = (-298.0 km/s, 0, 0) $\mathbf{B}_{imf}$ (Bx,By,Bz) = (0,0, -0.5 nT)	OMNI Web
PARTICLE PRECIPITATION FLUXES	HPI = 0.5	NOAA/SWPC

Figure 2 contains sample neutral temperatures from the quiet time GITM simulation. These are meant to provide benchmarks and comparison points for the user. These plots show a constant altitude slice at 400 km, creating a latitude vs longitude contour plot.

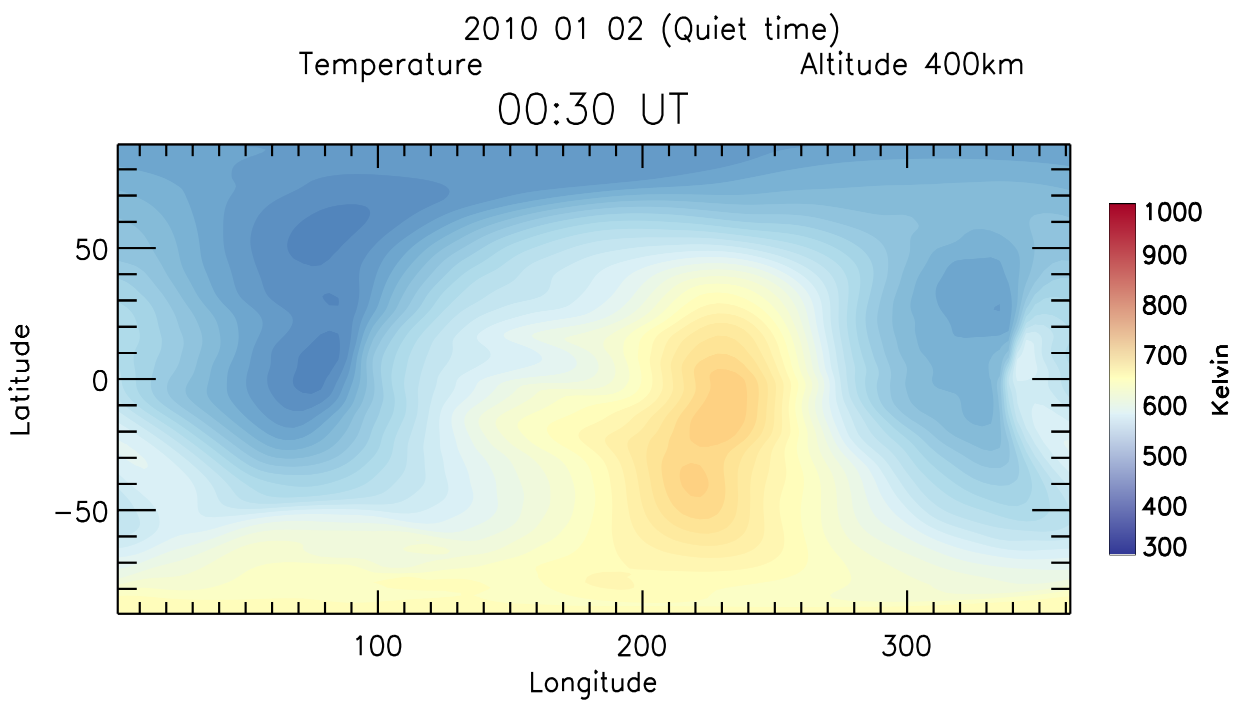

Figure 2. Simulated neutral temperatures (contours) in K, at a constant altitude of 400 km and timestamp 00:30 UT.

Figure 3 depicts a series of snapshots of the neutral temperatures over the northern high latitudes to help provide additional calibration points for users accessing the GITM simulation outputs. The contours are neutral temperatures (scale provided to the right), while the latitudes are denoted by the circular dotted lines and plots extend from the pole down to 50^0 North. Finally, the plots are organized according to solar local time (not magnetic local time) with noon at the top of each circular plot, midnight at the bottom, dusk on the left, and dawn on the right. Each contour is taken at 400 km altitude.

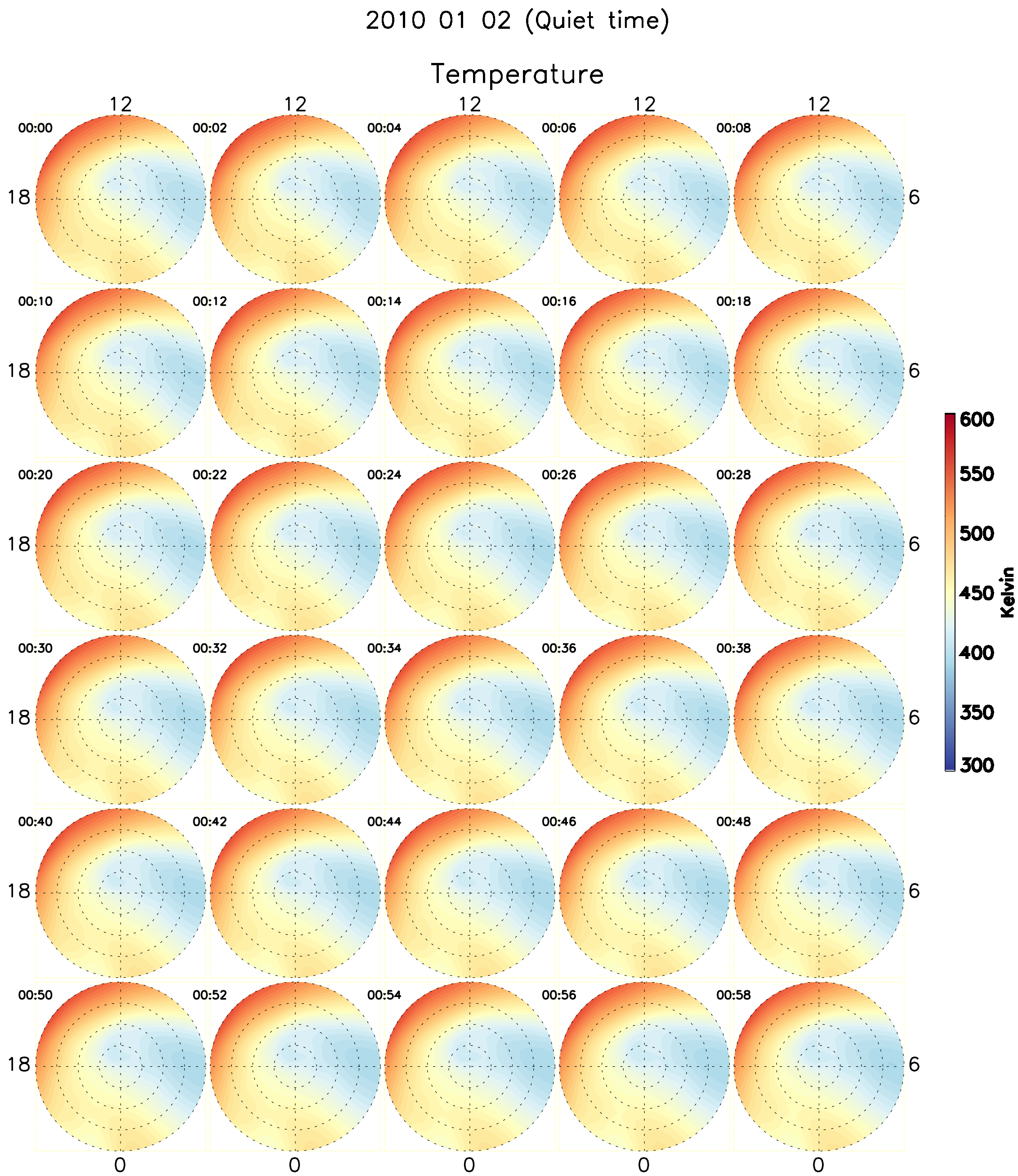

Figure 3. Time series of the simulated neutral temperatures (contours) in K, at a constant altitude of 400 km for northern high latitudes. Dotted lines represent latitudes ($50^0 – 90^0$ N) and the figures are organized according to local times (noon at the top, midnight at the bottom, dusk on the left, and dawn on the right.

3.2 Isolated Substorm Simulation

This simulation approximates the thermosphere response to an isolated substorm that occurred the January 6, 1998 - 00:00 - 06:00 UT timeframe (cf, *DeJong et al. [2018]*). **Figure 4** summarizes the key upstream drivers and geomagnetic indices during this timeframe and **Figure 5** presents the GITM outputs at a single stamp during this time period at 400 km. As noted in Section 2.2, the precipitating auroral electron fluxes were specified by Polar/UVI auroral imaging data, using the methods of *DeJong et al. [2018].* Moreover, the potential patterns for the high-latitude electrodynamics were specified using the Assimilative Mapping of Ionospheric Electrodynamics (AMIE) using ground-based magnetometers (*Ridley and Kihn [2004], Ridley et al. [2000]*). This method was chosen to enable GITM to simulate more rapid, smaller scale variations in the thermosphere fields

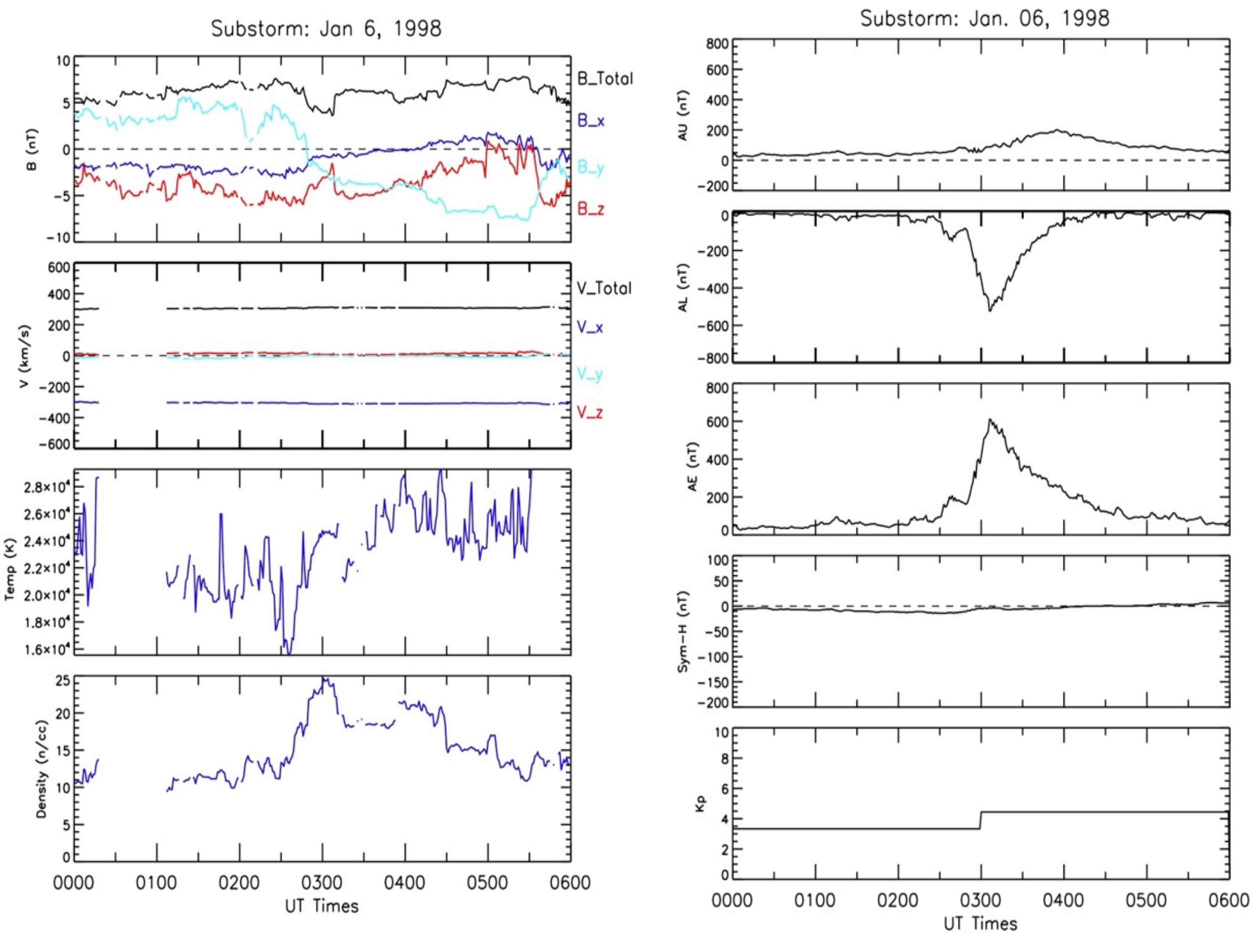

Figure 4. Upstream conditions during the isolated substorm of Jan 06, 1998 (left panel) and geomagnetic indices during the same period (right panel).

Table 4. Input parameters for the isolated substorm simulation.

	Index/Parameter	Data Source
Solar Activity	F10.7-cm	OMNI Web
Solar Wind Conditions	Assimilative Mapping of Ionosphere Electrodynamics	Ground-based magnetometer data
PARTICLE PRECIPITATION FLUXES	Polar/UVI auroral images (varies over time)	Polar/UVI (*DeJong et al. [2018]*)

Figure 6 depicts a series of snapshots of the neutral temperatures over the northern high latitudes to help provide additional calibration. The contours represent the neutral temperatures (scale on the right), while the latitudes are depicted by the circular dotted lines and the plots extend from the pole down to 50° N latitude. Finally, the plots are organized according to solar local time (not magnetic local time) with noon at the top of each circular plot, midnight at the bottom, dusk on the left, and dawn on the right. Each contour is taken at 400 km altitude.

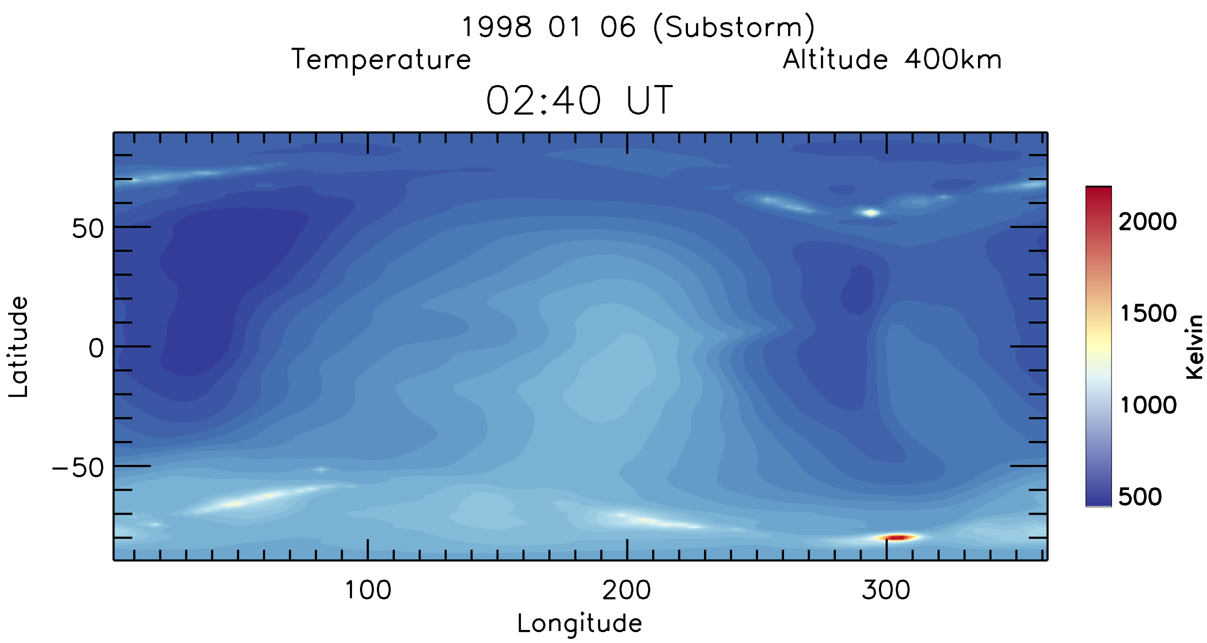

Figure 5. Simulated neutral temperatures at 400 km and UT 2:40 hours, during the Jan 06, 1998 Substorm.

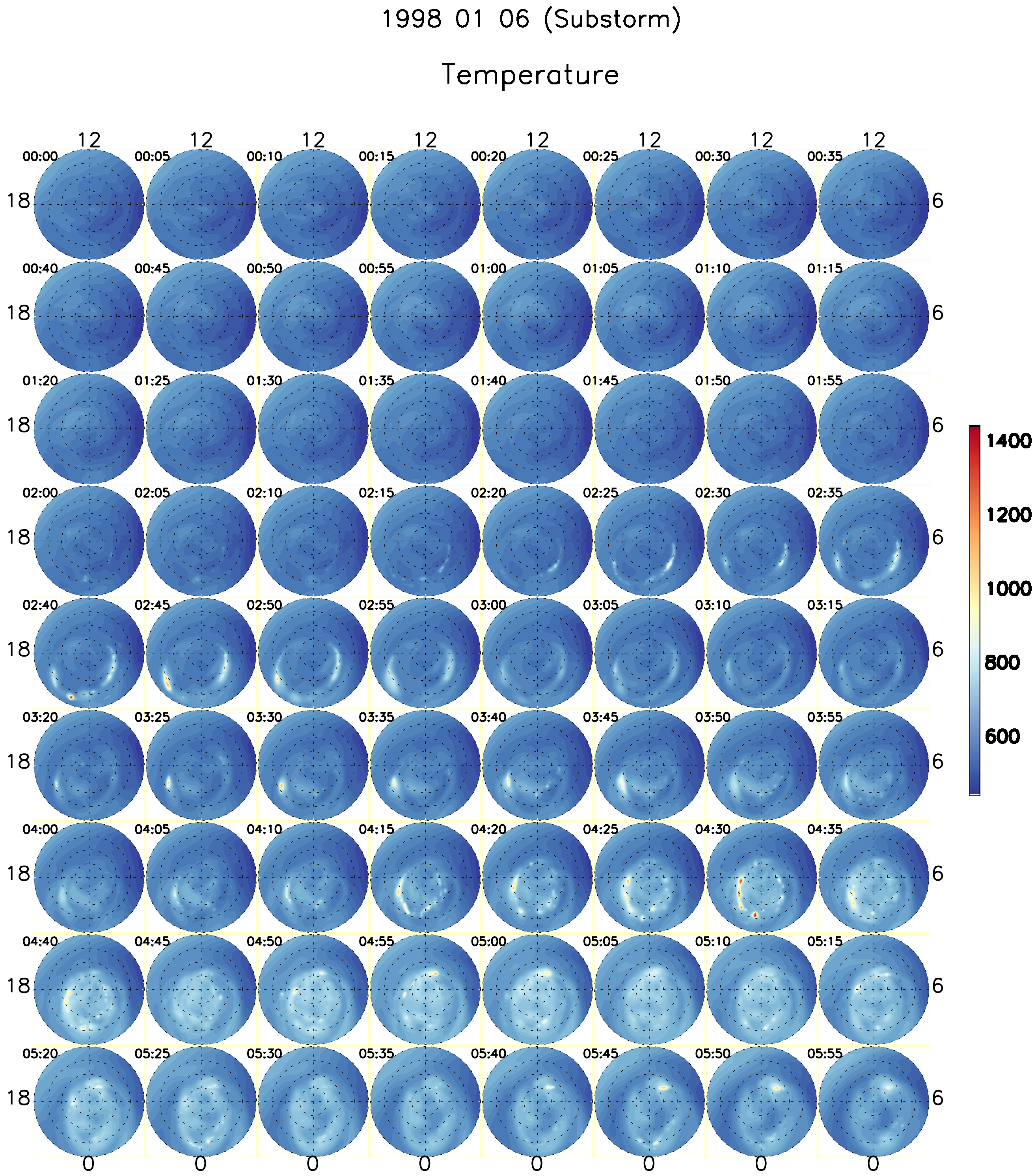

Figure 6. Time series of the simulated neutral temperatures (contours) in K, at a constant altitude of 400 km for northern high latitudes. Dotted lines represent latitudes (50º-90º N) and the figures are organized according to local times (noon at the top, midnight at the bottom, dusk on the left, and dawn on the right).

3.3 Steady Magnetospheric Convection Event

This GITM simulation reproduces the conditions during a steady magnetospheric convection event (SMC) that occurred during the February 23, 1997 - 00:00 - 06:00 timeframe. As with the substorm in **Section 3.2**, AMIE potential patterns were used to drive the ion electrodynamics and auroral imaging was used to specify auroral electron precipitation fluxes, as was done in DeJong et al. [2018]. **Figure 7** presents the upstream drivers during this time frame in the left panel, obtained from the OMNI database, and the right panel illustrates the geomagnetic response. **Figure 8** presents a calibration contour plot, illustrating the temperature distribution at 400 km at a single timestamp during the SMC event.

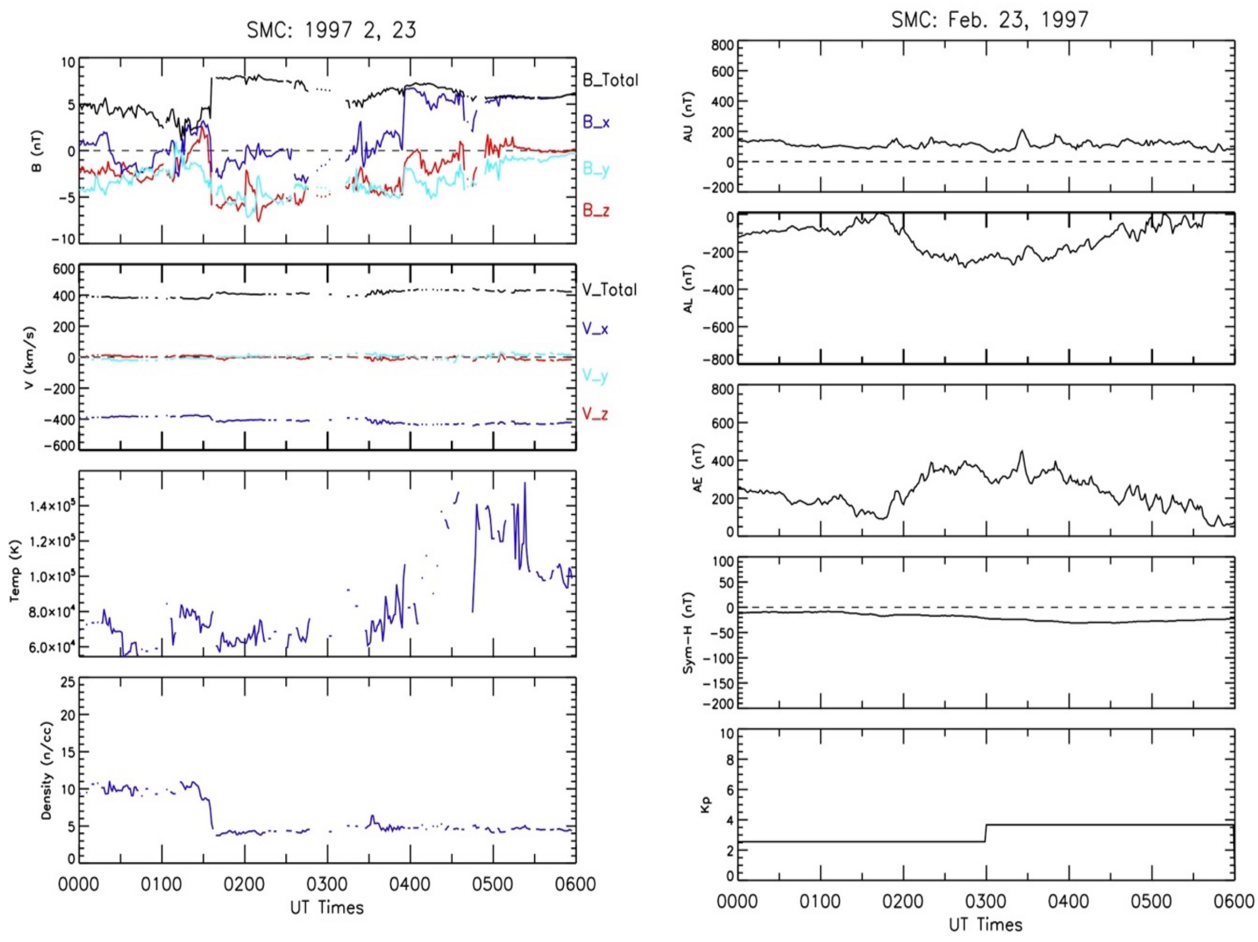

Figure 7. Upstream conditions during the SMC that occurred on Feb 22, 1997 (left panel) and geomagnetic indices during the same period (right panel).

Like **Figure 6**, **Figure 9** depicts a series of snapshots of the neutral temperatures over the northern high latitudes to help provide additional calibration. The contours represent the neutral temperatures (scale on the right), while the latitudes are depicted by the circular dotted lines and the plots extend from the pole down to 50° N latitude. Finally, the plots are organized according to solar local time (not magnetic local time) with noon at the top of each circular plot, midnight at the bottom, dusk on the left, and dawn on the right. Each contour is taken at 400 km altitude

Table 5. Input parameters for the SMC simulation.

	Index/Parameter	Data Source
Solar Activity	F10.7-cm	OMNI Web
Solar Wind Conditions	Assimilative Mapping of Ionosphere Electrodynamics	Ground-based magnetometer data
PARTICLE PRECIPITATION FLUXES	Polar/UVI auroral images (varies over time)	Polar/UVI (DeJong et al. [2018])

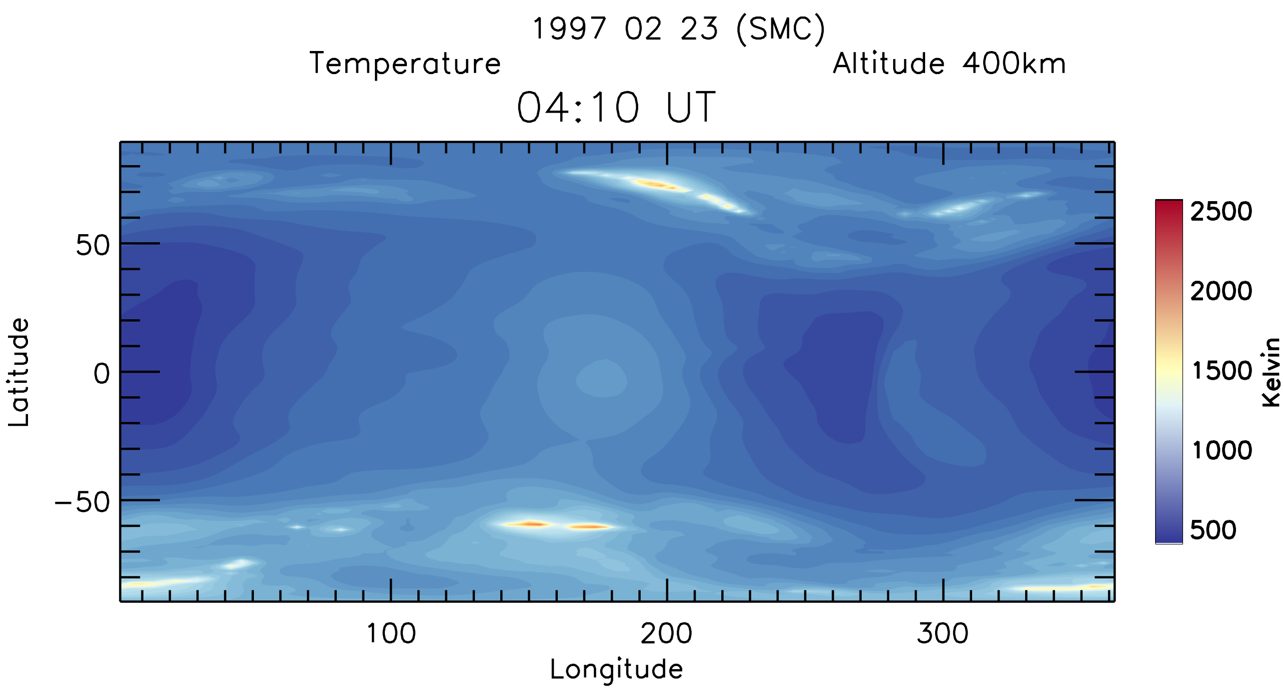

Figure 8. Simulated neutral temperature contours at 400 km at 04:10 UT during the Steady Magnetosphere Convection event on Feb 23, 1997.

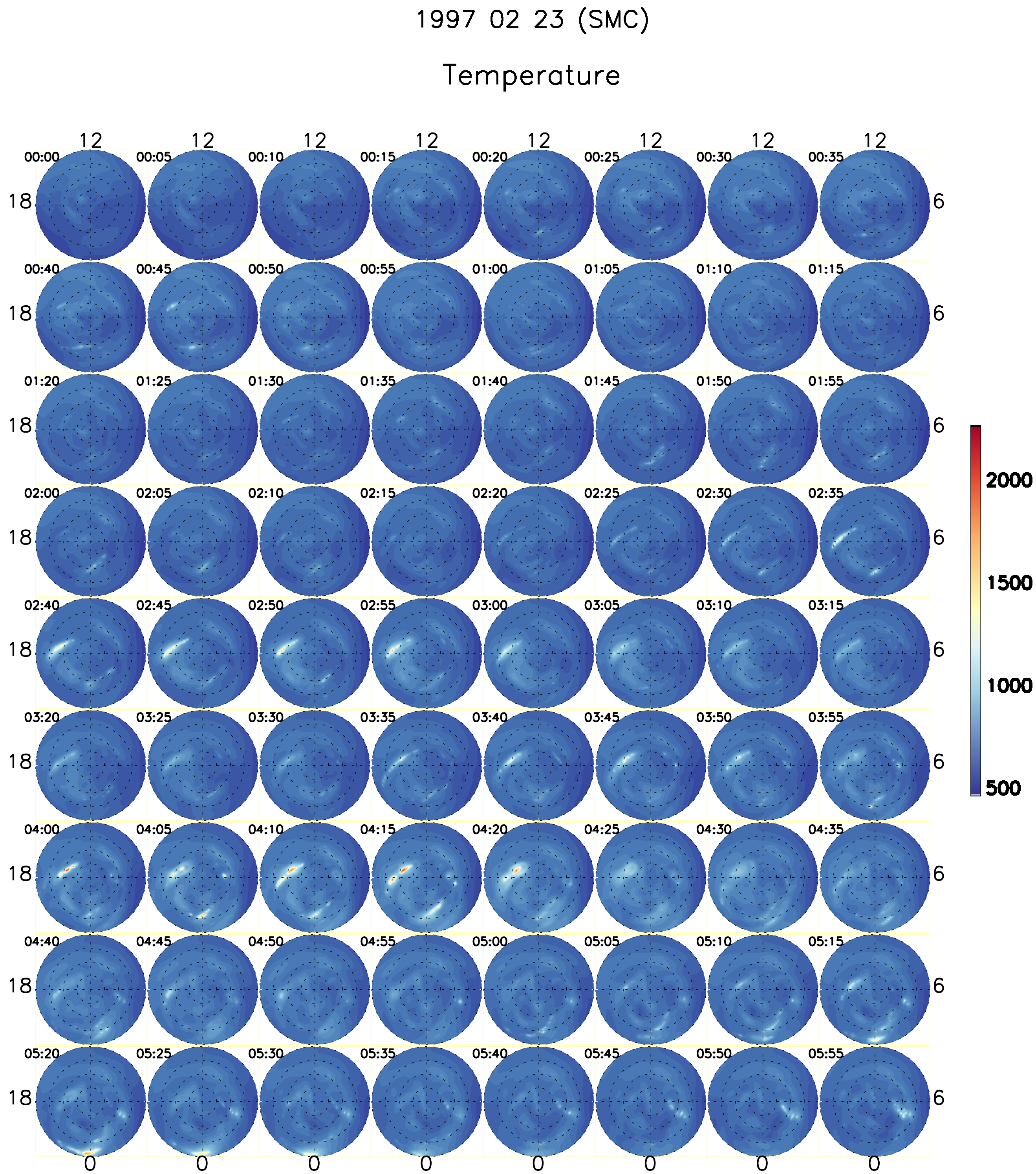

Figure 9. Time series of the simulated neutral temperatures (contours) in K, at a constant altitude of 400 km for northern high latitudes. Dotted lines represent latitudes ($50^0 – 90^0$ N) and the figures are organized according to local times (noon at the top, midnight at the bottom, dusk on the left, and dawn on the right.

3.4 Storm Time Simulation

This GITM simulation approximates the thermosphere response during the famous “Halloween Storms” of October, 2003. **Figure 10** depicts the strong upwind solar wind drivers (left panel) and the similarly strong geomagnetic response (right panel). Upwind solar wind data from the OMNI database were input as a function of time during the October 29 -31 timeframe. The results included in this archive are from the early onset of a strong storm near 18 hours UT on October 29, 2003. This time period is meant to provide the user with an approximation of how the thermosphere may behave during extreme solar events. **Figure 11** presents a calibration contour plot, illustrating the neutral thermal structure at 400 km at 18:30 UT.

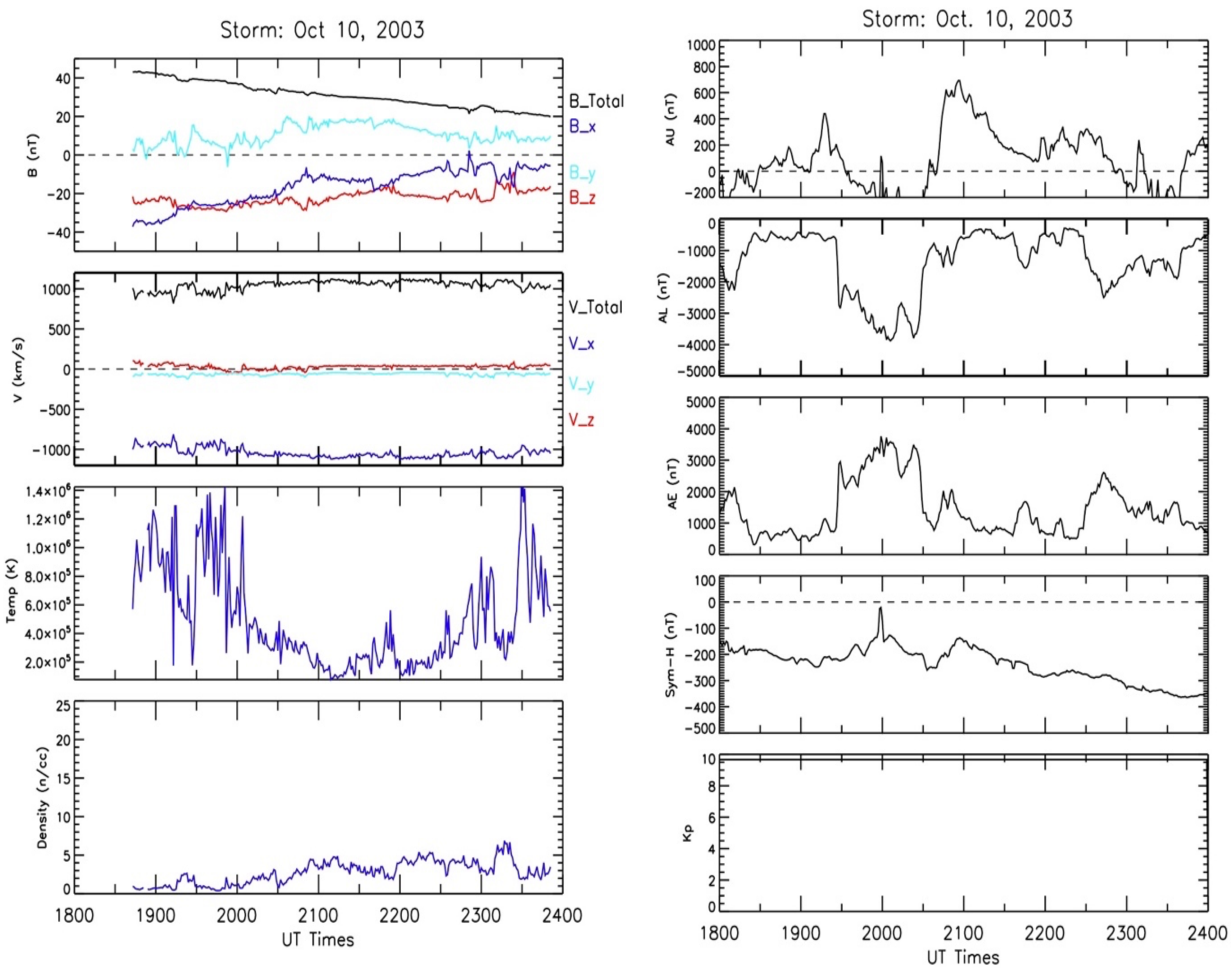

Figure 10. Upstream conditions during the Halloween Storm that occurred on Oct. 10, 2003 (left panel) and geomagnetic indices during the same period (right panel).

Like **Figures 6 & 9**, **Figure 12** depicts a series of snapshots of the neutral temperatures over the northern high latitudes to help provide additional calibration. The contours represent the neutral temperatures (scale on the right), while the latitudes are depicted by the circular dotted lines and the plots extend from the pole down to 50° N latitude. Finally, the plots are organized according to solar local time (not magnetic local time) with noon at the top of each circular plot, midnight at the bottom, dusk on the left, and dawn on the right. Each contour is taken at 400 km altitude

Table 6. Inputs for the storm time simulation.

	Index/Parameter	Data Source
Solar Activity	F10.7-cm	OMNI Database
Solar Wind Conditions	Density, Temperature, $\mathbf{V}_{sw}$, $\mathbf{B}_{imf}$	OMNI Database for 10/20/2003 – 10/31/2003 timeframe
Auroral Particle Precipitation Fluxes	NOAA/POES HPI	OMNI Database

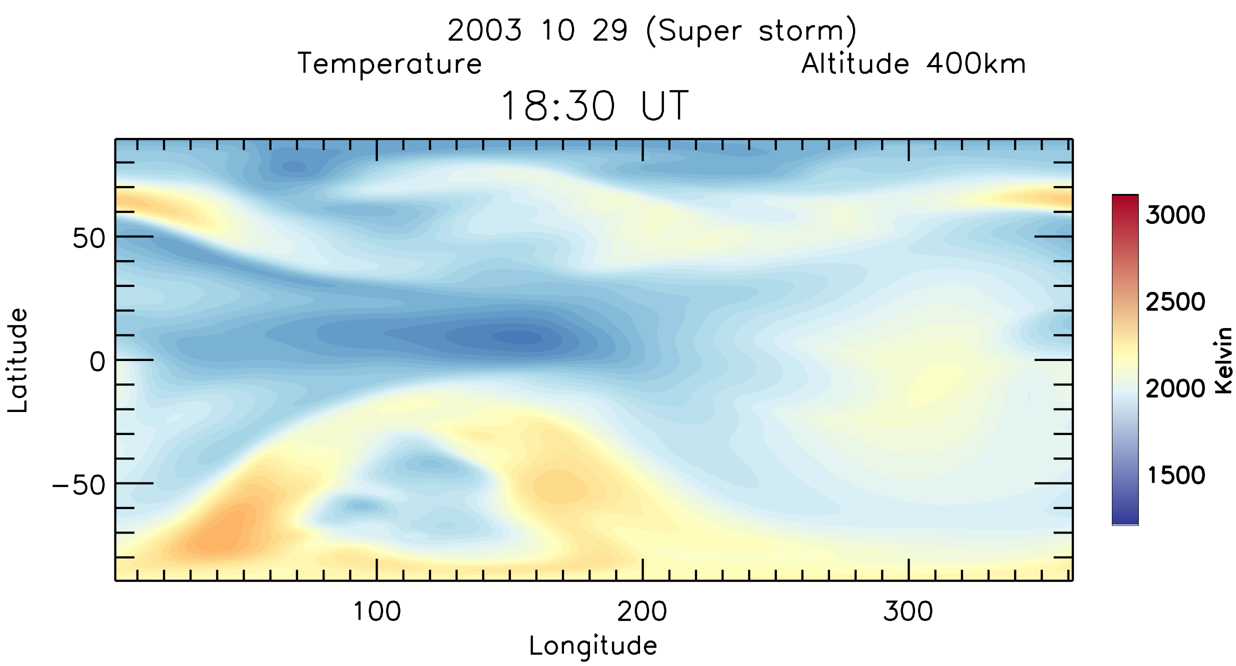

Figure 11. Simulated neutral temperatures (in K) at 400 km, during the storm time epoch at 18:30 UT hours.

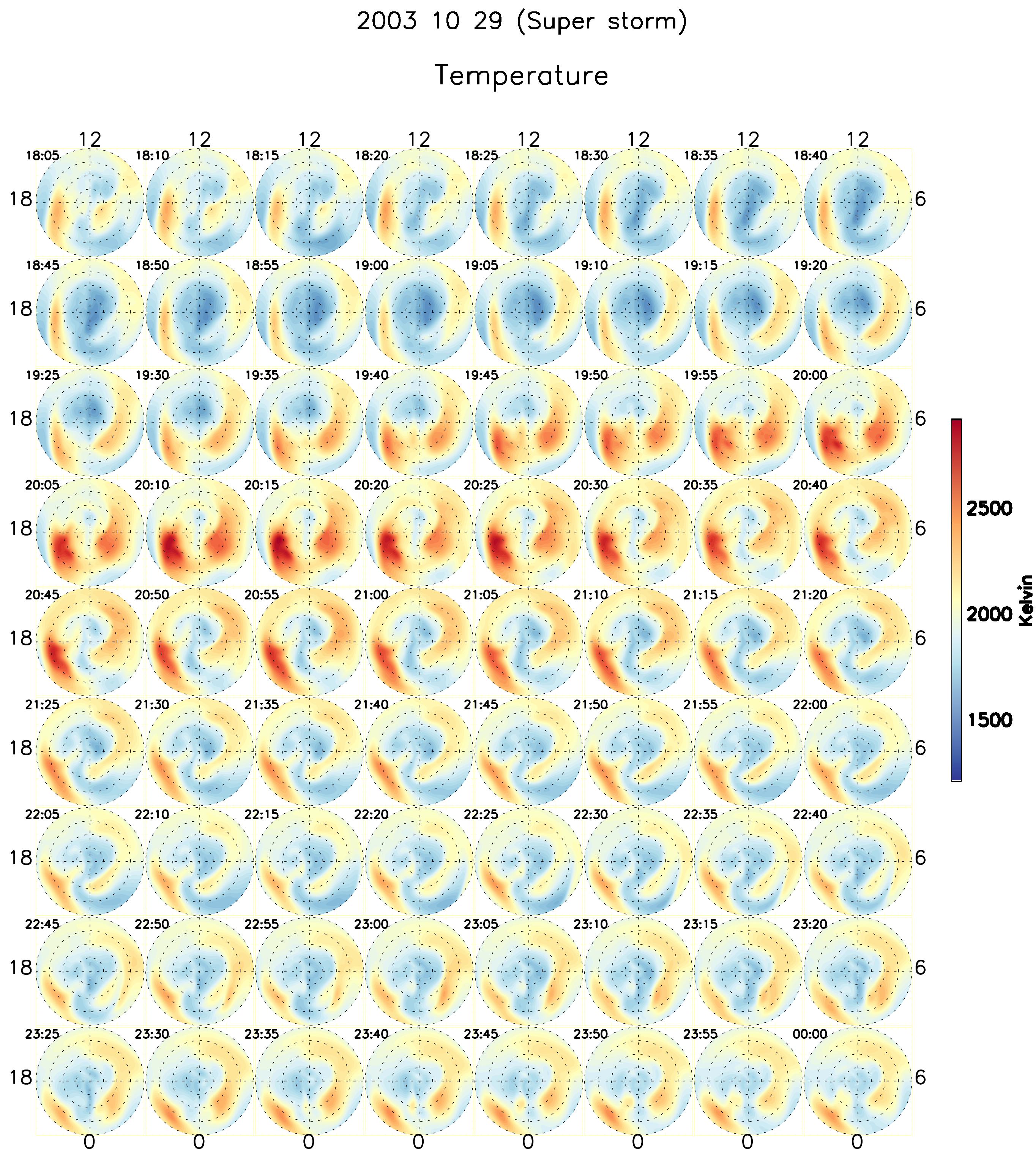

Figure 12. Time series of the simulated neutral temperatures (contours) in K, at a constant altitude of 400 km for northern high latitudes. Dotted lines represent latitudes ($50^0 – 90^0$ N) and the figures are organized according to local times (noon at the top, midnight at the bottom, dusk on the left, and dawn on the right).

4 ACCESSING THE SYNTHETIC ATMOSPHERE FILES

The GITM outputs (synthetic atmosphere files) are available as binary (.bin) files directly accessible through the Community Coordinated Modeling Center (CCMC) at NASA Goddard Space Flight Center (GSFC). Details for visualizing and downloading the GITM output files are provided at https://ccmc.gsfc.nasa.gov/missionsupport/GDC_support.php. The quiet time simulation (**Section 3.1**) can be accessed via the following link:

https://ccmc.gsfc.nasa.gov/results/viewrun.php?domain=IT&runnumber=GDC_Quiet_082020_IT_1.

Additional information about the GITM output file formats and for a repository of Python processing codes can be accessed on the GITM Github repository: https://github.com/aaronjridley/GITM/tree/master/srcPython.

5 REFERENCES

1. Bell et al. [2014], Developing a self-consistent description of Titan's upper atmosphere without hydrodynamic escape, JGR, 110, 4957-4972.

2. Bougher et al. [2015], Mars Global Ionosphere-Thermosphere Model: Solar cycle, seasonal, and diurnal variations of the Mars upper atmosphere., JGR Planets, 120, doi: 10.1002/2014JE004715.

3. Chamberlain et al. [2008], Flare Irradiance Spectral Model (FISM): Flare component algorithms and results, Space Weather, 6, S05001, doi:10.1029/2007SW000372.

4. DeJong et al. [2018]. Comparison of the Ionosphere During an SMC Initiating Substorm and an Isolated Substorm. JGR: Space Physics, **https://doi.org/10.1029/2017JA025055**

5. Deng, Y., et al. [2019], Impact of flow bursts in the auroral zone on the ionosphere and thermosphere. JGR: Space Physics, 124. doi.org/10.1029/2019JA026755.

6. Picone, J. M., A.E. Hedin, D.P. Drob, and A.C. Aikin [2002], NRLMSISE-00 empirical model of the atmosphere: Statistical comparisons and scientific issues, J. Geophys. Res., 107(A12), 1468, doi:10.1029/2002JA009430.

7. Richards, P.G. et al. [1994], EUVAC A solar EUV flux Model for aeronomic calculations. JGR, 99, https://doi.org/10.1029/94JA00518.

8. Richmond, A., [1995], Ionospheric electrodynamics using magnetic apex coordinates, J. Geomag. Geoelec. 47, 191.

9. Ridley, A., G. Crowley, and C. Freitas [2000], A statistical model of the ionospheric electric potential, Geophys. Res. Lett., 27, 3675

10. Ridley, A., and E. Kihn [2004], Polar cap index comparisons with AMIE cross polar cap potential, electric field, and polar cap area, Geophys. Res. Lett., 31, L07801, doi:10.1029/2003GL019113.

11. Ridley, A. J. et al. [2006], The Global Ionosphere-Thermosphere Model (GITM), JASTP, 68, 839-864.

12. Vichare, G. et al. [2012], Quiet-time low latitude ionospheric electrodynamics in the non-hydrostatic Global Ionosphere-Thermosphere Model, JASTP, 80, 161-172.

13. Weimer, D. R. [2005], Improved ionospheric electrodynamic models and application to calculating Joule heating rates, *Journal of Geophysical Research, 110,* A05306, doi:10.1029/2004JA010884.

14. Zhu, J. et al. [2016], Simulating electron and ion temperature in a global ionosphere thermosphere model: Validation and modeling an idealized substorm , JASTP, 138-139, pp. 243-260.