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Ionosphere Dynamics and Applications

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Gang Lu
Editors

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PREFACE

The ionosphere is a layer within the atmosphere that extends from about 60 kilometers above the Earth's surface to about 1,000 kilometers in altitude. It consists of charged particles (i.e., electrons and ions) due to ionization of neutrals by solar radiation and energetic particle precipitation from the magnetosphere.

Since its discovery more than 100 years ago, the ionosphere has become an active research area and our understanding of ionospheric dynamics continues to evolve due to advances in observational technologies and new capabilities in theory and numerical modeling.

Ionospheric dynamics are affected by many different forcings, including solar flares, geomagnetic storms, tides and waves from the lower atmosphere, as well as disturbances triggered by earthquakes and tsunamis. The ionosphere behaves very differently under different solar and geomagnetic conditions, and its variability has direct impacts on radio communication and satellite navigation system.

Although our knowledge of the ionosphere has greatly advanced in recent decades, many important aspects of ionospheric dynamics are still not well understood, especially during geomagnetic storms, because of the complexity of the coupled magnetosphere-ionosphere-thermosphere system.

This book, divided into five parts, provides a comprehensive overview of global ionospheric research ranging from the polar cap to the equatorial region. Part 1 addresses magnetosphere-ionosphere coupling in the high-latitude ionosphere, ion outflow, and ionospheric convection in the polar cap and auroral zone. Part 2 concerns interhemispheric asymmetries, ionospheric structures such as large-scale storm enhanced density plumes, and meso- and small-scale structures in the subauroral and mid-latitude ionosphere. Part 3 focuses on the low-latitude ionosphere, including equatorial

ionospheric electrodynamics, equatorial spread F, equatorial electrojet, and equatorial ionization anomaly. Part 4 covers global ionospheric processes such as penetration electric fields, magnetosphere-ionosphere coupling at middle and subauroral latitudes, sudden stratospheric warming impacts on the ionosphere, longitudinal dependence of ionospheric dynamics, and travelling ionospheric disturbances. Part 5 discusses ionospheric effects on HF wave propagation and satellite navigation, as well as ionospheric disturbances caused by earthquakes and tsunamis.

The chapters are written in the form of review articles, providing a coherent description of each topical area. Each chapter includes historical evolution, recent progress, latest results, current understanding, and future challenges of the specific topics. Theoretical analyses, numerical modelings, and observational results from ionospheric radars, satellites, and other space-borne and ground-based instruments are presented.

The book will serve as a useful reference for active researchers and scientists in the space science community, as well as for graduates and upper-level undergraduate students at universities, and engineers and environment officers/operators in government agencies who are interested in space weather applications.

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Part I

The Polar Cap and Auroral Ionosphere

Magnetospheric Energy Input to the Ionosphere

Cheryl Huang

ABSTRACT

The high-latitude region of the ionosphere-thermosphere (IT) system responds to solar wind driving via complex physical processes. The goal of global models of IT coupling is to specify and forecast the effect of magnetospheric energy input, in particular, energy dissipation into Joule heating and increase in kinetic energy of neutral and charged particles. Established paradigms for IT coupling have been challenged by recent investigations into the nature of energy input and the locations where energy is deposited. These results have forced a reexamination of our fundamental assumptions, which are captured in a series of empirical and physics-based models of energy input. An assessment of these models reveals areas of significant discrepancy between model output and observations. This chapter summarizes the current understanding of magnetospheric energy input, and indicates research areas that remain to be explored.

1.1. INTRODUCTION

The paradigm for coupling between the magnetosphere and ionosphere was established in a series of seminal papers in which connection of the Earth's magnetic field to the interplanetary magnetic field (IMF) was postulated to drive ionospheric convection (Axford & Hines, 1961; Dungey, 1961; Axford, 1969). In this view, based on magnetohydrodynamic (MHD) fluid theory, the solar wind connects to the Earth's magnetosphere, allowing solar wind momentum to be transferred across the boundary of the magnetosphere to set into motion magnetospheric plasma. Given the Earth's magnetic field, B , motion of charged particles, V , is possible only if an electric field, E is generated where $E = -V \times B$.

This paradigm explained magnetic activity in which energy enters the high-latitude ionosphere and is manifest

as auroral brightening. Supporting this paradigm were the discovery of energetic particle precipitation in the auroral zones (Frank & Ackerson, 1971), and persistent field-aligned currents (FACs) in the same latitude range (Zmuda et al., 1970). These discoveries contributed to widespread acceptance that (1) MHD reconnection is the dominant mechanism through which solar wind energy enters the ionosphere-thermosphere (IT) system; (2) energy input and dissipation is highly localized in the auroral zones under active and quiet conditions. This hypothesis has been widely explored and challenged in recent years.

Ultimately the impact of energy deposition is heating of the ionosphere and thermosphere, commonly referred to as Joule heating. The transition from energy input to Joule heating involves the conductivity of the medium. Limitations on the length of this chapter preclude a full summary of Joule heat and conductivity, both complex topics in themselves, but brief descriptions of the physical processes are included for completeness.

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1.2. ENERGY ENTERING THE IONOSPHERE-THERMOSPHERE (IT) SYSTEM

1.2.1. Electromagnetic and Particle Energies

The magnetosphere-ionosphere-thermosphere (MIT) coupled system is strongly driven by the solar wind. In order to specify the IT response to magnetospheric energy input, the sources of forcing and the physical processes by which the system responds must be understood. The magnetosphere couples to the ionosphere through the magnetic field of the Earth so that magnetospheric electric field, E , and magnetic field, B , couple to ionospheric E and B fields. FACs provide the communication between the magnetosphere and the solar wind to the ionosphere. Solar UV radiation energy maintains ionization, and solar wind coupling with the magnetosphere provides additional energy via fluctuations in the E and B fields.

The energy that enter the IT system from the magnetosphere takes two forms, electromagnetic (EM) in the form of Poynting flux, and kinetic, in the form of precipitating particles. The majority of magnetospheric energy maps to the high-latitude region of the Earth. Thus, both types of energy occur at high latitudes in the polar cap, auroral zones, and subauroral regions.

The Poynting flux vector, S , is written

$$S = \frac{E \times B}{\mu_0}, \quad (1.1)$$

where μ_0 is the permeability of free space. The magnetic field, B , includes the Earth's magnetic field, the steady state contribution from large-scale currents, and EM wave fields. Only the perturbation wave field, δB , produces energy that dissipates in the ionosphere (Kelley et al., 1991; Richmond, 2010), and only contributions to S from the perturbation magnetic field are considered relevant to energy input to the IT system.

Poynting's theorem in differential form is written

$$\nabla \cdot S + \frac{\partial W}{\partial t} + j \cdot E = 0, \quad (1.2)$$

where energy, W , in the EM wave is

$$W = \frac{1}{2} \left(\frac{1}{\mu_0} \delta B^2 + \epsilon_0 E^2 \right), \quad (1.3)$$

ϵ_0 is the permittivity of free space, j is the current density, E is the electric field, and $j \cdot E$ is the energy dissipation or conversion rate. It is usually assumed that there is little change in the wave energy with time in comparison with the $j \cdot E$ term and $\partial W / \partial t$ is usually ignored. This term is commonly referred to as the Joule heating rate, but it includes the energy transferred into bulk kinetic energy (Thayer & Semeter, 2004; Richmond, 2010). The kinetic

energy term is usually regarded as less important (Lu et al., 1995) though some would disagree (Thayer & Semeter, 2004).

S , as defined above, is the perturbation Poynting flux, $S = \frac{E \times \delta B}{\mu_0}$.

Richmond (2010) pointed out that the interpretation of Poynting's theorem as normally applied for ionospheric energy dissipation requires that the sides of the volume over which the Poynting flux is dissipated be equipotentials. Gary et al. (1994) argued that individual flux tubes can be regarded as the appropriate volume for correct application of Poynting's theorem.

Figure 1.1, reproduced from Knipp et al. (2004), shows the partition of energy input from 1975 to 2003, based on (1) estimates of power in the solar spectrum from the SOLAR2000 model (Tobiska et al., 2000); (2) estimates of auroral zone particle power based on observations from the Defense Meteorological Satellite Program (DMSP) and NOAA TIROS and Polar-Orbiting Operational Environmental Satellites (POES); and (3) a combination of the Polar Cap (PC) index (Troshichev et al., 1988) and the Dst index used to parameterize estimates of Joule power. As stated by the authors, the indirect estimates of Joule heat are probably conservative. However Figure 1.1 shows that Joule heat entering the ionosphere is the dominant form of energy input, far exceeding the energy attributed to auroral particle precipitation. The ratio of Joule heat to auroral precipitation power ranges from a factor of 2 on average, to greater than an order of magnitude during large magnetic storms.

From equation (1.2), Joule heat due to dissipation of electromagnetic energy is

$$Q = j \cdot E. \quad (1.4)$$

This is equivalent to

$$Q = \sigma E^2, \quad (1.5)$$

where σ is the conductivity (Banks et al., 1981). Radar measurements of the ion convection determine E . Combining E with models of the conductivity, Q , can be calculated. A comparison of the electromagnetic to particle power shows a ratio ranging from 1 (Brekke, 1976; Banks, 1977) to 4 (Ahn et al., 1983b). In these studies, there is a focus on the auroral zone due to the location of radar observatories, which determine not only E but, to a large extent, σ as well (Ahn et al., 1983a).

A more direct measure of incoming EM power is to calculate the Poynting flux entering the ionosphere, which obviates the need to use a model for conductivity. This was done by Huang and Burke (2004) for a superstorm during which four DMSP spacecraft measured large FACs simultaneous with intense electric fields. It should

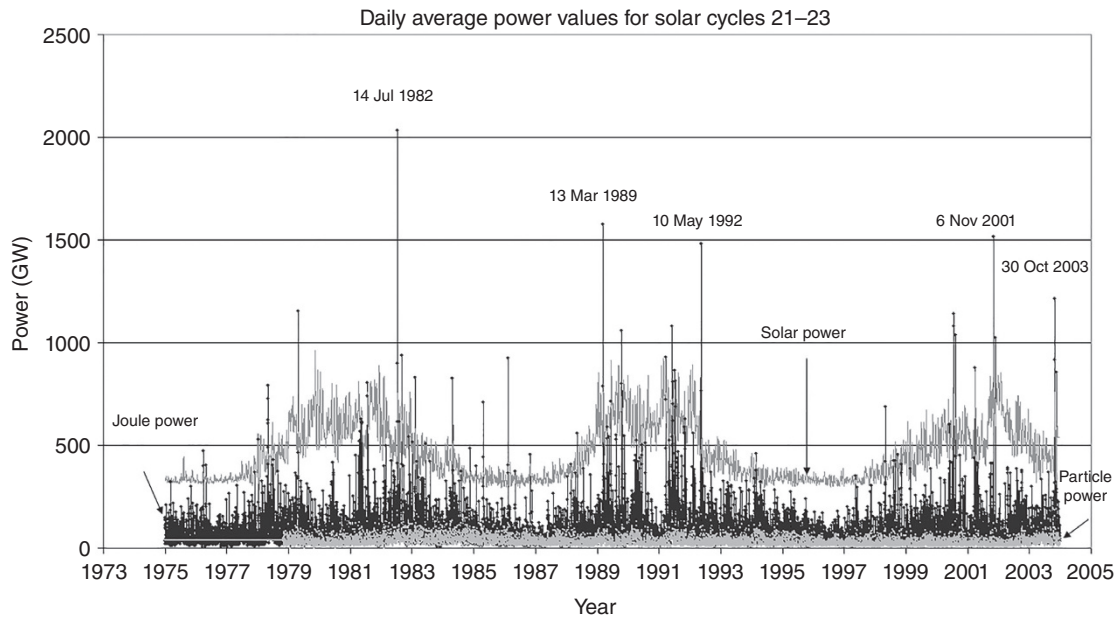


Figure 1.1 Solar power, particle power, and Joule power from 1975–2003 (reproduced from Fig. 4, Knipp et al., 2004. Reproduced with permission of Springer Nature).

be noted that the calculation of Poynting flux from DMSP usually uses only the two components of horizontal velocity perpendicular to the ram direction. There is uncertainty in the measured ram velocity and this component is omitted. The estimated EM power over a 20-minute interval measured by DMSP was approximately 500 GW, comparable with the solar power over the dayside hemisphere shown in Figure 1.1. A second point in our discussion is that while all four DMSP spacecraft crossing the current sheet measured magnetometer deflections of greater than 1,200 nT magnetometers, at conjugate locations on the ground magnetometers measured deflections of the order of a few tens of nT. This point will be discussed in more detail below. It is widely accepted that Poynting flux dominates the total energy input in the IT system during periods of magnetic activity. This was confirmed in a detailed study of the energy budget for a magnetic storm on 5–6 August 2011 (Huang et al., 2014). While particle energy may not be dominant in considerations of total energy deposition, it plays a leading role in energy dissipation via conductivity as shown in equation (1.5).

Ionospheric conductivities are described by Maeda (1977) and in the World Data Center A (Kyoto) website (<http://wdc.kugi.kyoto-u.ac.jp/ionocond/exp/icexp.html>). A number of models of conductivity and conductance have been derived based on particle precipitation (Fuller-Rowell & Evans, 1987; Wallis & Budzinski, 1981; Spiro et al., 1982; Roble & Ridley, 1987; Hardy et al., 1987; Robinson et al., 1987; Gjerloev & Hoffman,

2000; McGranaghan et al., 2016, & others). Models have also been developed, which are based on UV observations (e.g., Lummerzheim et al., 1991; Coumans et al., 2004), and which account for proton precipitation (Galand & Richmond, 2001; Coumans et al., 2004). The complexity of the conductivity resulting from particle precipitation has been emphasized by McGranaghan et al. (2016), who point out that three-dimensional spatial variations in even the average precipitation patterns are normal. When temporal variability is added, the task of capturing conductivity accurately becomes even more challenging.

1.2.2. The Weimer Model

A series of papers by Weimer (1995; 2005) provided an empirical model of EM energy input to the IT system, based on observations of electric and magnetic fields by Dynamics Explorer 2 (DE2). The model represents the high-latitude ($|\lambda| > 45^\circ$ MLat) electric potentials as spherical harmonics, which were correlated with measured interplanetary magnetic field (IMF) (Weimer 1995). Examples of the electric potentials in the Northern Hemisphere, shown in Figure 1.2, are generated for solar wind and IMF input by the Weimer (2005) model, hereafter abbreviated as W05. Empirical maps of the FACs were also developed, using scalar magnetic Euler potentials (Weimer, 2001). Figure 1.3 illustrates the magnetic Euler potentials for the same solar wind and IMF as in Figure 1.2. A combination of the electric potentials with the FACs from the Euler potentials yields Poynting flux.

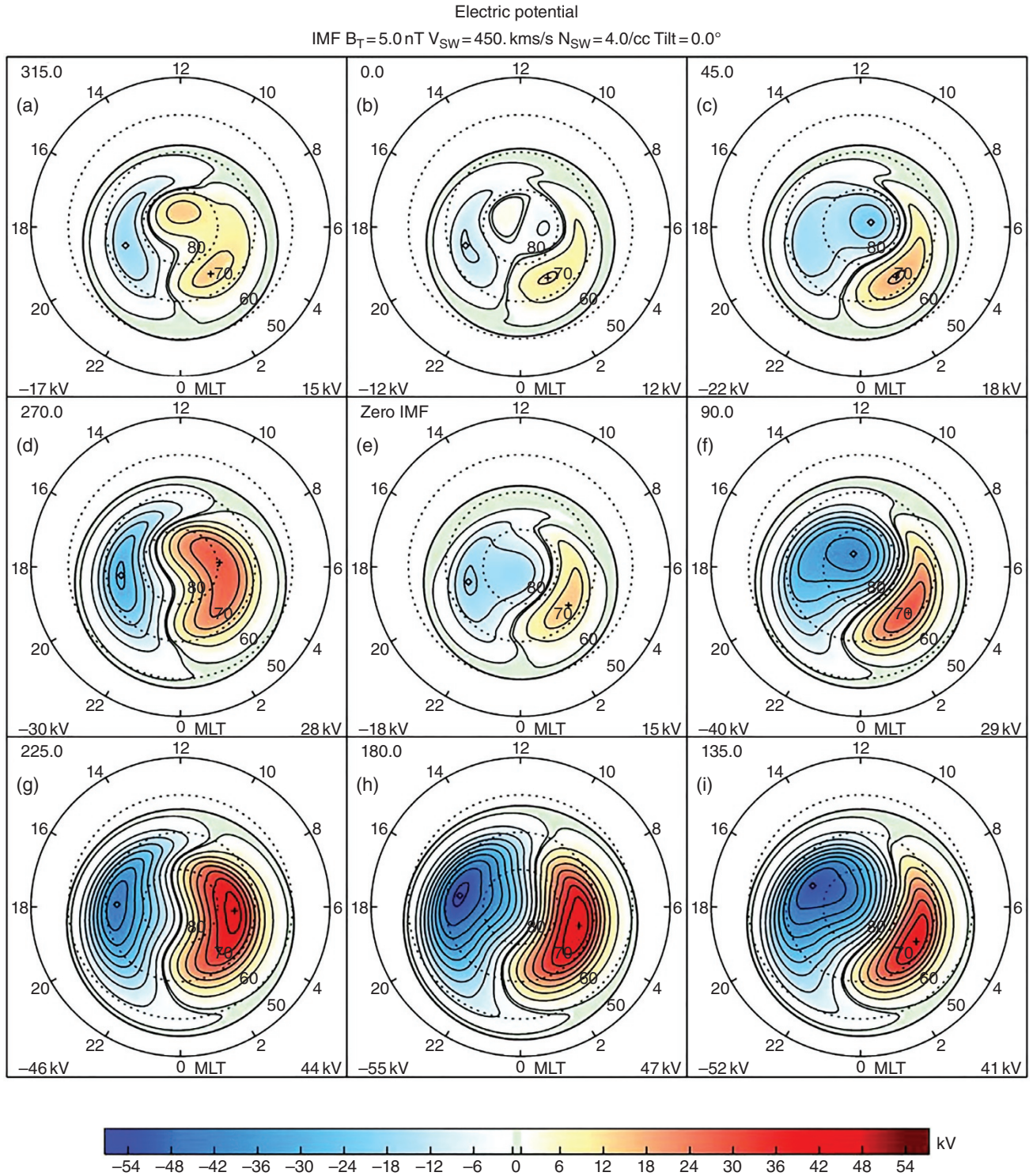


Figure 1.2 (a)–(i) Polar cap electric potentials in the Northern Hemisphere, mapped as a function of AACGM latitude and MLT. Figures (a)–(d) and (f)–(i) show the patterns for eight different clock angle orientations of the IMF vector in the GSM Y-Z plane; the angle in degrees is indicated in the top left corner of each map. The IMF has a fixed magnitude of 5 nT, the solar wind velocity is 450 km s⁻¹, the solar wind number density is 4 cm⁻³, and the dipole tilt angle is 0°. Figure (e) shows the potential for zero IMF, with the same solar wind conditions. Minimum and maximum potential values are printed in the bottom left and right corners of each map, with locations indicated by the diamonds and pluses. (reproduced from Fig. 2, Weimer et al., 2005. Reproduced with permission of John Wiley & Sons).

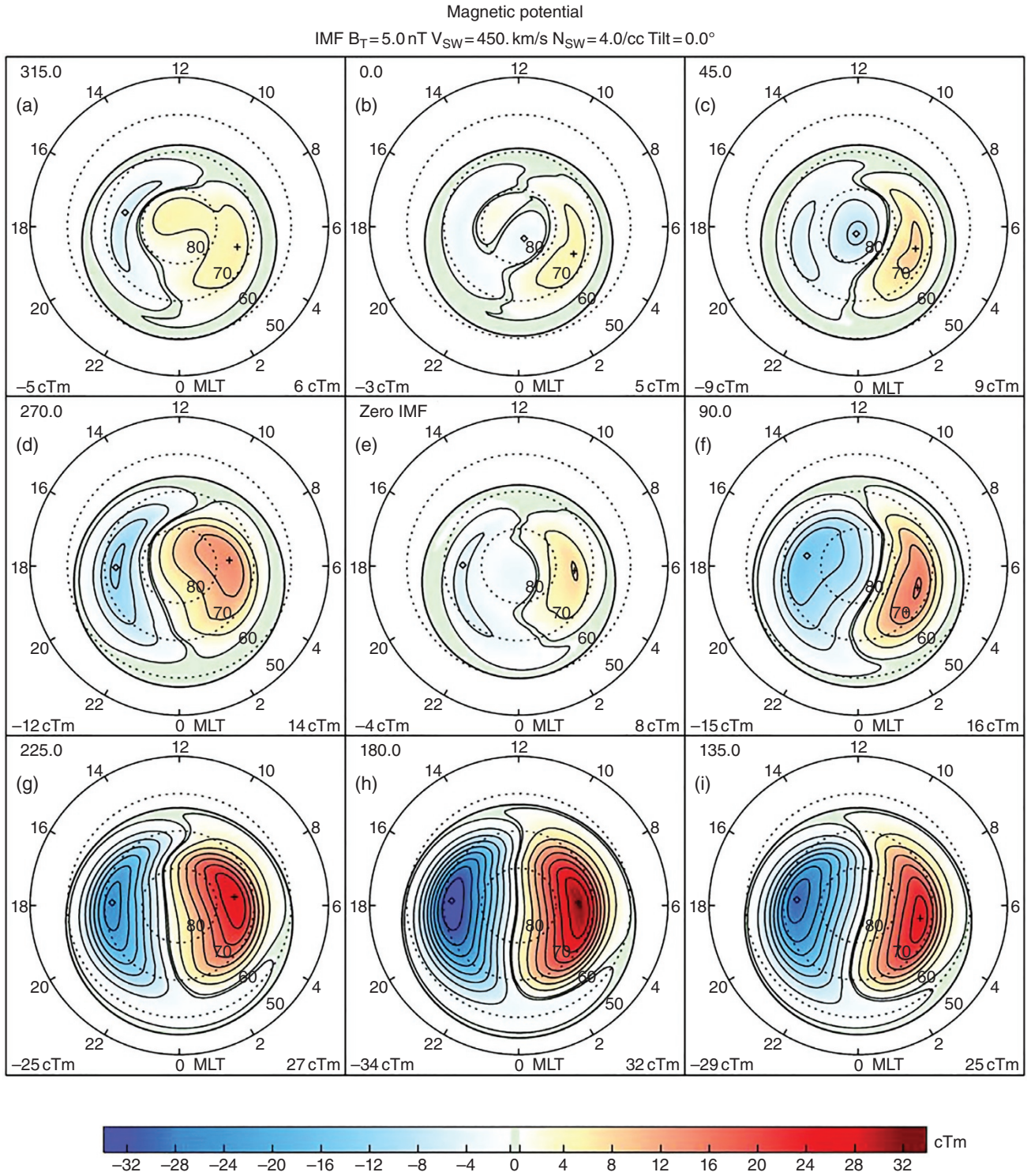


Figure 1.3 (a)–(i) Magnetic Euler potentials in the Northern Hemisphere, mapped as a function of AACGM latitude and MLT. The format and the IMF/solar wind parameters are the same as in Figure 1.2 (reproduced from Fig. 3, Weimer et al., 2005. Reproduced with permission of John Wiley & Sons).

In steady state, the Poynting flux into the ionosphere is approximately equal to the energy dissipated by Joule heating. This assumes that energy, which is used to generate neutral winds, is negligible, an assumption which may not always be true (Thayer & Semeter, 2004). One of the advantages of this model is that Joule heat can be estimated directly without the need for an estimate of conductivity.

As in any empirical model, the results are obtained by averaging over observations. In the case of the Weimer model, the observations are obtained from the approximately 18-month lifetime of the DE2 mission. Despite the sparseness of the original data set, the model has been highly successful in providing high-latitude electric fields

required to model the IT response to magnetospheric energy input. While W05 can be used to specify the Joule heat as a standalone model, the major application of the code is in providing the high-latitude electric field required by the General Circulation Models (GCMs), which will be discussed below.

The main drawback to W05 is the lack of dynamical behavior inherent during periods of magnetic activity. Empirical models cannot capture the highly fluctuating magnetospheric energy input during storms. This is evident in a comparison of Poynting flux measured along the DMSP orbit with predicted values from the model, as shown in Figure 1.4, reproduced from Figure 10 of Huang et al. (2017a). On the left are shown the estimated

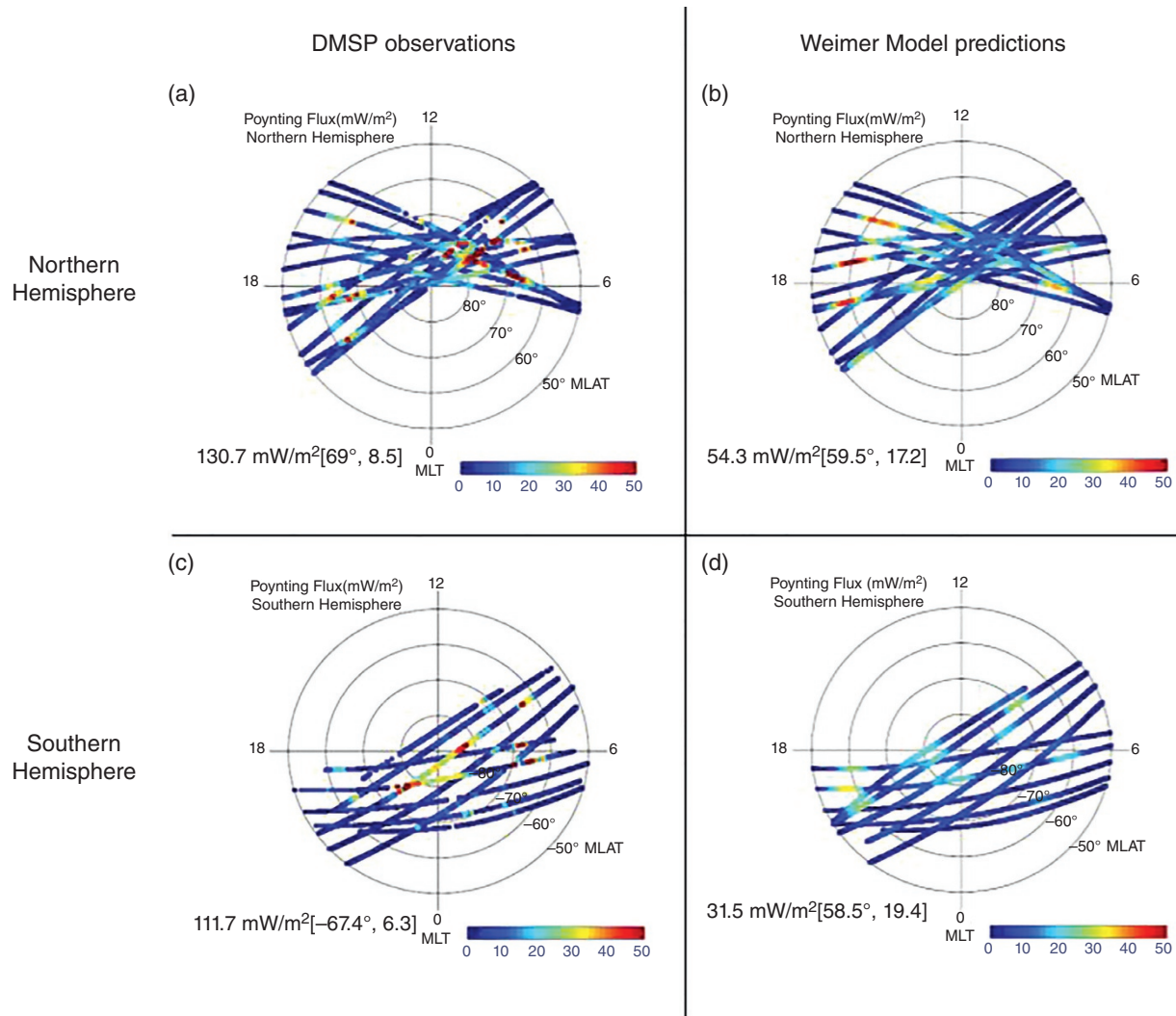


Figure 1.4 Comparison between observed Poynting flux from DMSP (a)–(c) with the W05 model predictions along the DMSP orbit (b)–(d) for the 5 August 2011 storm. Northern Hemisphere values are shown in (a) and (b); Southern Hemisphere results are shown in (c)–(d) (figure reproduced from Fig. 10 by Huang et al., 2017a. Reproduced with permission of Elsevier).

values of Poynting flux from the DMSP measurements of cross-track horizontal velocity and FACs during a magnetic storm, which occurred on 5–6 August 2011. The Northern Hemisphere (NH) is shown above, the Southern Hemisphere (SH) below. Measured values along the orbit track are shown as overplots with the highest value plotted last. On the right are the model predictions of W05 along the same orbital tracks as DMSP plotted in the same way. The highest value of Poynting flux in each panel is indicated at the bottom left of the panel, together with the magnetic latitude (MLat) and magnetic local time (MLT) of the location where that value of Poynting flux occurred.

The discrepancies in the values and spatial distribution of Poynting flux between observations and W05 in this case are clear. The model captures the average distribution and magnitude of EM energy entering the ionosphere, but dynamic variations, which characterize the storm, are missed. In different events, the discrepancies can be similar or different. This is not intended as a criticism of the model, merely to point out the limited ability of empirical models to represent dynamic processes such as magnetic storms.

1.2.3. The Cosgrove Model

A newer empirical model of EM input has been developed by Cosgrove et al. (2014) (hereafter referred to as Cosgrove14) based on data from the FAST satellite. At the outset, the paper states that one goal of the model is to provide the high-latitude electric field driver for GCMs. A major difference between the Weimer and Cosgrove models lies in the way Poynting flux is calculated. In W05, the EM energy is estimated from the average electric field $\langle E \rangle$ and the average magnetic perturbation $\langle \delta B \rangle$ as $S = \langle E \rangle \times \langle \delta B \rangle / \mu_0$. In Cosgrove14, the vector product, $S = E \times \delta B / \mu_0$, is calculated before any averaging or functional fits are applied. In this way, perturbations in the measured E and B are captured more accurately. As pointed out in past studies, variability in the electric field can contribute to the total Joule heat (Codrescu et al. 1995; Cosgrove & Codrescu, 2009). In the standard formulation employed in W05, Joule heat is computed as the mean of $\langle E^2 \rangle$. However, if there is a high level of fluctuation about the mean of E (i.e., if $\langle |E - \langle E \rangle|^2 \rangle$ is large), then the contribution to Joule heat from the variability is missing if it is assumed that $\langle |E| \rangle$ represents the total electric field. Codrescu et al. (2000) used radar measurements to calculate the $\langle |E - \langle E \rangle|^2 \rangle$ term, and found that the variability was comparable with the mean value of E . In Cosgrove14, the direct estimate of Joule heat from the measured E attempts to avoid this problem.

Possibly as the result of the methodology, or because the data from which this model is derived is more

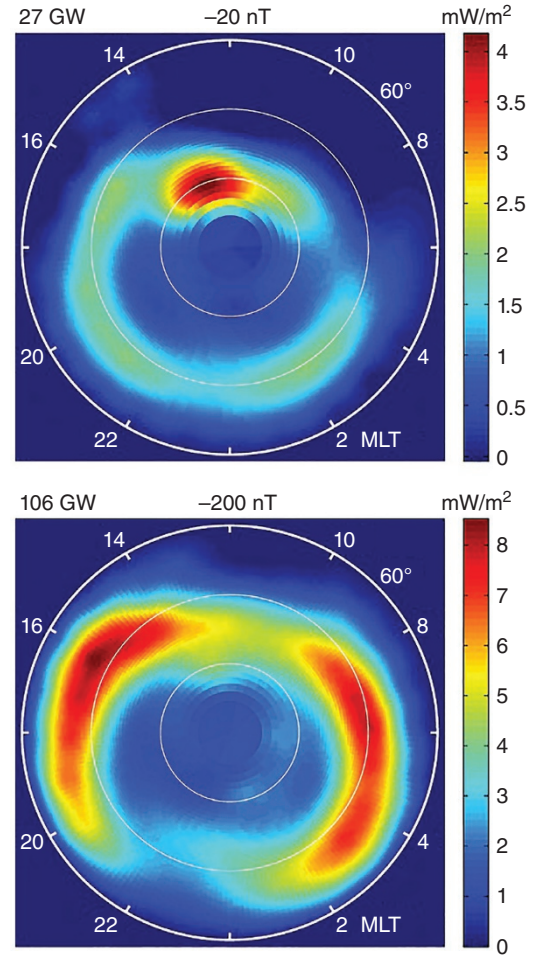


Figure 1.5 Cosgrove14 output for high and low magnetic activity for northward IMF. The upper and lower panels have different color bars to prevent saturation. The AL index is shown at center above each panel. The integrated Poynting flux is shown at left above each panel. The Poynting flux for high magnetic activity is similar to that for southward IMF, regardless of actual IMF. IMF clock angle is 0° , magnetic dipole tilt angle is 0° , solar wind velocity is 450 km s^{-1} , solar wind number density is 4 cm^{-3} , and IMF strength in the GSM y - z plane is 5 nT (figure and caption reproduced from Cosgrove et al., 2014. Reproduced with permission of John Wiley & Sons).

comprehensive, the model predictions of Poynting flux in the cusp is significantly larger than that forecast by W05. Figure 1.5 (reproduced from Figure 5 in Cosgrove et al., 2014) illustrates the cusp feature for northward IMF, for high (top) and low (bottom) magnetic activity. In this model, the pattern of Poynting flux for high magnetic activity is generally similar to the upper panel of Figure 1.5, regardless of IMF orientation.

However the basis of Cosgrove14 is a representation of the high-latitude Poynting flux by spherical harmonical

fits to averages of the measurements. This arrives at the same problem with W05, namely that the model predictions cannot reproduce the highly variable energy input into the IT system characteristic of high magnetic activity. As stated in the paper (Cosgrove et al., 2014), “averaging over a large number of events, as is done to produce this model, will result in significant smearing. Because of this, the model output is not representative of an instant of time, but rather reflects an expected value for each UT, MLT, MLAT, and set of geophysical parameter values.” The Cosgrove14 model, which is relatively new, has yet to undergo the testing and validation that occurred with W05 and previous version of the Weimer models.

1.2.4. Assimilative Modeling of Ionospheric Electrodynamics (AMIE)

This model relies on inversion of observations, initially of perturbations in the magnetic field measured by ground magnetometers (Richmond & Kamide, 1988, and references therein; Richmond, 1992), to infer the electrodynamic state of the ionosphere. In addition to currents measured at the ground, the model was expanded to include measurements of electric fields by radar and satellite, and magnetic perturbations from satellite. However, given the wide distribution of ground magnetometer sites and the relative sparsity of other forms of data AMIE ingests, the model is mostly driven by ground-based magnetic field perturbations.

For a full description of the methodology used in the model, the reader is referred to the paper by Richmond and Kamide (1988). Briefly, the model uses as basis functions, the electrostatic potential, Φ , the electric field, E , the field-aligned current density, J_P , the height-integrated horizontal ionospheric electric current density, I , and magnetic perturbations δB . The basis functions for the potential, φ , are assumed to be complete, while the other basis functions, E , I , J_P , can be derived from φ , assuming knowledge of the conductance tensor, Σ . Using Gauss-Markoff optimization of the linear expansion of the basis terms in magnetic latitude and longitude, the model derives the best fit of the coefficients in the expansion to the observations, which are assimilated.

In general, the model has been successful in reproducing electrodynamics in the high-latitude ionosphere (Lu et al., 1995; Ridley et al., 1997, and many others). As in the case of the W05 and Cosgrove14 models, AMIE has been used widely as input to the GCMs. Unlike the empirical models, AMIE captures near-real-time variations in high-latitude electrodynamics, with some smoothing in the assimilation scheme. Temporal and spatial resolution depend on the data to be assimilated.

However, there are two caveats. The assumption that the currents in the ionosphere can be represented by

equivalent currents on the ground needs to be applied with caution. The assumption is valid in the case of Hall currents, which are detected by ground magnetometers. Comparisons of satellite-based measurements from CHAMP and ground detections of currents from the IMAGE network have validated the equivalent current assumption (Ritter et al., 2004). However, ground-detection of Pedersen current is inhibited by the shielding effect of FACs (Araki et al., 1989). As a result, correlation of ground- and space-based observations of Pedersen currents is poor (Ritter et al., 2004). In practice, AMIE uses an empirical model to relate the measured Hall current to Pedersen current (Ahn et al., 1983a). But the empirical models are frequently based on observations limited to the auroral regions. Application of the results to subauroral or polar latitudes is questionable.

The only region at high latitudes in which Hall current dominates is the auroral zone in which energetic particle precipitation is the norm (Newell et al., 2005, and references therein). At latitudes poleward and equatorward of the auroral zone, or Boundary Plasma Sheet as described by Newell et al. (1991), which are characterized by soft electron precipitation, the use of empirical models to estimate Pedersen conductivity may distort the true picture. The lack of ground signature of ionospheric electrodynamics was illustrated in a study of a superstorm on 6 April 2000 by Huang and Burke (2004). During the storm, four DMSP spacecraft detected intense FACs, with ΔB between 1,000 and 1,400 nT at 840 km altitude, at latitudes equatorward of 60° MLat. At the conjugate location on the ground, the maximum magnetic perturbation was under 50 nT.

The second cautionary note on application of AMIE is related to the first, and derives from the conductance that is required for the synthesis of observations. The standard model referenced for use with AMIE is by Ahn et al. (1983a). The estimate of conductivity in this model assumes energetic electron precipitation leading to Hall current at altitudes between 100 and 125 km. Pedersen conductivity is estimated from Hall conductivity as a ratio derived empirically. Robinson et al. (1987) give a similar relationship. However, these empirical ratios are derived for auroral precipitation in which electron energies are generally assumed to be ≥ 1 keV. Huang and Burke (2004) estimated the Pedersen conductance using measured magnetic deflections and precipitating electron fluxes from DMSP F13 and F15 satellites for the superstorm on 6 April 2000. The relation between conductance, magnetic field, and electric field is simply Ohm's law, $J = \Sigma \times E$, where J and E are the height-integrated current density and electric field, respectively. Figure 1.6 compares the values obtained from the DMSP data with the Robinson et al. (1987) formulas for Pedersen and Hall conductances. The horizontal bars indicate the time

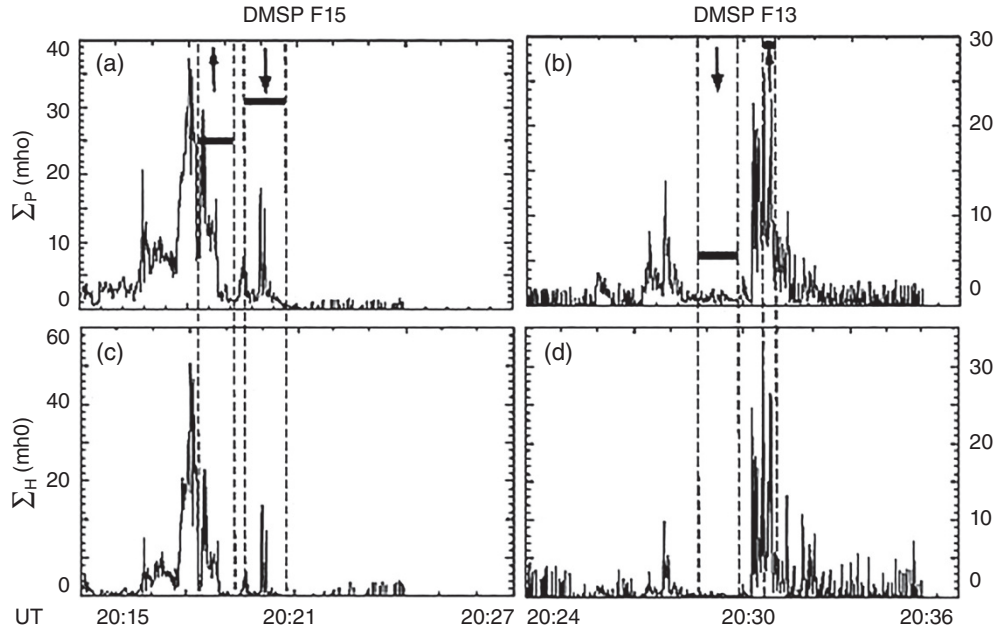


Figure 1.6 (a)–(b) Values of Pedersen (Σ_P) and (c)–(d) Hall (Σ_H) conductance estimated from energetic electron fluxes measured by (a) and (c) DMSP F15 and (b) and (d) F13 using the formula by Robinson et al. (1987) during a superstorm on 6 April 2000. F15 is located at -52° MLat, 221 MLT. F13 is located at 59.9° MLat, 6.7 MLT. Heavy horizontal lines indicate values of Σ_P estimated from measured δB_z and E_y variations (figure and caption based on Huang & Burke, 2004. Reproduced with permission of John Wiley & Sons).

intervals when Pedersen conductance can be estimated directly. It is clear that the empirical results (Ahn et al., 1983a; Robinson et al., 1987) do not represent the conductance well in regions where keV electrons are not dominant.

Given our understanding that EM energy dominates the energy budget, the assumptions underlying the model should be examined for relevance. In particular, the role of the auroral zone as the locus of all energy input has been questioned (Huang et al., 2014) based on the total energy budget during a magnetic storm. This may be addressed by AMIENextGen, an updated version of AMIE, which is being developed (Matsuo et al., 2015; Cousins et al., 2015; McGranaghan et al., 2016). In AMIENextGen, many of the data sources are based on satellite observations, which may avoid some of the difficulties with AMIE.

1.3. GENERAL CIRCULATION MODELS (GCMs) OF MIT COUPLING

The GCMs represented a significant advance in physics-based MIT modeling, capturing the essential physics in the IT system. They include the chemical reactions dominant at low altitudes, and the coupled equations of momentum, energy, and continuity for ion, electrons,

and neutrals (Rees et al., 1980; Fuller-Rowell et al., 1988, 2000; Dickinson et al., 1981, 1984; Roble et al., 1987; Ridley et al., 2006). They have been used to simulate the ionospheric response to energy deposition and dissipation at high latitudes in many publications. We focus on three of the most widely used models: the Thermosphere Ionosphere Electrodynamics Global Circulation Model (TIEGCM), the Coupled Thermosphere Ionosphere Plasmasphere Electrodynamics (CTIPE) model, and the Global Ionosphere-Thermosphere Model (GITM), all of which have been run for many years. Model runs on demand of all three are available at the Community Coordinated Modeling Center (CCMC) (<http://ccmc.gsfc.nasa.gov/>).

All three require specification of the high-latitude electric field or high-latitude Poynting flux and conductivity in order to simulate the effect of energy deposition and dissipation. The electric field or Poynting flux can be specified by W05, Cosgrove14, or AMIE as described in section 1.2. The conductivity can be obtained from empirical models by Roble and Ridley (1987) or Fuller-Rowell and Evans (1987).

The CTIPE model is a nonlinear, coupled thermosphere-ionosphere-plasmasphere physics-based code that includes a self-consistent electrodynamics scheme for the computation of dynamo electric fields. There are four distinct components that run simultaneously and

are coupled: a global thermosphere, a high-latitude ionosphere, a mid-and low-latitude ionosphere/plasmasphere, and an electrodynamic calculation of the global dynamo electric field (Fuller-Rowell & Rees, 1980; Codrescu et al., 2012). The thermospheric component is divided into a geographic latitude x longitude grid with resolution $2^\circ \times 18^\circ$. The vertical resolution is defined in terms of the logarithm of pressure from a lower boundary at 80 km altitude to altitudes above 500 km. The primary inputs to the model are the high-latitude electric field, usually provided by the Weimer (2005) empirical model, auroral electron precipitation from the empirical model by Fuller-Rowell and Evans (1987), and EUV radiation (Solomon & Qian, 2005). Full descriptions of the model with examples of output can be found in Codrescu et al. (2012). CTIpe is run in near-real time at the Space Weather Prediction Center (SWPC), and model output is available for comparison with observations at <http://helios.swpc.noaa.gov/ctipe/index.html>.

TIEGCM provides a three-dimensional, nonlinear representation of the coupled IT system. A self-consistent calculation of ionospheric wind dynamic effects (Richmond et al., 1992) is included. The primary external drivers of the model are solar irradiance, magnetospheric energy, and tidal perturbations at the lower boundary of the model. Magnetospheric energy inputs include particle precipitation and high-latitude electric fields, which drive convection. The current version of TIEGCM (v2) uses a fixed grid with spatial resolution of $2.5^\circ \times 2.5^\circ \times$ half scale height spatial resolution (longitude x latitude x altitude) with 30 second temporal resolution. As with CTIpe, the vertical extent of the model is defined by pressure with typical range of 97 km to 500 km. The model can be downloaded directly from the NCAR website at <http://www.hao.ucar.edu/modeling/tgcm/>.

GITM is the most recent of the widely used GCMs. It differs from CTIpe and TIEGCM as follows: (1) spatial resolution is flexible; (2) the assumption of hydrostatic equilibrium is dropped allowing for vertical acceleration; (3) the adoption of an altitude grid instead of scaling by pressure; (4) advection is solved explicitly; (5) chemistry is solved explicitly without the assumption of chemical equilibrium. As a result, the time step in GITM is 2–4 s. The model uses the same magnetospheric drivers as CTIpe and TIEGCM, viz. high-latitude electric fields and energetic particle precipitation.

As described in section 1.2 (energy entering the IT system), the primary coupling to magnetospheric energy input is via the empirical models of the high-latitude electric field provided by the W05 or Cosgrove14 models, or an inversion of assimilated high-latitude data from the AMIE model. More rarely, MHD models such as the Block-Adaptive-Tree-Solarwind-Roe-Upwind-Scheme (BATS-R-US) (Powell et al., 1999), Open Geospace

General Circulation Model (OpenGGCM) (Raeder et al., 1998), or Lyon-Fedder-Mobarry (LFM) model (Lyon et al., 2004) can be coupled directly to the IT models (CTIpe, TIEGCM, GITM, or others), which removes the need for separate high-latitude electric field specification.

1.4. MODEL ASSESSMENT

Rastaetter et al. (2016) carried out a comprehensive comparison of a number of empirical and physics-based models for 6 events selected for the GEM-CEDAR modeling challenges. The goal of the challenge was specification of Poynting flux. DMSP F15 observations were provided for validation purposes. The models used in the comparison included:

1. Space Weather Modeling Framework (SWMF) (Toth et al., 2005, 2012), which couples BATS-R-US to the Rice Convection Model (Wolf et al., 1982; Toffoletto et al., 2003), which, in turn, is coupled to the Ridley Ionosphere model (Ridley et al., 2004);
2. OpenGGCM coupled to the Coupled Thermosphere Ionosphere Model (CTIM) (Fuller-Rowell et al., 1996), an earlier version of CTIpe (Two versions of OpenGGCM with different resolution were part of the study);
3. Coupled Magnetosphere Ionosphere Thermosphere (CMIT) model (Wang et al., 2004; Wiltberger et al., 2004), which couples the LFM magnetosphere model to TIEGCM and the MIX ionosphere solver and coupler (Merkin & Lyon, 2010) (CMIT (LGM-TIEGCM-MIX) and LFM-MIX were run as separate models);
4. TIEGCM with W05 providing high-latitude electric fields;
5. CTIpe with W05 for high-latitude electric fields;
6. W05, three versions run with solar wind input provided by different models;
7. Cosgrove14, two versions run with solar wind input provided by different models.

The models were divided into physics-based (models 1–5 of the list above), or empirical (models 6 and 7 of the list above). Results of the comparison varied for the six selected events, which ranged from a relatively small storm event with the minimum in Dst of -40 nT, to the Halloween storm with $Dst_{\min}$ of -353 nT. Figures 1.7 and 1.8, reproduced from Figures 6 and 11 by Rastaetter et al. (2016), show the model versus data for the Halloween storm (29–30 October 2003) when Dst was -353 nT, and an interval from 9–12 July 2005 when $Dst_{\min}$ was -89 nT, respectively. We use these examples as illustrations of a strongly driven superstorm as the Halloween storm was, and an event of sustained low magnetic activity in July 2005 for contrast. In the figures, physics-based models are at left (panels (a) through (d)), empirical models are at right (panels (e) through (g)). The Poynting flux

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