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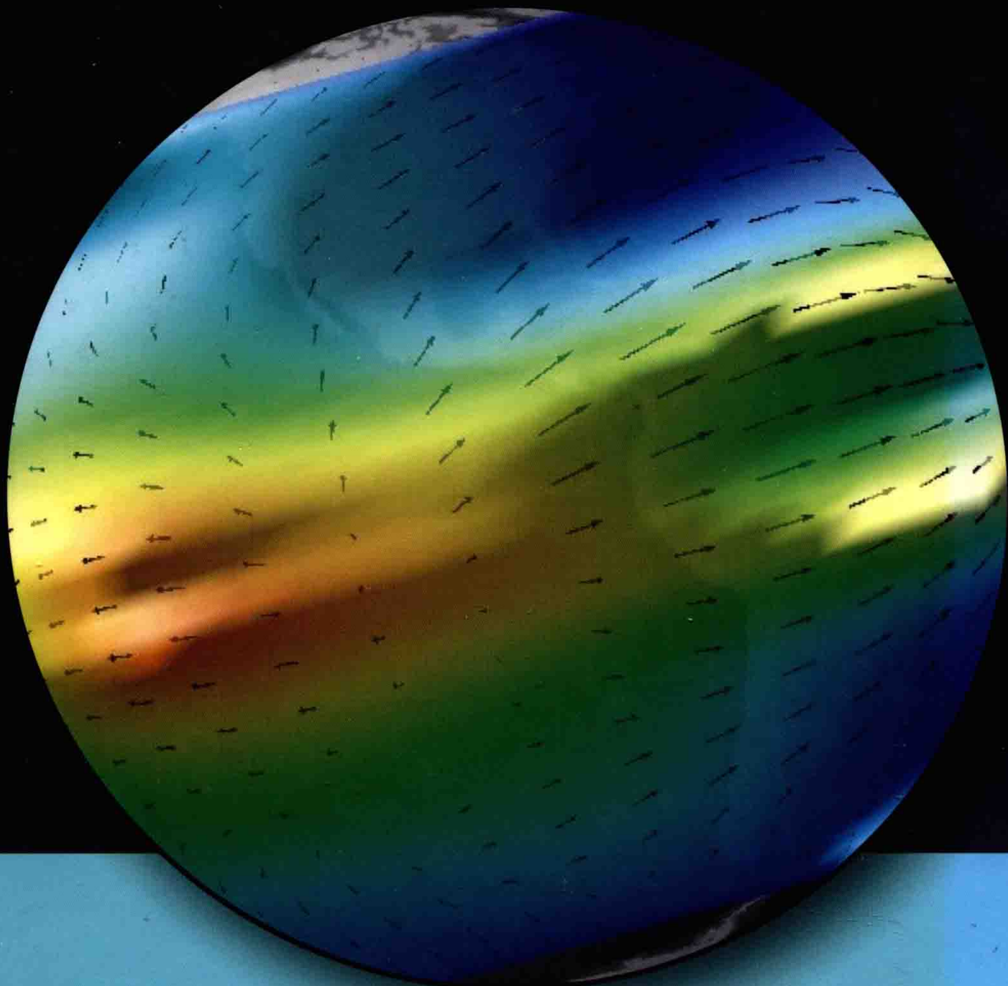
Modeling the Ionosphere-Thermosphere System



J.D. Huba, R.W. Schunk, and G.V. Khazanov
Editors

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Joseph Huba
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PREFACE

The importance of large-scale numerical models to understand the complex dynamics of the ionosphere/thermosphere (IT) system has been recognized for over three decades. Many ionosphere and thermosphere models have been developed, both as separate and coupled models; they have been used to investigate IT dynamics and compare model results to observational data. However, until a few years ago, there have been very few (if any) conference sessions or workshops devoted solely to the development and understanding of computational IT models.

To address this problem, a session on ionosphere/thermosphere modeling was organized by myself, Aaron Ridley, and Bob Schunk at the 2009 NSF CEDAR workshop held in Santa Fe, New Mexico. The session description was as follows:

> The workshop will focus on IT modeling of the low solar activity (solar minimum or quiet) time, low- to mid-latitude ionosphere. It is hoped that a description of each model will be presented, highlighting (1) basic equations actually solved, (2) numerical techniques, (3) strong and weak points (both physics and numerics), i.e., the good, the bad, and the ugly, and (4) simulation results from a specified day. Results from the different studies can be compared and an ensemble average could be presented and compared to data. Finally, issues that need to be resolved to improve models could be addressed.

The session was extremely successful (i.e., well attended with ample discussion; perhaps, in part, because of a favorable time slot early in the week). Given the enthusiasm for the topic, Bob Schunk suggested we hold a Chapman Conference on IT modeling. I agreed to look into the matter and subsequently submitted a proposal to AGU requesting a Chapman Conference with myself, Bob Schunk, and Aaron Ridley as the conveners. The proposal was accepted, and we held a Chapman Conference on "Modeling the Ionosphere/Thermosphere System" in Charleston, South Carolina, on 9–12 May 2011.

This monograph is an outgrowth of the conference and represents a compilation of different aspects of modeling the IT system. The papers include tutorials on basic ionosphere/thermosphere physics, descriptions of numerical methods and models, and applications to important ionospheric phenomena (e.g., onset and evolution of irregularities) and space weather (e.g., data assimilation). As such, this book serves to provide a basic introduction to IT modeling and to make the IT community aware of the strengths, as well as limitations, of current modeling capabilities and the need for future development.

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CONTENTS

Introduction

The science focus of the monograph is the physics of the coupled ionosphere/thermosphere (IT) system. This system is controlled largely by local ion-neutral processes, but there can be strong forcings from below (e.g., tides, gravity waves, and upper atmosphere winds) and above (e.g., solar EUV, high-latitude heating from precipitating electrons, and region 1 and 2 current systems) that impact its behavior. Thus, it is not an isolated system but can be thought of as a transition layer between the Earth's atmosphere and space; viewed from this vantage point, it is clear that it plays a vital role in forecasting space weather.

Given the complexity of the IT system, large-scale computational models of the ionosphere and thermosphere are required to provide a basic understanding of the key physical processes that govern the system, as well as to provide a quantitative description of its behavior that can be compared to observational data. Such models have been developed and are being used extensively to understand and model the IT system, as well as to aid in the development of space weather operational systems. The objective of the monograph is to provide the IT community with the following: (1) a basic description of IT models including the equations that are solved and the numerical methods and algorithms used, (2) examples of applications to the IT system with comparisons to data, (3) assessment of strengths and weaknesses of the models, (4) test simulations that elucidate those strengths and weaknesses, and (5) identification of future efforts to improve the IT modeling capability.

The monograph is divided into the following sections: (1) Physical Processes and Numerical Methods, (2) Ionosphere/Thermosphere Models, (3) Response From Forcings Below and Above, (4) Ionospheric Irregularities, (5) Data Assimilation Models, (6) Metrics and Validation, and (7) Space Weather and the Future. Each section contains papers that describe the current state of research in these areas, as well as providing insight into future development of models to improve our understanding of the ionosphere/thermosphere system.

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Ionosphere-Thermosphere Physics: Current Status and Problems

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The ionosphere-thermosphere (I-T) system is a highly dynamic, nonlinear, and complex medium that varies with altitude, latitude, longitude, time, season, solar cycle, and geomagnetic activity. Despite its complex nature, significant progress has been made during the last three decades in modeling the global I-T system. The climatology of the system has been clearly established, and the global I-T models have been able to reproduce the major I-T features. However, the global I-T models have been less successful in modeling weather features, and even with regard to climatology, there has been limited quantitative success when comparing global I-T models with measurements. The problem with the global models is that they are usually based on simple mathematical formulations, the model resolutions are coarse, the models contain uncertain parameters, the coupling between the I-T models is incomplete, and there is missing physics in all of the global models. Here the focus is on providing examples of the missing physics and how it affects the ionosphere and/or thermosphere.

1. INTRODUCTION

The ionosphere-thermosphere (I-T) system is a highly dynamic and complex medium that varies significantly, and this variation is particularly strong during geomagnetic storms and substorms. The complex nature of the I-T system results primarily from the fact that it is an open and externally driven system. It is subjected to solar UV/EUV radiation that varies continuously, and it exchanges mass, momentum, and energy with the lower atmosphere and magnetosphere. At high-latitudes, plasma convection, particle precipitation, and Joule heating are the main sources of momentum and energy for the I-T system, and all of the global I-T models include these processes. However, if these drivers are not properly/rigorously described, then the I-T model simulations can display significant errors. Despite this problem, the physics underlying the I-T climatology has been clearly established, and the global I-T models have been able to reproduce the major I-T features. However, the I-T models have been less successful in modeling weather features, especially when attempting long-term forecasts.

In addition to the need to properly describe the drivers of the I-T system, there are other problems connected with the global I-T models that need to be addressed if more reliable specifications and forecasts are desired. Some of the problems are that the coupled global models are usually based on relatively simple mathematical formulations, the spatial and temporal resolutions are coarse, many of the parameters in the models are uncertain, the coupling between the models is incomplete, and there is missing physics in all of the global models.

If the ionosphere simulated by a global I-T model is not correct, then the resulting thermosphere will be wrong and vice versa. This problem can be illustrated with the aid of the National Center for Atmospheric Research (NCAR) thermosphere-ionosphere nested grid (TING) model and the USU GAIM-GM data assimilation model [*Jee et al.*, 2007, 2008]. The NCAR TING model was run in its "standard" coupled mode for the period 1–4 April 2004, which contained both quiet and disturbed periods. The Utah State University Global Assimilation of Ionospheric Measurements - Gauss Markov (USU GAIM-GM) data assimilation model was run

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for the same period using slant TEC from ground receivers, bottomside N_e profiles from ionosondes, and in situ N_e densities along DMSP satellite orbits. As expected, the TING and GAIM-GM ionospheres were significantly different, particularly during disturbed times. Since the GAIM-GM model results were consistent with the available measurements, its reconstructed ionosphere is expected to be more realistic than that obtained from the coupled I-T TING ionosphere. To get a feel for what a different, and more realistic, ionosphere would do to the TING thermosphere, the TING model was rerun with the GAIM-GM ionosphere supplied to it at each TING time step in order to see the effect on the thermosphere of using a different ionosphere. There were large neutral wind, temperature, and composition differences when the GAIM-GM ionosphere was used in place of the self-consistent TING ionosphere, with T_n increases as large as 40% (409 K).

In the GAIM-TING study described above, the main problem with the "standard" TING simulation was probably related to the use of empirical plasma convection and particle convection models for the high-latitude drivers. Empirical models are not capable of describing high-latitude weather features, and the uncertainty in the high-latitude drivers can produce the largest errors in global I-T simulations, particularly during geomagnetic storms.

In addition, concerted efforts have been made to compare global, physics-based I-T models. In the Equatorial PRIMO (Problems Related to Ionospheric Models and Observations) study [*Fang et al.*, 2013], 12 models were compared for the same geophysical conditions in order to see how well the models reproduced the equatorial ionization anomaly (EIA). N_mF_2 versus latitude was compared at selected times. Typically, the spread in model results was more than a factor of 2 and was as large as a factor of 5. In general, the performance of the coupled models was worse than the stand-alone models; the coupled models had difficulty in describing the latitudinal variation of the EIA. There was also a coupling energetics and dynamics of atmospheric regions challenge for a systematic quantitative comparison of physics-based I-T models with observations; eight global models were evaluated. Nine events (two strong and four moderate storms, three quiet periods), three parameters (N_mF_2, h_mF_2, vertical drifts), and all latitudes were considered [*Shim et al.*, 2011]. As expected, no model ranked the best when all events, parameters, and latitudes were taken together. The physics-based I-T models frequently displayed significant differences from each other and from the data.

As noted above, there are many reasons why the global physics-based I-T models have problems. Here the focus will be on "some" of the physics that is missing in the global physics-based models, and therefore, this study is by no means complete. Other issues, such as instabilities, turbulence, uncertain parameters, numerical techniques, etc., will be addressed in other papers in this monograph. Ten topics relevant to missing physics have been selected as examples. Some of the topics are primarily important in local regions and, therefore, are relevant to local weather, whereas others are important for global I-T weather simulations. Subsections 2.6, 2.7, and 2.8 provide examples of the problems that arise when relatively simple mathematical formulations are used in global modeling.

2. MISSING PHYSICS IN GLOBAL PHYSICS-BASED IONOSPHERE-THERMOSPHERE MODELS

In what follows, some of the physical processes that are not included in most of the global physics-based I-T models will be highlighted. The physics may not be included in the I-T models for several reasons: there are insufficient data to warrant its inclusion, it is only applicable in a local geographical domain, the global model resolution is too coarse to incorporate the physics, it is too difficult to include it, an entirely new I-T model needs to be developed to include the physics, etc. With this in mind, it should be noted that a major advance in I-T modeling has been made during the last three decades, and the next major advance will come when the missing physics is included in the global physics-based I-T models.

2.1. Polar Wind and Auroral Ion Outflow

Figure 1 shows processes that affect the polar wind and auroral ion outflow at high latitudes. Most of these processes have been included in recent ionosphere-polar wind simulations [*Barakat and Schunk*, 2006], but the continual loss of plasma due to the polar wind and energetic ion outflow is not taken into account in the global I-T models. Typically, the upper boundary condition adapted in these global models allows the plasma to flow upward, when the electron and ion temperatures increase, and then downward, when the temperatures decrease, so that there is no net loss of plasma. However, the continual loss of plasma due to the polar wind and auroral ion outflow is significant and should have an appreciable effect on the I-T system. The H^+ outflow varies from about 1 to 5 $\times$ 10^8 cm^{-2} s^{-1}, and the O^+ outflow can be as large as 1–2 $\times$ 10^9 cm^{-2} s^{-1} in the auroral oval and during geomagnetic storms [cf. *Schunk*, 2007]. Unfortunately, the outflow is not uniform; there are propagating and stationary polar wind jets, polar wind tongues that extend across the polar cap, pulsating geomagnetic storms, flickering aurora, auroral arcs, etc. The nonuniform and continuous plasma outflow needs to be taken into account in the global I-T models if more reliable model predictions are desired.

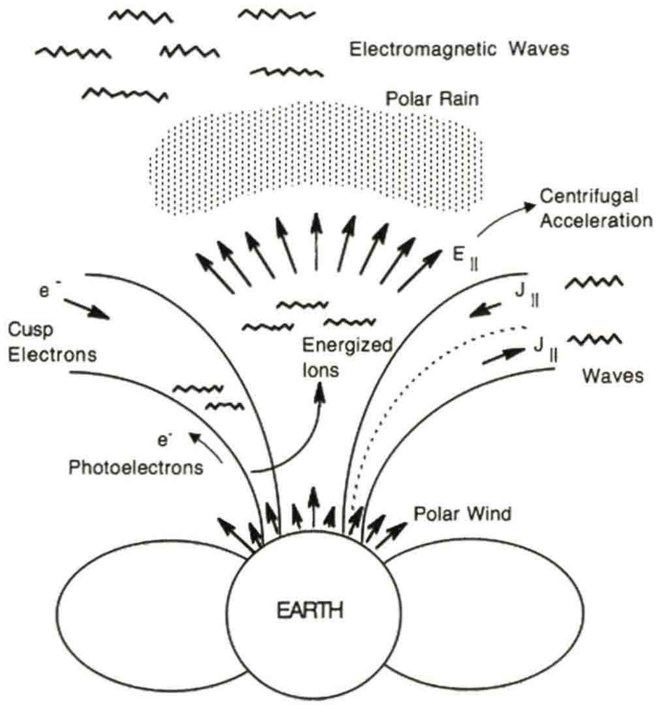

Figure 1. A schematic diagram showing the processes that affect the polar wind and energetic ion outflow from the ionosphere at high latitudes. From *Schunk and Sojka* [1997].

2.2. Downward Electron Heat Flow in the Polar Cap

As the polar wind plasma flows up and out of the topside ionosphere, it also interacts with the overlying polar rain. The energy gained by the polar wind electrons from their interaction with the hot polar rain electrons is subsequently conducted down into the underlying ionosphere, which acts to increase ionospheric electron temperatures [*Schunk et al.*, 1986]. The elevated electron temperatures then affect the ion temperatures and densities. Deductions based on model-measurement comparisons indicate that the downward electron heat flux varies from 0.5 to 1.5×10^{10} eV cm^{-2} s^{-1} over a range of solar cycle, seasonal, and geomagnetic activity conditions [*Bekerat et al.*, 2007]. Recently, time-dependent ionosphere model [*Schunk*, 1988; *Sojka*, 1989] simulations have been conducted of the effect that downward electron heat flows have on the high-latitude ionosphere [*David et al.*, 2011]. Three topside electron heat flux values were adopted in three separate simulations (0.0, 0.5, and 1.5×10^{10} eV cm^{-2} s^{-1}). Relative to the no heat flux case, the largest downward electron heat flow produced N_mF_2 changes of up to a factor of 10 in some regions of the polar cap. This effect is not included in most of current global I-T models.

2.3. Thermoelectric Heat Flow in Return Current Regions

In the ionosphere, the flow of heat is usually described by thermal conduction. In this case, $\mathbf{q} = -\lambda\nabla T$, where $\mathbf{q}$ is the heat flow vector, λ is the thermal conductivity, and T is the temperature. However, an electron heat flow can occur in response to both an electron temperature gradient (thermal conduction) and an electron current (thermoelectric heat flow). Therefore, in auroral return current regions, the electron heat flow along geomagnetic field lines is given by $\mathbf{q} = -\lambda\nabla T - \beta\mathbf{J}$, where β is the thermoelectric coefficient, and $\mathbf{J}$ is the field-aligned ionospheric return current. *Schunk et al.* [1987] studied the effect of ionospheric return currents on auroral electron temperatures for different seasonal, solar cycle, and upper boundary conditions. They found that thermoelectric heat flow is important for current densities greater than 10^{-5} A m^{-2} and that thermoelectric heat flow corresponds to an upward transport of electron energy. The upward transport of energy can result in electron temperatures that decrease with altitude, as shown in Figure 2. It is apparent that thermoelectric heat flow can be significant, but it is not included in the existing global I-T models.

2.4. Ion Temperature Anisotropy

When the convection electric field in the ionosphere is greater than about 50 mV m^{-1}, two processes occur. First, there is a rapid conversion of O^+ into NO^+, with the result that NO^+ becomes an important ion in the F region [*Schunk et al.*, 1975]. This rapid conversion is a consequence of the energy dependence of the $O^+ + N_2$ chemical reaction, and this process is included in all (or nearly all) of the global I-T models. However, in addition to the conversion of O^+ into NO^+, the ion temperature becomes anisotropic with the perpendicular temperature ($T_{i\perp}$) greater than the parallel temperature ($T_{i\parallel}$). Therefore, $T_{i\parallel}$ should be used in the ion momentum equation along the magnetic field, not T_i. Since T_i is greater than $T_{i\parallel}$, the use of T_i in the ion momentum equation results in an overestimation of the plasma density scale height above the F region peak (Figure 3). For a 100 mV m^{-1} electric field, the electron density at 600 km can be more than a factor of 2 too large if T_i is used in the momentum equation instead of $T_{i\parallel}$. This ion temperature anisotropy is probably not taken into account in most of the global I-T models.

2.5. Subauroral Red (SAR) Arcs

SAR arcs correspond to 6300 A emission that is confined to a narrow latitudinal region just equatorward of the auroral oval [cf. *Schunk and Nagy*, 2009]. The emission occurs during elevated magnetic activity and can be seen in both

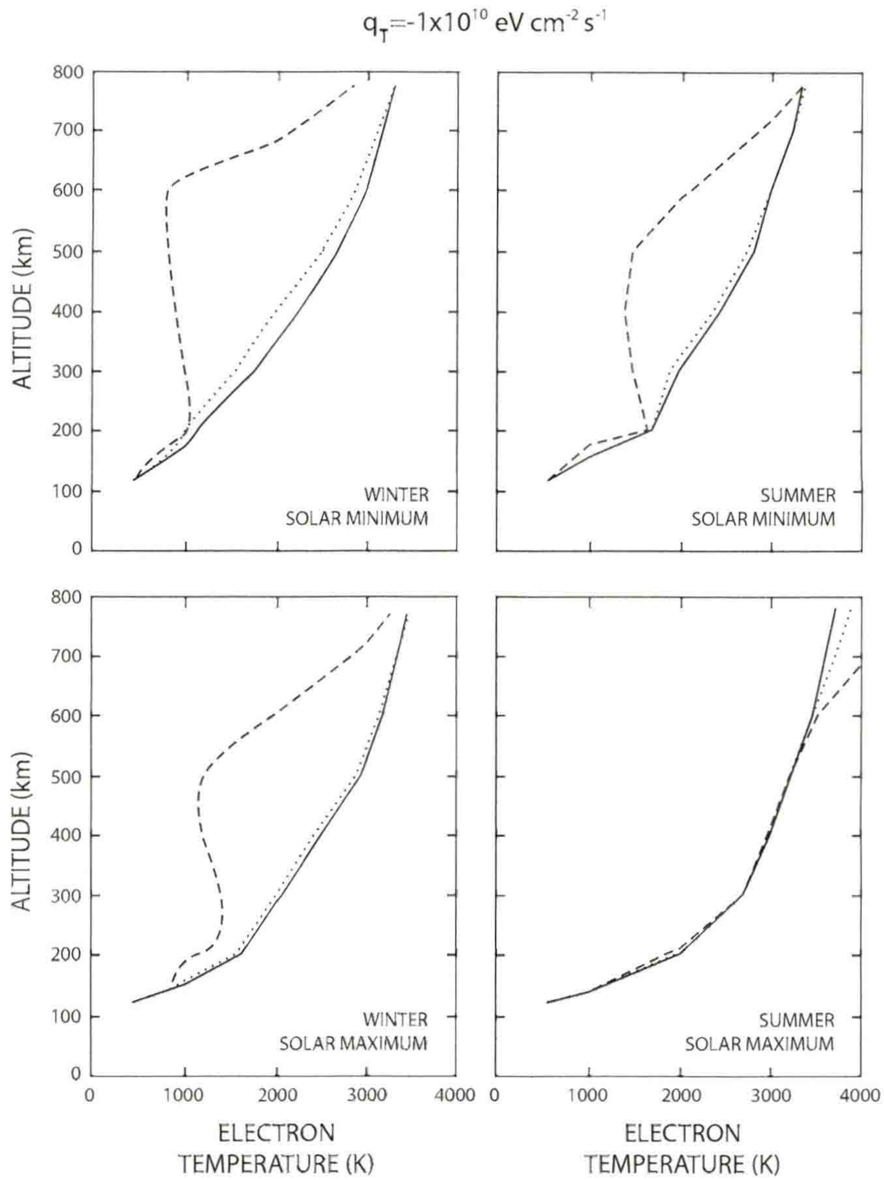

Figure 2. Electron temperature profiles for three values of the field-aligned auroral return current for winter and summer conditions at both solar minimum and maximum. The field-aligned current values are 0 (solid curves), -1×10^{-5} (dotted curves), and -5×10^{-5} (dashed curves) A m^{-2}. An upper boundary (800 km) heat flux of -1×10^{10} eV cm^{-2} s^{-1} was used for these simulations to account for the interaction of the ionospheric electrons with the hot polar rain electrons. From *Schunk et al.* [1987].

hemispheres and at all longitudes. The peak emission rate typically is localized in the 350–400 km altitude range. The emission originates from the interaction of the ring current with plasma on outer plasmaspheric flux tubes. Through Coulomb collisions and wave-particle interactions, energy is transferred from the ring current to the thermal electrons, and then, the energy is conducted down into the ionosphere. The elevated electron temperature is then capable of exciting the oxygen red line.

SAR arcs are useful for illustrating an important process that is not included in all of the global coupled I-T models. This process involves N_2 vibrational excitation. In addition to exciting the oxygen red line, elevated electron temperatures can increase the population of vibrationally excited N_2, which then acts to increase the rate of the $O^+ + N_2 \Rightarrow NO^+ + N$ reaction. The net result can be a rapid conversion of O^+ into NO^+. Figure 4 shows the possible effect of vibrationally excited N_2 on the N_e profile via the associated O^+ to NO^+ conversion

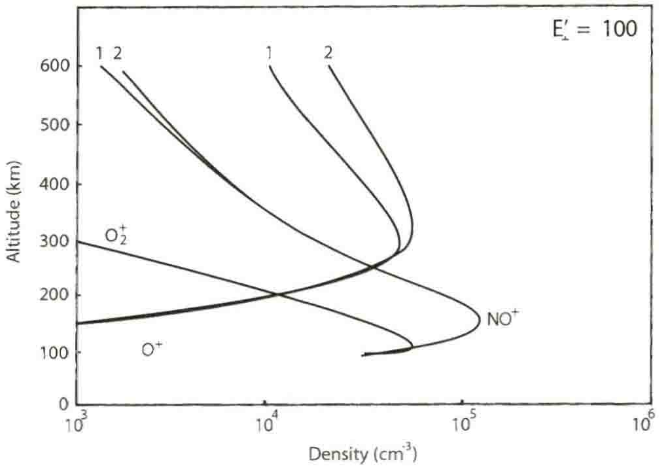

Figure 3. Ion density profiles calculated for a daytime high-latitude ionosphere subjected to a 100 mV m^{-1} electric field. The curves labeled 2 were calculated with T_i, and the curves labeled 1 were calculated with $T_{i\parallel}$. From *Schunk et al.* [1975].

process. The top panel shows the adopted SAR arc T_e profile, and the bottom panel shows the calculated N_e. Note that N_2 vibrational excitation can have a dramatic effect on the shape of the N_e profile. Since excited N_2 molecules are prevalent in and around the auroral oval, these molecules need to be taken into account in the global coupled I-T models.

2.6. Collisionless Plasma Flow

The current global ionosphere and ionosphere-plasmasphere models [*Bailey and Sellek*, 1990; *Millward et al.*, 1996; *Richards and Torr*, 1996; *Schunk et al.*, 2004] are based on relatively simple mathematical formulations. Specifically, the adopted continuity, momentum, and energy equations are simplified by ignoring nonlinear and/or complicated terms. It is also assumed that the plasma is collision dominated, which means that the momentum equation reduces to a diffusion equation (see section 2.7 for further details).

With regard to the energy equation, either an empirical model is adopted for the plasma temperatures or collision-dominated energy and heat flow equations are solved. With the collision-dominated transport formulation, the temperatures are isotropic, and the heat flow is simply given by the collision-dominated expression $\mathbf{q} = -\lambda \nabla T$. However, above about 3000 km, the plasma becomes collisionless in the polar wind, along SAR arc and plasmapause field lines, and in the plasmasphere after geomagnetic storms [*Demars and Schunk*, 1987a, 1987b]. When the plasma becomes collisionless, the use of isotropic temperatures and collision-dominated thermal conductivities is not valid. In a collisionless plasma, there are different species temperatures parallel and perpendicular to the magnetic field, and there are separate heat flow vectors for the transport of parallel and perpendicular energies. Hence, a *rigorous formulation* of the plasma flow requires a kinetic, semikinetic, generalized transport, or macroscopic particle-in-cell approach, all of which are difficult to implement for a global coupled I-T-P model. An example of collisionless heat flow is shown in Figure 5, where the heat flow vectors (parallel to **B**) for parallel and perpendicular energies are plotted versus altitude for SAR arc conditions [*Demars and Schunk*, 1986]. The simulation was from the

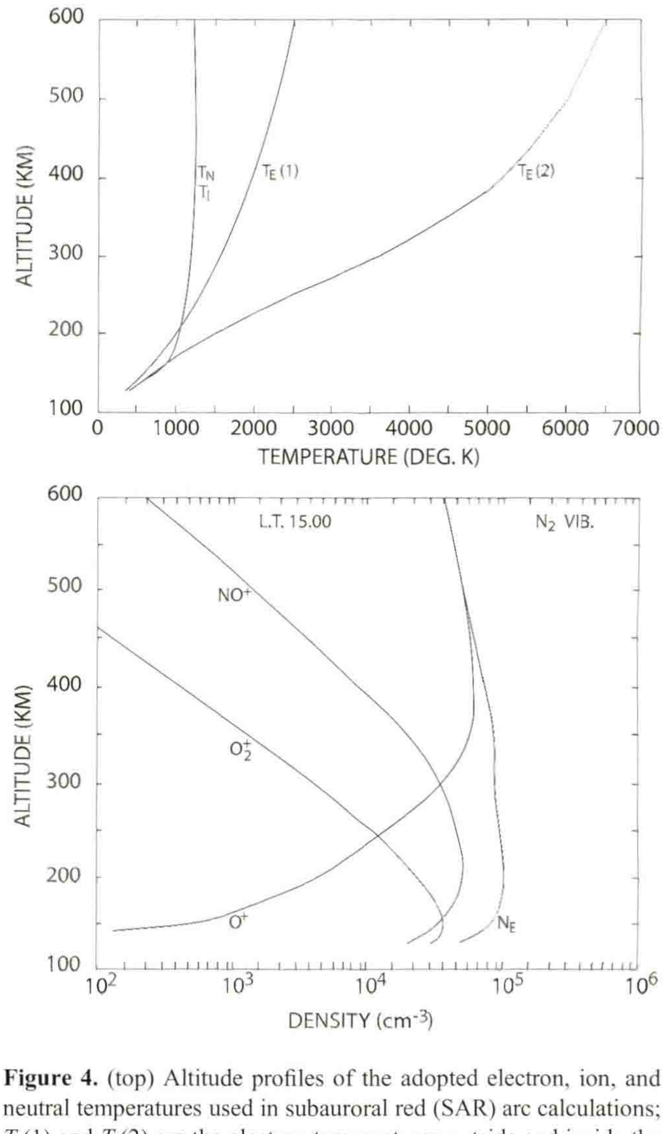

Figure 4. (top) Altitude profiles of the adopted electron, ion, and neutral temperatures used in subauroral red (SAR) arc calculations; $T_e(1)$ and $T_e(2)$ are the electron temperatures outside and inside the SAR arc, respectively. (bottom) Calculated ion and electron density profiles in a SAR arc including the effect of N_2 vibrational excitation and the associated increase in the $O^+ + N_2 \Rightarrow NO^+ + N$ reaction. From *Raitt et al.* [1976].

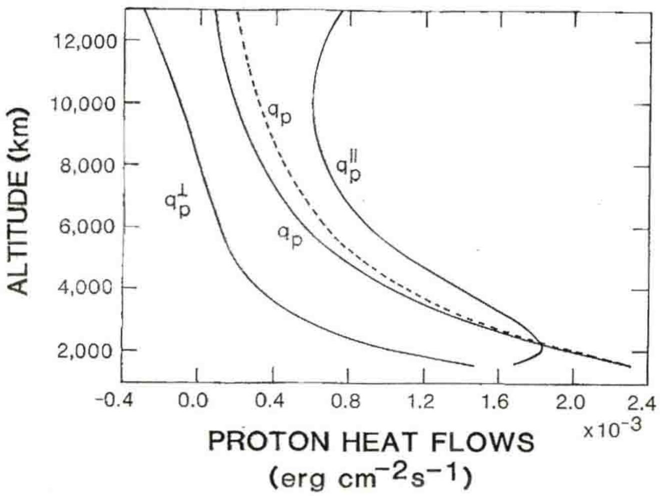

Figure 5. Proton heat flows along **B** for the transport of parallel energy ($q_p^{\|}$), perpendicular energy ($q_p^{\perp}$), and total energy (q_p) along a SAR arc field line, where $q_p = (q_p^{\|} + 2q_p^{\perp})/2$. Solid curves correspond to the solution of the 16-moment bi-Maxwellian transport equations. The dashed curve is not relevant to the discussion in the paper. From *Demars and Schunk* [1986].

solution of the 16-moment bi-Maxwellian transport equations. Note that with the more rigorous mathematical formulation, the density, drift velocity, and temperature solutions are significantly different from those obtained from the simplified diffusion and heat conduction equations commonly used in global coupled I-T-P models [see *Demars and Schunk*, 1986, 1987a, 1987b].

2.7. Ionosphere-Plasmasphere Coupling

As noted above, the four well-known physics-based global models of the coupled ionosphere-plasmasphere are based on a relatively simple diffusion formulation, which means that the nonlinear inertial term in the momentum equation ($\partial \mathbf{u}/\partial t + \mathbf{u}\cdot\nabla\mathbf{u}$) is not included [*Bailey and Sellek*, 1990; *Richards and Torr*, 1996; *Millward et al.*, 1996; *Schunk et al.*, 2004; *Scherliess et al.*, 2004]. The neglect of this term is useful for numerical reasons, but there are two negative consequences. Specifically, wave phenomena are not included, and the model cannot rigorously describe supersonic flow. The latter restriction is serious because after a geomagnetic storm, the upflow from the ionosphere that refills the depleted plasmasphere is supersonic. The neglect of the nonlinear inertial term, which acts to slow the upflow, not only means that the altitude profiles are wrong but that the refilling rate is too fast.

Another simplification is that none of the global I-P models couple to the ring current via wave-particle interactions, which means that the models do not properly describe the electron and ion thermal structure in the plasmasphere. Typically, the temperatures in the outer plasmasphere obtained from the global I-P models are too low (~4000–5000 K), whereas measurements indicate they are typically 8000–10,000 K [*Titheridge*, 1998]. To circumvent this problem, *Schunk et al.* [2004] adopted the empirical plasmasphere temperature model developed by *Titheridge* [1998]. Although this temperature model is based on an extensive satellite database, it is simplified in that it is a static empirical model.

Typically, the transport equations adopted to describe plasmasphere refilling determine the physics that is obtained. As noted above, a global I-P model that is based on a momentum equation that includes the nonlinear inertial term produces a different solution than that obtained from the four global I-P models that ignore this term (diffusion approximation), especially after geomagnetic storms. However, more advanced mathematical formulations can still lead to other completely different solutions [*Rasmussen and Schunk*, 1988]. In this latter study, the plasmasphere refilling was simulated with both a single-stream and a two-stream H^+ model. Specifically, the authors solved the H^+ continuity and momentum equations along a closed geomagnetic flux tube for a depleted plasmasphere. The momentum equation included the nonlinear inertial term so that wave phenomena and supersonic plasma flows could be properly modeled. In one simulation, a single H^+ stream was assumed, and in the second simulation, two independent H^+ streams were assumed (one from the Northern Hemisphere and one from the Southern Hemisphere). Figure 6 compares the plasmasphere refilling for the two cases. In both cases, the upflow is supersonic. For the single-stream simulation, there is only one H^+ velocity at each location along the flux tube, and when the counterstreaming H^+ flows from the conjugate hemispheres meet, a zero velocity results, and a pair of shocks is automatically triggered. The shocks then propagate toward lower altitudes, creating high-density plasma between the shock pair. In this case, the plasmasphere fills from the top down. On the other hand, for the case when the refilling is modeled with separate northern and southern H^+ streams, the counterstreaming supersonic flows penetrate each other, and shocks do not form. In this case, the plasmasphere fills from the bottom up. Hence, totally different results are obtained depending on how the plasmasphere refilling is modeled, with more rigorous mathematical formulations yielding more reliable solutions.

2.8. Plasma and Neutral Density Structures

Troposphere weather features can take on global characteristics, but most of the weather features are more localized, including hurricanes, tornados, snowstorms, fog banks,