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Journal of Atmospheric and Solar-Terrestrial Physics 69 (2007) 2071–2080

Journal of ATMOSPHERIC AND SOLAR-TERRESTRIAL PHYSICS

www.elsevier.com/locate/jastp

Multimoment convecting flux tube model of the polar wind system with return current and microprocesses

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Accepted 31 July 2007
Available online 31 August 2007

Abstract

Multimoment fluid simulation frameworks, which effectively account for anomalous transport due to microprocesses, combine best features of small-scale kinetic and global-scale MHD models. The most practical models of this type, 1D flux tube models, have been successfully used for realistic simulations of space plasmas including polar wind and magnetosphere–ionosphere coupling processes characterized by a wide range of temporal and spatial scales. Our earlier flux tube models with field-aligned current and microprocesses have been formulated for spatially stationary flux tubes. However, horizontal convection due to electric fields is an important aspect of the high-latitude ionosphere–polar wind system and typical time scales of the polar wind upflow are comparable to the transit time across the polar cap. To take into account this important feature we have added flux tube convection to our earlier model. Using typical convecting flux tube that starts outside auroral oval, then enters and leaves downward current region, it has been shown that anomalous transport effects due to current-driven microinstabilities significantly alter dynamics of several plasma moments and should be taken into account for an accurate interpretation and prediction of the observed data. Future applications of our new model have also been discussed.

Keywords: Polar wind; Current-driven instabilities; Multi-moment simulation

1. Introduction

Ionospheric and magnetospheric plasma dynamics is characterized by a wide range of temporal and spatial scales. In many cases the processes of different scales are coupled (e.g., magnetosphere–ionosphere coupling phenomena). Small-scale phenomena usually require a kinetic description. However, existing computer power limits the kinetic model applications to rather small regions in space and time. Therefore, global-scale models are usually based on the MHD equations which assume near-Maxwellian distribution functions and neglect temperature anisotropies, heat flows, and numerous kinetic effects. Although these simplifications allow numerical analysis of such models in large space and time regions, they can significantly limit the quantitative and even qualitative accuracy of the obtained results.

To fill the gap between small-scale kinetic and global-scale MHD descriptions multimoment fluid models have been introduced (Barakat and Schunk, 1982; Mitchell and Palmadesso, 1983; Ganguli

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doi:10.1016/j.jastp.2007.08.004

and Palmadesso, 1987; Schunk and Sojka, 1989; Mitchell et al., 1992). In comparison with a MHD description, multimoment fluid models more accurately describe non-Maxwellian features, including temperature anisotropy, anisotropic heat flows, and can incorporate macroscopic consequences of the kinetic effects via anomalous transport coefficients (Mitchell and Palmadesso, 1983; Ganguli and Palmadesso, 1987). It is important that these models are significantly less computation intensive compared to kinetic models.

The multimoment models have been applied to a wide range of problems including large-scale modeling of the polar wind (Ganguli et al., 1987; Schunk and Sojka, 1989), auroral return current regions (Ganguli and Palmadesso, 1987), magnetosphere–ionosphere coupling (Mitchell et al., 1992), and potential structures generation (Ganguli et al., 1994). These investigations demonstrated importance of such non-Maxwellian features as temperature anisotropy, mirror force, field-aligned currents, and anisotropic heat flows for an accurate prediction of the large-scale plasma evolution.

Earlier flux tube models with non-Maxwellian features, field-aligned current and microprocesses (Mitchell et al., 1992; Ganguli et al., 1987, 1994; Ganguli and Palmadesso, 1987) were formulated for spatially stationary flux tubes, i.e., no flux tube convection was taken into account. However, horizontal motion is an important aspect of the high-latitude ionosphere–polar wind system. Because of magnetospheric electric fields, this system is in a constant state of motion, convecting into and out of the polar cap, cusp, nocturnal oval, nighttime trough and sunlight. This horizontal convection is significant because the typical time scales of the polar wind upflow (in and out of the topside ionosphere) are comparable to the transit time across the polar cap.

Convecting flux tube multimoment model was introduced by Schunk and Sojka (1989, 1997). A number of important aspects of the ionosphere–polar wind system including geomagnetic storm development have been simulated using this model (e.g., Schunk and Sojka, 1997; Demars and Schunk, 2002). However, besides simplification of the energy equations for higher altitudes (no heat flow), this model does not include field-aligned currents and effective anomalous effects due to microinstabilities. The model was applied in 90–9000 km altitude range.

Here, we have generalized the earlier model (Mitchell et al., 1992; Ganguli et al., 1994) to include flux tube convection. The result of the generalization is a multimoment convecting flux tube model with anisotropic ion temperature and heat flows as well as field-aligned current and anomalous effects due to current-driven electrostatic ion-cyclotron (CDEIC) instability. In the present version, the electron temperature is considered to be uniform and determined by the nonstationary lower-end boundary conditions. The model is applied from 800 km to 10 R_E altitude.

This paper is organized as follows. A model description and corresponding set of equations are given in Section 2. In Section 3, simulation results of the polar wind for a typical trajectory of a flux tube and different geomagnetic activities are provided. Finally, in Section 4, the summary of our work and the relevance of our results to space observations are discussed.

2. Model description

The model is designed to simulate dynamics of a fully ionized multispecies (e^-, H^+, O^+) plasma in a flux tube encompassing magnetic field line and is based on the flux tube model described by Mitchell et al. (1992) and Ganguli et al. (1994). The model is applied to high-latitude topside ionosphere and simulation region extends in altitude from 800 km to $10R_E$.

The model incorporates anisotropic temperatures and heat flows, field-aligned current and anomalous effects due to CDEIC instability (Ganguli and Palmadesso, 1987). Plasma state is described by number density n_s, velocity v_s, parallel temperature $T_{s\parallel}$, and transverse temperature $T_{s\perp}$. From these moments we construct the flux tube quantities and their associated continuity, momentum, parallel and transverse energy equations. Equations used here are identical to those given in Ganguli et al. (1994, equations 1a– 1e).

In this version of the model we simplify electron energy equation by assuming electron temperature to be uniform in altitude and determined by its value at the lower end of the flux tube. This allows to increase simulation time step which is now mainly determined not by electron but rather ion thermal velocity at the lower end. This simplification being not crucial for the main topics considered in this paper allows to simulate multiple convecting flux tubes over ~14 h of real time using reasonable computer resources.