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Dynamic model of the magnetosphere: Case study for January 9–12, 1997

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Abstract. The dynamics of the magnetospheric current systems are studied in the course of the specific magnetospheric disturbance on January 9–12, 1997, caused by the interaction of the Earth's magnetosphere with a dense solar wind plasma cloud. To estimate the contribution of the different sources of the magnetospheric magnetic field to the disturbance ground measured, a dynamic paraboloid model of the magnetosphere is used. The model input parameters are defined by the solar wind density and velocity, by the strength and direction of the interplanetary magnetic field, and by the auroral AL index. The total energy of the ring current particles is calculated from the energy balance equation, where the injection function is determined by the value of the solar wind electric field. New analytical relations describing the dynamics of the different magnetospheric magnetic field sources dependent on the model input parameters are obtained. The analysis of the magnetic disturbances during the January 9–12, 1997, event shows that in the course of the main phase of the magnetic storm the contribution of the ring current, the currents on the magnetopause, and the currents in the magnetotail are approximately equal to each other by an order of magnitude. Nevertheless, in some periods one of the current systems becomes dominant. For example, an intense Dst positive enhancement (up to +50 nT) in the course of the magnetic storm recovery phase in the first hours on January 11, 1997, is associated with a significant increase of the currents on the magnetopause, while the ring current and the magnetotail current remain at a quiet level. A comparison of the calculated Dst variation with measurements indicates good agreement. The root mean square deviation is ~ 8.7 nT in the course of the storm.

1. Introduction

The interaction of a magnetic cloud with the Earth's magnetosphere on January 9–12, 1997, is the subject of many studies [*Baker et al.*, 1998; *Reeves et al.*, 1998; *Shue et al.*, 1998; *Lu et al.*, 1998; *Jordanova et al.*, 1999]. The subsequent magnetic storm and its associated magnetospheric disturbances were detected by several spacecrafts and by the on-ground observatories involved in the International Solar Terrestrial Physics Program (ISTP).

A dense cloud of the solar wind plasma was of rather complicated structure. A southward interplanetary magnetic field (IMF) in its leading part caused a significant substorm activity during the interaction with the magnetosphere. A strong increase of the relativistic electron fluxes at the geosynchronous orbit was observed [*Baker et al.*, 1998; *Reeves et al.*, 1998]. The trailing half of the magnetic cloud contained a strong northward IMF and was accompanied by a large density enhancement that strongly compressed the magnetosphere. Because of the significant compression of the magnetosphere, several magnetopause crossings by the geostationary orbit took place. The magnetopause dynamics were analyzed by *Shue et al.* [1998].

Magnetic storms are accompanied by global changes in the whole Earth's magnetosphere. A global magnetospheric modeling is necessary for the investigation of these events. However, the most usually quoted empirical models of the magnetosphere developed by *Tsyganenko* [1995] [see also *Tsyganenko and Stern*, 1996] which are based on the interpolation of the experimental data are hardly appropriate to describe the disturbed magnetosphere.

The latest version of the Tsyganenko model [*Tsyganenko*, 1995], T96, uses the observed values of Dst, Bz_{IMF}, and the solar wind dynamic pressure to parameterize the intensity of the magnetospheric current systems. In the T96 model these parameters are replaced with the Kp index which has been used in the earlier versions of the Tsyga-

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nenko models. The T96 (as the earlier Tsyganenko models) was constructed using the minimization of the deviation from a data set of the magnetospheric magnetic field measurements gathered by several spacecrafts during many years. The disturbed periods are relatively rare events during the observation time, so their influence on the model coefficients is negligibly small. That is why the T96 model's applicability is limited by Dst, Bz_{IMF}, and the solar wind dynamic pressure low values.

The investigation of the magnetospheric current systems during magnetic storm is possible if use is made of the modern dynamic model of the magnetospheric magnetic field, the paraboloid model [*Alexeev et al.*, 1996]. An important advantage of this model is that it can describe the magnetic field of each magnetospheric current system as a function of its own time-dependent input parameters. A functional dependence of the model input parameters on the empirical data obtained by the satellites and on-ground observatories is determined by a set of submodels. We use the term "submodel" for the analytical definition of each model input parameter (for example, the magnetopause standoff distance, R_1) as a function of the solar wind pressure, IMF, and/or AL index and Dst index. To investigate the Dst sources during the January 9–12, 1997, event we will analyze the ground magnetic field in terms of the paraboloid model of the magnetosphere, which allows us to distinguish the contributions of different large-scale current systems.

Dst index is calculated from the measurements of the horizontal H component of magnetic field at four low-latitude ground observatories. A quiet level contribution is subtracted from the measurements at each station, and the obtained values are averaged to compute Dst. So, Dst index represents a variation of the azimuthally symmetric magnetic field at the Earth's surface. It is usually supposed that the ring current, the tail current, and the Chapman-Ferraro current are the main contributors to Dst:

$$Dst = Dr + Dt + Dcf \; . \tag{1}$$

We can also present Dst as

$$Dst = Br + Bt + Bcf - B_q \; , \tag{2}$$

where Br, Bt, and Bcf are the ground magnetic fields produced by the ring current, the tail current, and the Chapman-Ferraro current, respectively. B_q is a quiet day magnetic field perturbation which includes the ring current, the tail current, and the Chapman-Ferraro current contributions. It has been shown by *Dremukhina et al.* [1999] that under the quiet conditions in the framework of the paraboloid model, the sum of the contributions of the quiet ring current, of the current on the magnetopause, and of the magnetotail current is approximately equal to zero. This means that $B_q \approx 0$, and we can calculate Dst without subtracting the quiet day contribution from the model results [see also *Greenspan and Hamilton*, 2000]. We will investigate the Dst sources by using (2).

The question of the relative contributions of the magnetospheric current systems to the Dst variations is still not answered, in spite of a large number of investigations devoted to this problem [*Campbell*, 1973; *Arykov and Maltsev*, 1993; *Maltsev et al.*, 1996; *Alexeev et al.*, 1996; *Kalegaev and Dmitriev*, 2000; *Dremukhina et al.*, 1999; *Greenspan and Hamilton*, 2000; *Turner et al.*, 2000]. It is usually assumed that the ring current gives the main contribution to the variation of the magnetic field horizontal component measured at the Earth's surface near the geomagnetic equator. The magnetospheric tail dynamics gives a significant contribution to the processes of energy storage and transfer in the course of magnetospheric substorms and magnetic storms [*Kamide et al.*, 1998]. However, the tail current contribution to Dst is commonly estimated by the value of $\sim$ 20 nT [*Tsyganenko and Sibeck,* 1994]. *Turner et al.* [2000] give an estimation of $\sim 25\%$ for the current sheet contribution to the Dst variation. They calculated a tail current contribution to Dst equal to 22 nT at the maximum of the magnetic storm on January 9-12, 1997.

Arykov and Maltsev [1993], *Maltsev et al.* [1996], and *Alexeev et al.*, [1996] have shown that during strong magnetic storms the contribution of the magnetotail current sheet can be compared to that of the ring current. The significant contribution of the tail current to Dst was explained by the decrease of the dimensions of the inner magnetosphere during disturbances and by an increase of the electric currents in the current sheet due to the substorm activity [see *Pulkkinen et al.,* 1992]. *Kaufmann* [1987] mentioned the significant current growth in the inner part of the magnetotail current sheet during strong magnetic storms. The enhancement of the current in the distant magnetotail during intense magnetic storms was confirmed by the Geotail and ISEE 3 satellite measurements. Magnetic field strengths exceeding the mean values by a factor of 5-10 were measured [*Kokubun et al.,* 1996; *Ho and Tsurutani*, 1997].

Compression of the inner magnetosphere during disturbances is confirmed by auroral oval dynamics. *Starkov* [1993] proposed an empirical formula for the midnight latitude, φ_n, of the equatorward boundary of the auroral oval versus Dst:

$$\varphi_n = 74.9^\circ - 8.6 \log_{10}(-Dst) \; . \tag{3}$$

The equatorward shift of the oval during disturbances described by (3) is a well-known manifestation of the magnetospheric dynamics (the tail current dynamics, mainly). A similar relationship between the maximum Dst and the minimum latitude of the westward electrojet in the course of a storm was pointed out by *Chorosheva* [1986] on the basis of a statistical study covering 27 years (1957–1983). For the event under consideration this effect is confirmed by the data of the high-latitude observations at the meridian chains of magnetometers, by the data on the fluxes of precipitating particles measured by the Defense Meteorological Program (DMSP) satellites, and by the data of Ultraviolet Imager (UVI) observations obtained by the Polar satellite. It will be shown below that starting from 0600 UT on January 10, 1997, the earthward edge of the tail current sheet approaches the distances down to 3.7 R_E from the Earth.

The present paper studies the magnetic disturbance on

January 9 – 12, 1997, using the paraboloid model of the magnetosphere. This event is not one of the classical magnetic storms considered by *Alexeev et al.* [1992, 1996], *Kalegaev et al.* [1998], and *Kalegaev and Dmitriev* [2000]. The main aim of the paper is to investigate the contributions to Dst of the ring current, of the current on the magnetopause, and of the magnetospheric tail current system and to compare them to the results of *Turner et al.* [2000]. This analysis allows us to investigate the level of applicability of the different kinds of magnetospheric models. The version of the T96 model used by *Turner et al.* [2000] does not take into account the time dependence of the geocentric distance to the earthward edge of the current sheet, because the earthward boundary of the magnetotail current system is chosen to be constant (6 R_E). Our estimation is confirmed by the DMSP and Polar data, which show that R_2 moves down to 3.7 R_E. For this reason the most essential part of the magnetotail current system is excluded from the consideration by *Turner et al.* [2000]. The paraboloid model depends on the parameters of magnetospheric origin and takes into account the movements of the magnetotail in accordance with the level of geomagnetic activity. Here we will investigate magnetotail inner part dynamics in the magnetic storm development, the role of the different parameters especially of magnetospheric origin, and the validity of the different magnetospheric models.

To estimate the accuracy of our model calculations of the magnetospheric field at geosynchronous orbit, a comparison with the data obtained on board the geostationary satellites GOES 8 and 9 will be performed. For the verification of our calculations of the magnetotail current contribution to Dst, the obtained values of the model parameters will be used to calculate the auroral oval boundaries, which will be compared to the boundaries obtained using the DMSP precipitation data and the Polar UVI images.

2. Paraboloid Model of the Earth's Magnetosphere

The paraboloid model of the magnetosphere constructed by *Alexeev and Shabansky* [1972], *Alexeev* [1978], and *Alexeev et al.* [1996] is based on the solution of the Laplace equation. The condition $B_n = 0$ on the magnetopause holds for each large-scale magnetospheric current system. As a result, the changes of the locations and intensities of various current systems can occur nonsynchronously, with different characteristic times, and without a violation of the condition $B_n = 0$.

A solution of this problem for the case when a magnetic field source is a dipole has been obtained by *Alexeev and Shabansky* [1972]. This solution has been presented by *Alexeev et al.* [1975] for the infinitely thin current sheet of the magnetospheric tail, and by *Alexeev and Bobrovnikov* [1997] for the current sheet of a finite thickness. *Greene and Miller* [1990] presented a version of the paraboloid model with an arbitrary focal distance. The method of the paraboloid model construction was also described in detail by *Stern* [1985].

The magnetospheric magnetic field in the paraboloid model is a sum:

$$\mathbf{B}_m = \mathbf{B}_d(\psi) + \left(1 + \frac{M_{rc}}{M_E}\right)\mathbf{B}_{cf}(\psi, R_1) + \mathbf{B}_t(\psi, R_1, R_2, \Phi_\infty) + \mathbf{B}_{rc}(\psi, b_r) \ , \quad (4)$$

where $\mathbf{B}_d$ is the dipole field, $\mathbf{B}_{cf}$ is the field of the currents on the magnetopause which screen the dipole field, $\mathbf{B}_t$ is the field of the magnetospheric tail current system (cross-tail currents and closure magnetopause currents), $\mathbf{B}_{rc}$ is the ring current magnetic field, M_E is the Earth's magnetic moment, and M_{rc} is the ring current dipole moment. The field of the current on the magnetopause which screens the ring current magnetic field is described by the term $(M_{rc}/M_E)\mathbf{B}_{cf}(\psi, R_1)$. The paraboloid model enables the calculation of each magnetospheric magnetic field source separately. This is important for the study of the burst nonstationary events in the magnetosphere, as the different magnetospheric current systems change with the different characteristic times. The input parameters of the paraboloid model of the magnetospheric magnetic field are (1) the geomagnetic dipole tilt angle, ψ; (2) the geodistance to the subsolar point, R_1; (3) the geodistance to the earthward edge of the magnetotail current sheet, R_2; (4) the magnetic flux in the tail lobes, Φ_∞; and (5) the intensity of the ring current magnetic field at the Earth's center, b_r. During the quiet periods the magnitudes of the input parameters are $R_1 = 10\ R_E$, $R_2 = 7\ R_E$, $b_r = -10$ nT, and $\Phi_\infty = 3.7 \times 10^8$ Wb [*Stern and Alexeev,* 1988].

$\mathbf{B}_d$, $\mathbf{B}_{cf}$, and $\mathbf{B}_t$ are determined by their scalar potentials V_d, V_{cf}, and V_t, respectively ($\mathbf{B}_d = -\nabla V_d$, $\mathbf{B}_{cf} = -\nabla V_{cf}$, and $\mathbf{B}_t = -\nabla V_t$). Here $V_d = (R_E/R)^3 B_0(z\cos\psi + x\sin\psi)$, and $B_0 \approx -3 \times 10^4$ nT. The scalar potential V_{cf} is found from the Laplace equation with the boundary condition at the magnetopause: $(\mathbf{B}\cdot\mathbf{n}) = 0$, where $\mathbf{n}$ is the normal to the magnetopause. The potential V_{cf} is an expansion in terms of the Legendre polynomials and associated Legendre functions in the dayside magnetosphere and an expansion into the series of the Bessel functions in the nightside magnetosphere. The scalar potential V_t of the magnetic field of the tail current system is also an expansion into the series of the Bessel functions [see *Alexeev*, 1978; *Alexeev and Bobrovnikov*, 1997].

The ring current magnetic field, $\mathbf{B}_{rc}$, is proportional to the dipole vector potential for $R > R_2$ [see *Alexeev and Feldstein,* 2001]. In the region $R < R_2$, $\mathbf{B}_{rc} = \nabla \times \mathbf{A_{rc}}$, where the vector potential $\mathbf{A_{rc}}$ has only an azimuthal component, which equals to

$$A_\phi = \frac{\sqrt{2}\, M_{rc} R \sin\theta}{108\ {R_E}^3}\left[\frac{432}{(R^2 + 36\ {R_E}^2)^{3/2}} - 1\right] \ . \quad (5)$$

Here $M_{rc} = M_E(10 - b_r)/(810\ \text{nT})$.

The model input parameters (ψ, R_1, R_2, Φ_∞, and b_r) are calculated from a data set of the measurements in the Earth's environment. The relations between the model parameters and the experimental data are named "submodels". The necessary data set should include the data on the solar wind and IMF, as well as the values characterizing the disturbance level of the magnetosphere. At each moment the input parameters determine the instant state of the magnetosphere. The dynamics of the magnetosphere can be presented as a sequence of these states.

In the works of *Alexeev et al.* [1992, 1996] the IMP 8 data of the solar wind, the data of the meridian chains of magnetometers, as well as AL and Dst indices have been used. *Kalegaev et al.* [1998], *Kalegaev and Dmitriev* [2000], and *Dremukhina et al.* [1999] also made use of the DMSP satellites data for the definition of the auroral oval location and of the Active Magnetopsheric Particle Tracer Explorers (AMPTE)/CCE data for the determination of the ring current contribution to Dst. Such a variety of experimental data is usually unavailable. Therefore a question arises of how to construct the submodels depending on the minimal but sufficient set of empirical parameters. It has been noted by *Ostapenko and Maltsev* [1997] that for the magnetospheric dynamics the most geoeffective parameters are the solar wind dynamic pressure, the Bz component of the IMF, and the Dst index. The role of the parameters of the magnetospheric origin should be especially emphasized. It is impossible to describe the dynamics of a disturbed magnetosphere only in terms of a direct impact of the solar wind without a consideration of the current state of the magnetosphere defined by its previous history [see, e.g., *Vassiliadis et al.,* 1999; *Sitnov et al.,* 2000]. In this sense the current values of the Dst index describing the magnetic storm development and the AL index characterizing the intensity of the substorm disturbances correctly determine the magnetospheric state together with the solar wind parameters. The below consideration will deal with the simplified submodels using a set of the experimental data that are not so abundant as those in our earlier papers [*Alexeev et al.,* 1992, 1996; *Kalegaev et al.,* 1998; *Kalegaev and Dmitriev*, 2000; *Dremukhina et al.,* 1999].

3. Submodels: Calculations of the Main Parameters of the Magnetospheric Current Systems

The submodels present the empirical relations or auxiliary models describing the functional dependences of the parameters of the large-scale magnetospheric current systems on the measured values. The geomagnetic dipole tilt angle ψ allows us to take into account the daily and seasonal variations of the magnetic field due to the Earth's rotation. The largest daily variation of the angle ψ occurs during the solstices; therefore the dependence on ψ should be taken into account for the correct modeling of the magnetic storm in January, 1997. Angle ψ is calculated by the formula given by *Alexeev et al.* [1996].

The distance from the Earth to the subsolar point on the magnetopause, R_1, is calculated from the balance between the solar wind dynamic pressure and the pressure of the magnetospheric magnetic field. In our calculations, *Shue et al.*'s [1997, 1998] model was used to calculate the R_1 versus the solar wind pressure P_{sw} and IMF B_z data.

The distance to the earthward edge of the magnetotail current sheet, R_2, was calculated by the formula

$$R_2 = 1/\cos^2\varphi_n\,, \tag{6}$$

where R_2 is expressed in R_E and φ_n is the midnight latitude of the equatorward boundary of the auroral oval calculated by (3) [*Starkov,* 1993].

The magnetic flux in the magnetotail lobes, Φ_∞, is assumed to be

$$\Phi_\infty = \Phi_0 + \Phi_s\,, \tag{7}$$

where Φ_0 is the magnetic flux in the magnetotail lobes during the quiet periods and Φ_s is the time-dependent lobe magnetic flux associated with the magnetotail current increase in the course of substorm disturbances. A measure of the substorm activity is the intensity of the westward electrojet and hence the auroral index AL. Φ_s is determined by the value of the auroral AL index of geomagnetic activity [see *Alexeev et al.,* 1996; *Lui et al.,* 1992; *Lopez and von Rosenvinge,* 1993]. After *Alexeev et al.* [1996] we use $\Phi_0 = 3.7\times10^8$ Wb and

$$\Phi_s = \frac{-AL}{7}\frac{\pi R_1^2}{2}\sqrt{\frac{2R_2}{R_1}+1}\,. \tag{8}$$

The ring current intensity is characterized by the value of the ring current magnetic field at the Earth's center calculated by the Dessler-Parker-Sckopke relation [*Dessler and Parker,* 1959; *Sckopke,* 1966],

$$b_r = -\frac{2}{3}B_0\frac{\varepsilon_r}{\varepsilon_d}\,, \tag{9}$$

where ε_r is the total energy of the ring current particles, $\varepsilon_d = (1/3)B_0M_E$ is the energy of the geomagnetic dipole beyond the Earth's surface, and B_0 is the geodipole magnetic field at the Earth's equator.

It was suggested by *Burton et al.* [1975] that the total ring current particles' energy is controlled by two processes, injection (U) and losses:

$$\frac{d\varepsilon_r}{dt} = U - \frac{\varepsilon_r}{\tau}\,, \tag{10}$$

where τ is the lifetime of the ring current particles.

To determine the ring current magnetic field variation at the Earth's center, the energy balance equation (10) and the DPS equation (9) were used:

$$\frac{db_r}{dt} = F(E) - \frac{b_r}{\tau}\,, \tag{11}$$

where $F(E)$ is the injection function. The determination of $F(E)$ and τ is independent and a very difficult problem.

Burton et al. [1975] and *O'Brien and McPherron,* [2000] defined $F(E)$ by the solar wind electric field:

$$F(E) = \begin{cases} d(E_y - 0,5) & E_y > 0.5 \text{ mV/m} \\ 0 & E_y < 0.5 \text{ mV/m}\,. \end{cases} \tag{12}$$

Here $E_y = |VB_z|$ is the dawn-dusk component of the electric field in the solar wind for $B_z < 0$. It is assumed that

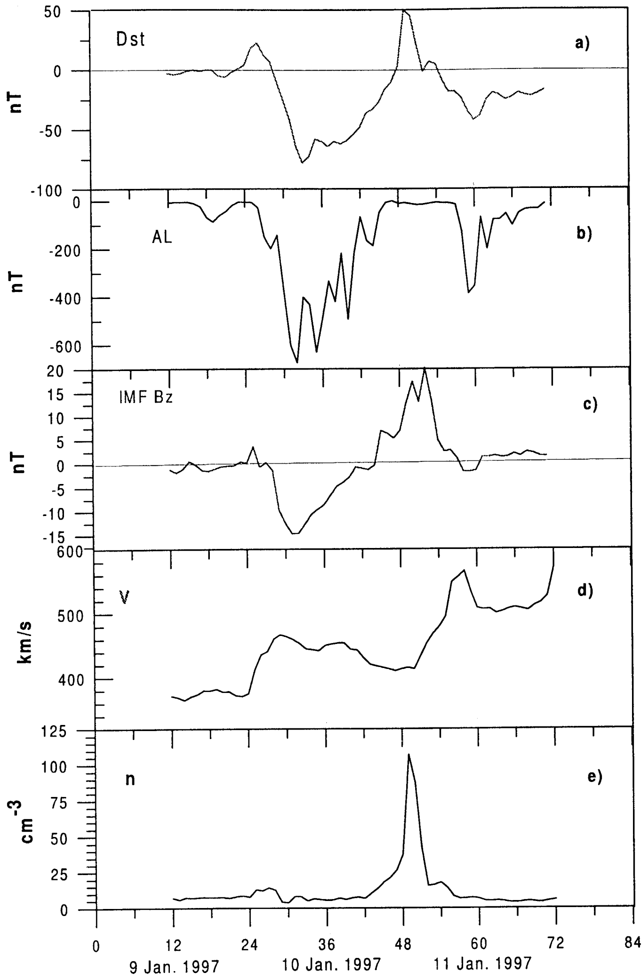

Figure 1. Empirical data used for the calculations of the model input parameters: (a) Dst, (b) AL, (c) IMF B_z component of the solar wind, (d) velocity, and (e) density for January 9–12, 1997.

$E_y = 0$ for $B_z > 0$. The constant d was obtained by *O'Brien and McPherron* [2000] in terms of the statistical analysis of hourly Dst data over the 30 years.

Unfortunately, the averaged values are not appropriate for the concrete case studies. To determine the injection amplitude d we will use the results of *Jordanova et al.* [1999], where the ring current injection U for the magnetic storm on January 9-12 was calculated on the basis of the models of magnetospheric electric field. For the maximal ring current injection value 2.2×10^{30} keV h^{-1} presented by *Jordanova et al.* [1999], we can estimate that $d = -1.3$ nT m mV^{-1} h^{-1}.

We will use the lifetime of the ring current particles, τ, defined by *O'Brien and McPherron* [2000]:

$$\tau(\text{hours}) = 2.4\, e^{9.74/(4.69+E_y)} \quad . \tag{13}$$

To determine the ring current contribution to Dst (as well as the contributions of other current systems) we must take into account the induced currents inside the Earth. After *Langel and Estes* [1985] we assume that the ring current contribution to Dst is $Dr = 1.3 b_r$ due to the Earth currents [see also *Greenspan and Hamilton*, 2000]. Equation (11) describes the variation of the ring current magnetic field discarding the contribution of a quiet ring current. Since the quiet ring current in the paraboloid model yields $b_r = -10$ nT, the magnetic field on the Earth's equator produced by the ring current should be calculated using the equation $Br = Dr - 13$ nT.

4. Calculations

Let us calculate the magnetic field produced by the magnetospheric sources at the Earth's equator in the course of the January 9 – 12, 1997, event. This event is associated with an accelerated flow of the dense solar wind plasma arriving in the Earth's environment. Figure 1 shows the Dst and AL indices (Figures 1a and 1b). The hourly averaged Wind data on the plasma and magnetic field are presented in Figures 1c–1e. The time delay ($\sim$ 25 min) between the measurements in the Earth's vicinity and on board the Wind spacecraft is taken into account.

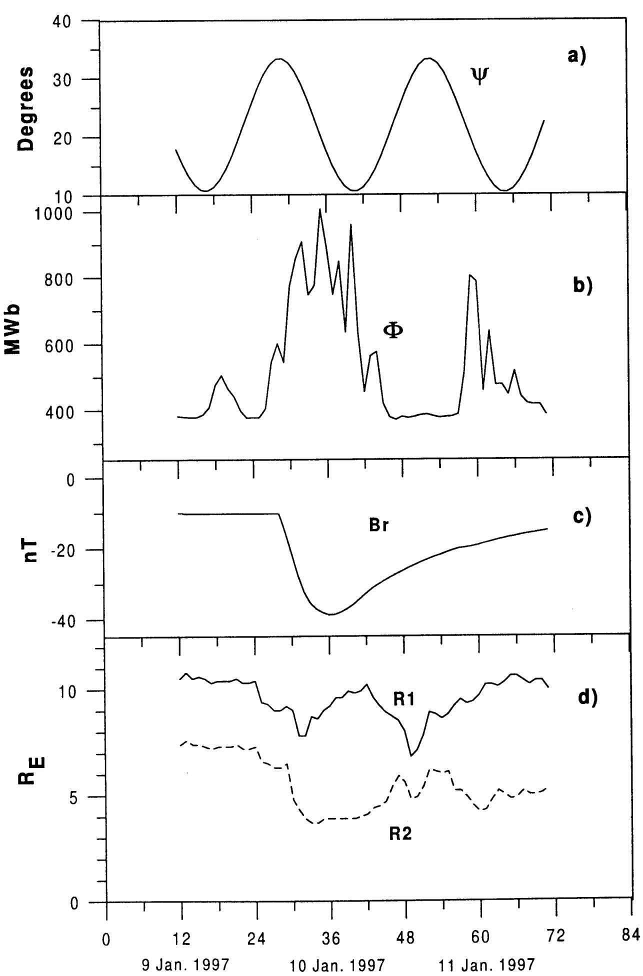

Figure 2. The model input parameters for January 9–11, 1997: (a) the tilt angle, ψ; (b) the magnetic field flux through the magnetotail lobes, Φ_∞; (c) the ring current magnetic field at the Earth's center, b_r; and (d) the distances to the magnetopause subsolar point (solid curve), R_1, and to the earthward edge of the magnetotail current sheet (dashed curve), R_2.

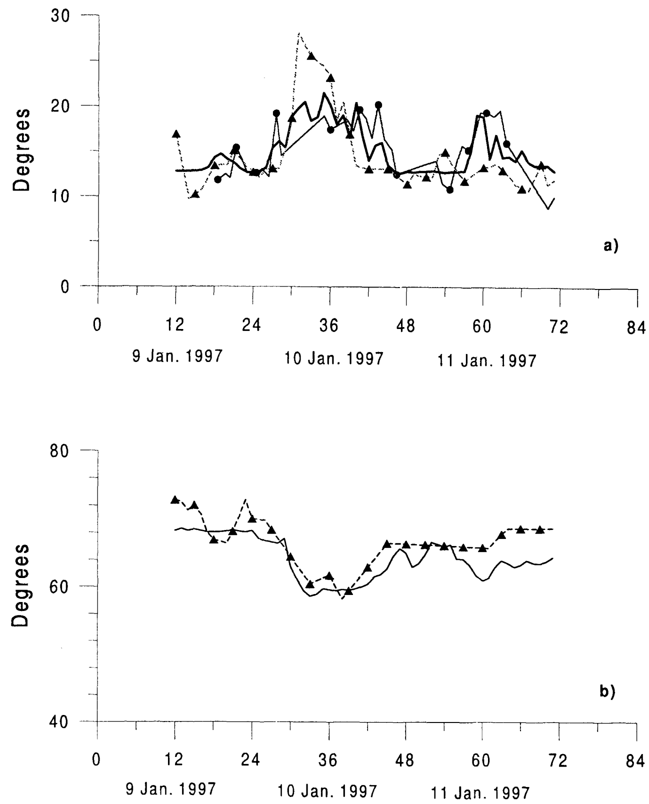

Figure 3. (a) Comparison of the polar cap radius calculated from the magnetic flux value Φ_∞ (solid curve) with radii obtained from the measurements on board DMSP F10-F13 (marked with triangles) and from the Polar Ultraviolet Imager (UVI) images (marked with circles). (b) Comparison of the midnight latitude of the equatorward boundary of the polar oval calculated by Equation (3) (solid curve) and that calculated by the data measurements on board DMSP F10-F13 (marked with triangles).

The input parameters of the paraboloid model were determined by the above mentioned submodels. Figure 2 presents the time variations of the model input parameters: the tilt angle (Figure 2a) and the magnetic field flux across the magnetotail lobes (Figure 2b). Figure 2c shows b_r, calculated by (11). Figure 2d shows the distances to the magnetopause subsolar point and to the earthward edge of the tail current sheet.

Since the magnetic field flux across the magnetotail lobes shown in Figure 2b is equal to the magnetic flux over the polar cap, we can calculate the polar cap radius θ_{pc} from the relation

$$\sin^2 \theta_{pc} = \Phi_\infty / (2B_0 \pi R_E^2) \ . \qquad (14)$$

Figure 3a compares the polar cap radius calculated by (14) to the radii obtained from the observations on board DMSP F10-F13 and on board Polar. Figure 3a shows good agreement between the calculations and the experimental data obtained from the independent sources. So, the model estimation of Φ_∞ can be used to identify the polar cap boundaries. Figure 3b compares the midnight latitude of the equatorward boundary of the auroral oval calculated by (3) to those determined using the particle spectra measured on board the DMSP F10-F13 satellites by classification proposed by *Newell et al.* [1996] and *Feldstein and Galperin* [1996]. The obtained agreement with observations confirms our suggestions about Φ_∞ and R_2 made above.

Using the model input parameters ψ, Φ_∞, R_1, R_2, and b_r, we can calculate the contribution of the magnetospheric magnetic field sources Bcf, Br, and Bt to the variation of the magnetic field measured at the Earth's equator. The induced Earth currents cause an increase of all components by a factor of 1.3 [*Langel and Estes*, 1985].

The paraboloid model calculations are demonstrated in Figure 4. The magnetospheric magnetic field variation is calculated at the geomagnetic equator at each hour of magnetic local time (MLT) and averaged over the equator. Figures 4a–4c present the Dst sources Bcf, Br, and Bt and their parts arising owing to the Earth currents. Figure 4d compares the Dst and the calculated magnetic field. A good agreement is obtained for both the relatively quiet and disturbed periods. The calculations in terms of the paraboloid model give an RMS deviation from Dst (δB) of $\sim$ 8.7 nT. Here δB can be written as

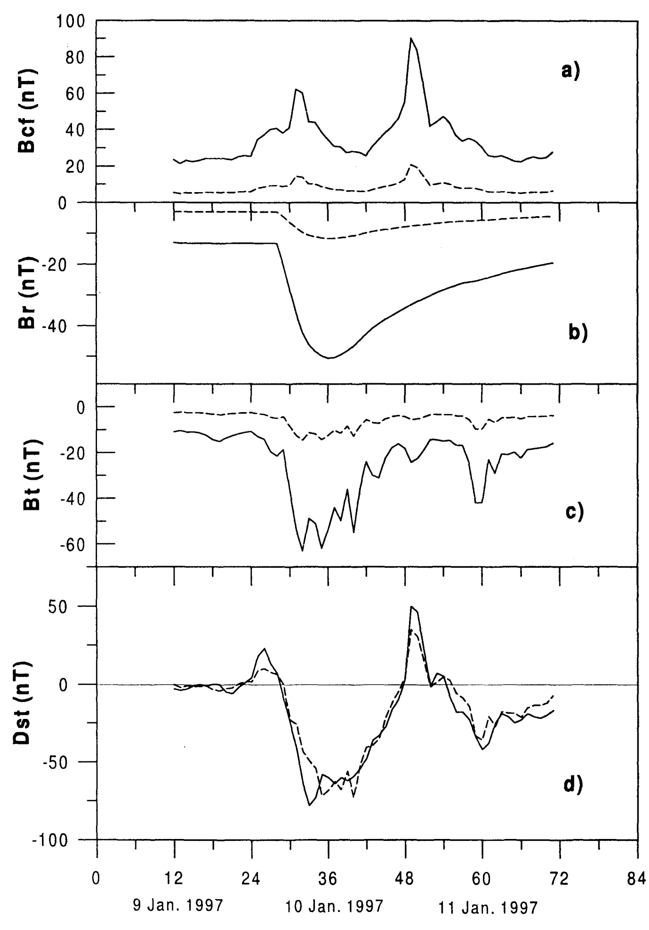

Figure 4. (a) Magnetic field of currents on the magnetopause, (b, c) the ring current magnetic field and tail current magnetic field, respectively, at the Earth's surface (solid curves) and the corresponding magnetic field due to currents induced inside the Earth (dashed curves), and (d) Dst (heavy solid curve) and total magnetic field, B_M (dashed curve), calculated at the Earth's surface in the course of the magnetic storm on January 9–12, 1997.

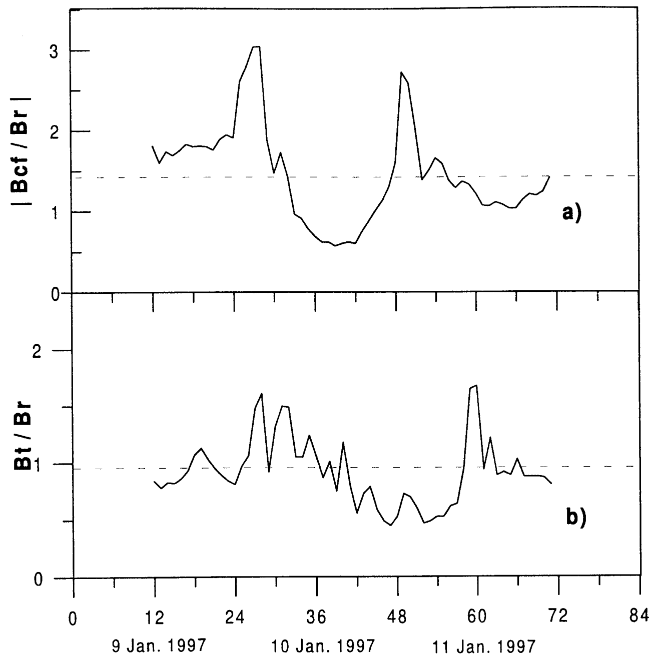

Figure 5. The relative roles of magnetospheric current systems during the magnetic storm on January 9–12, 1997: (a) $|Bcf/Br|$ and (b) Br/Br. Dashed lines show the corresponding average values.

$$\delta B = \sqrt{\frac{1}{N}\sum_{i=1}^{N}[Dst(UT_i) - \mathbf{\Delta B}_m(UT_i)]^2}\,, \qquad (15)$$

where $\mathbf{\Delta B}_m = \mathbf{B_m} - \mathbf{B_d}$ (see Equation (4)).

Figure 5 presents the calculated profiles of relations $|B_{cf}/B_r|$ (Figure 5a) and B_t/B_r (Figure 5b) during the magnetic storm and their average values of 1.46 and 0.92, respectively. Figure 5b confirms again the fact that the contributions of the ring current and of the magnetotail current are comparable by the order of magnitude during the magnetic disturbances.

5. Magnetospheric Magnetic Field Contributions to Dst

Figures 4a–4c show the components of the calculated magnetic field: the magnetic field of the current on the magnetopause (Figure 4a), the ring current magnetic field (Figure 4b), and the magnetic field of the magnetotail current (Figure 4c). The characteristic feature is an abrupt increase of the contributions produced by the magnetotail current and the ring current starting from 0500 UT on January 10, 1997. The magnetopause current increases began several hours earlier. The maximum contributions of the tail current ($\simeq$ -60 nT) and of the ring current ($\simeq$ -50 nT) are attained near 0900 UT, January 10, 1997, just before the magnetic storm recovery phase. The next magnetopause current enhancement associated with the solar wind pressure pulse occurred at the first hours of January 11 during the storm recovery phase. The tail and the ring current contributions are at the quiet level at that time. The second pressure pulse enforced the rapid ring current decay.

Bt presented in Figure 4c depends on the input parameters R_1, R_2, and Φ_∞. The time variation of them is determined by the solar wind empirical parameters (solar wind pressure and IMF B_z) as well as by the magnetospheric ones (latitude of the auroral oval equatorward boundary at midnight and AL). Two enhancements in the Bt profile are directly caused by the perturbations in the solar wind (at 0900 UT on January 10, 1997) and in the magnetosphere (at 1200 UT on January 11, 1997).

Turner et al. [2000] studied the tail current dynamics during the same magnetic storm in terms of the T96 model. It was supposed that the tail current is bounded by the box $-5\ R_E < z < 5\ R_E$, $-50\ R_E < x < -6\ R_E$. The tail current contribution was presented in Figure 3c of *Turner et al.* [2000]. We can see two peaks in the Bt profile corresponding to the two solar wind pressure pulses. This dependence is similar to that existing for the Chapman–Ferraro currents' magnetic field. The Bt obtained using the paraboloid model (Figure 4c) shows another, more complicated dynamics. The second tail current activation (at 1200 UT on January 11, 1997) does not correspond to any perturbation in the solar wind. It indicates the influence of the parameters of the magnetospheric origin associated with the AL increase and the auroral oval expansion due to the high auroral activity (see Figure 1).

It was found by *Turner et al.* [2000] that the contribution of the magnetotail current sheet to Dst at the January 1997 storm maximum was -22 nT. This value represents the difference between the instant and the quiet tail current fields. To compare our results with those obtained by *Turner et al.* [2000] we should take into account that the T96 and the paraboloid models give the different values of ground magnetic field during quiet periods used in the Dst calculations. In the paraboloid model this value is close to zero; in the T96 model it is about -22 nT [see *Turner et al.,* 2000]. These values are the sum of the quiet day contributions of all the Dst sources. The main reason for such a discrepancy is the difference of the parameterization of the large-scale magnetospheric current systems used in the models. To analyze correctly the models' validity we must compare the contributions of magnetic field sources to the ground magnetic field. Taking into account the T96 quiet tail current contribution ($\simeq$ -15 nT [see *Tsyganenko and Sibeck,* 1994]) we obtain $\simeq$ -37 nT. The effect of the Earth currents (factor 1.3) gives the value $\simeq$ -48.1 nT for the tail current contribution in terms of the T96, which is close to that obtained in terms of the paraboloid model (-60 nT).

The reason for the residual difference between the present calculations and those of *Turner et al.* [2000] is the tail current inner edge dynamics which are taken into account in the paraboloid model in accordance with the auroral oval expansion due to the substorm activity. In the calculations made by *Turner et al.* [2000] the dynamics of the inner edge of the tail current sheet are neglected. So, the difference in the results of the investigations of the January 1997 storm is associated with the difference of the tail current parameterization used in the T96 and paraboloid models.

To show more clearly the parameterization for the paraboloid model let us present the approximation of the model magnetic field horizontal component. At the Earth's surface the magnetic field strength of the external sources contributing to Dst can be written as

$$H = Bcf + Bt + Br \ . \tag{16}$$

Using *Alexeev*'s [1978] spherical function expansion and the aproximate formula by *Alexeev et al.* [2000], we can present the magnetospheric magnetic field sources as

$$Bcf = 26\left(1+\frac{M_{rc}}{M_E}\right)(0.45\sin^2\psi+1)\left(\frac{10R_E}{R_1}\right)^3 \ (\mathrm{nT}),$$
$$Bt = -\frac{39}{\alpha_0}\,e^{-\frac{R_2}{R_1}}\left[\frac{\sqrt{2.4}}{\alpha_0}\left(\frac{10R_E}{R_1}\right)^2-\frac{AL}{280\ nT}\right] \ (\mathrm{nT}),$$
$$Br = -1.3\cdot(10-b_r) \ (\mathrm{nT}), \tag{17}$$

where $\alpha_0 = \sqrt{1+2R_2/R_1}$. The effect of the Earth currents (factor 1.3) and the enhancement of the currents on the magnetopause due to the ring current in $(1 + M_{rc}/M_E)$ times are taken into account.

Assuming the subsolar distance to be proportional to $p_{sw}^{-1/6}$, we can see from (17) that the magnetopause current contribution is proportional to $\sqrt{p_{sw}}$, and that the geotail contribution during the quiet periods correlates with the solar wind dynamic pressure as $p_{sw}^{1/3}$ but not as $\sqrt{p_{sw}}$. Moreover, under the disturbed conditions, the term dependent on AL and associated with the auroral activity becomes dominant (see Equation (17)).

6. Discussion

The obtained results are in accordance with the conclusions of our earlier papers about a significant role of the magnetotail current sheet during the disturbed periods associated with the development of a strong magnetic storm [*Alexeev et al.*, 1992; 1996; *Kalegaev et al.*, 1998; *Kalegaev and Dmitriev*, 2000; *Dremukhina et al.*, 1999]. We can see from the analysis of a very specific magnetic disturbance on January 9–12, 1997, that the magnetospheric dynamics depend on all the magnetospheric magnetic field sources, which appear to be comparable by the order of magnitude. The paraboloid model can be successfully applied, especially in the disturbed periods, when the empirical models are often not valid.

The important feature of the T96 model is (as reported by the author in the T96_01 model's description) its applicability only for 20 nT $> Dst > -100$ nT, 0.5 nPa$< p_{sw} <$ 10 nPa, and -10 nT$< Bz_{\mathrm{IMF}} <$ 10 nT. In the course of the storm under consideration (January 9-12, 1997) the upper value of p_{sw} is significantly beyond the 10 nPa limit.

In contrast to the empirical models, the paraboloid model [*Alexeev et al.*, 1996] is a dynamic model. The magnetospheric dynamics are described by the time dependence of the model input parameters on the empirical data, thus enabling the description of the strong disturbances with a characteristic time of $\sim$ 1 hour. The model is not restricted by the Dst amplitude or by the solar wind pressure values, so it can be used for the overall period of January 9–12, 1997.

The calculation results and the new relations (17) show that the magnetopause current and the tail current dependences on the solar wind dynamic pressure, p_{sw}, are different. The magnetopause current contribution to Dst is proportional to $p_{sw}^{1/2}$, but the tail current contribution includes the term which is proportional to $p_{sw}^{1/3}$. This conclusion is in agreement with the results obtained by *Fairfield and Jones* [1996]. They showed on the basis of the statistical study that the dependence on p_{sw} of the magnetic field strength in the tail lobe is different from that used for the magnetopause current (proportional to $p_{sw}^{1/4}$). In the paraboloid model the tail current field includes an additional term which is controlled by the auroral activity (via AL index). The comparison of the auroral oval boundaries calculated in terms of the paraboloid model with in situ observations by the Polar and DMSP satellites shows a good coincidence between the model results and the observations, and this comparison confirms the chosen parameterization of the geotail current system.

Turner et al. [2000] has studied the contribution of the magnetotail current system to the Dst variation for the magnetospheric disturbance on January 9–12, 1997, caused by the arrival of a cloud of the dense solar wind plasma to the Earth. On the basis of the T96 model a conclusion was made that the contribution of the current sheet to Dst is 22 nT at the storm maximum. As was shown above, the result obtained by *Turner et al.* [2000] does not contradict the statement of a significant contribution of the tail current to Dst during disturbances [*Alexeev et al.*, 1996]. The contribution of the current sheet can be underestimated, owing to some features of the physical model of the magnetotail magnetic field proposed by *Turner et al.* [2000]. The currents within the region $-5\ R_E < z < 5\ R_E$, $-50\ R_E < x < -6\ R_E$ chosen as a geotail current system location actually are only a part of the real tail current system. The closure currents on the magnetopause and the currents in the inner part of the geotail current sheet which give the significant contribution to the Dst variation (especially in the course of substorm) were not taken into account. So, the results of the calculations by *Turner et al.* [2000] underestimate the magnetotail current role during the magnetic disturbance on January 9–12, 1997.

Calculating the influence of the tail current on the Dst variation, *Turner et al.* [2000] separated the effect of the Earth current induced by the tail current from the effect of the tail current itself. However, both of these current systems change simultaneously, and it is necessary to sum their magnetic fields when the tail current contribution to Dst is calculated.

The dynamics of the Dst components (the magnetic fields of the current on the magnetopause, of the ring current, and of the magnetotail current) are defined by the time variation of the input parameters. The current on the magnetopause depends significantly on the distance to the subsolar point and, ultimately, on the solar wind dynamic pressure. An abrupt increase of the current on the magnetopause at 0000 UT January 11, 1997, just corresponds to the solar wind plasma pressure pulse (see Figure 1). We can see the cor-

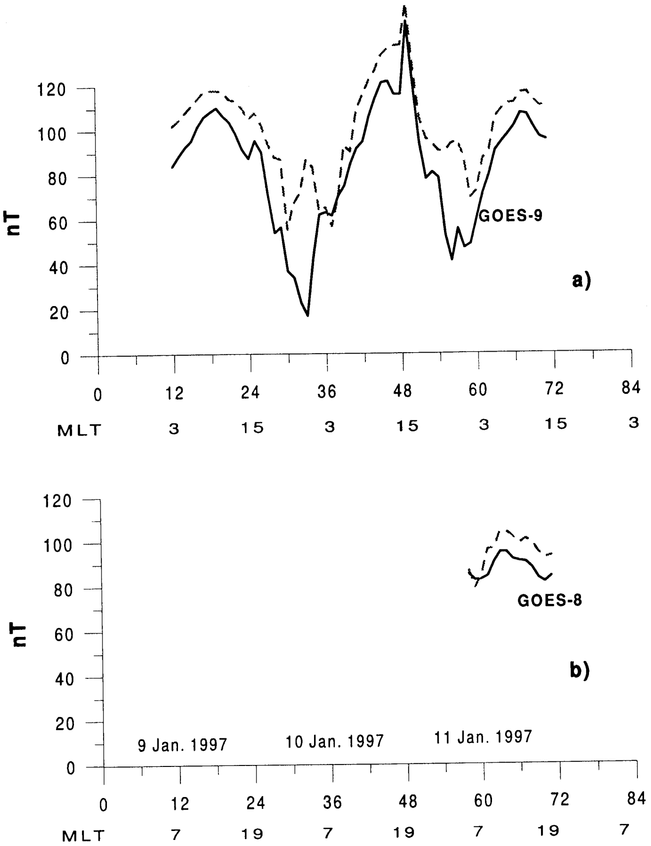

Figure 6. Comparison of the magnetic fields calculated in terms of the paraboloid model and measured during the magnetic storm on January 9–12 , 1997, along the (a) GOES 9 orbit and (b) GOES 8 orbit.

responding peak in the tail current contribution to Dst calculated by T96 [see *Turner et al.*, 2000, Figure 3c]. That means that the similar dependences of contributions of the magnetopause and geotail currents on the solar wind pressure are used in the T96 model. The paraboloid model uses the different dependence for each current system. For example, the tail and the ring current contributions during the pressure pulse on January 11, 1997, under northward IMF remain at the quiet level. Figure 4c and (17) show the strong influence of the parameters of magnetospheric origin on the magnetic storm development.

Thus the discrepancy of the results obtained in the present paper and in that of *Turner et al.* [2000] is explained mainly by the use of different quantitative models. The quality of a model and its flexibility are defined by the possibility of reflecting the dynamics of the large-scale current systems. The empirical models do not yet allow one to determine correctly the time dependence of each large-scale current system. In the paraboloid model the submodels are used for the calculation of the parameters of the large-scale magnetospheric current systems. These submodels can take into account the significant features of various magnetospheric current systems.

Figure 6 presents the calculations of the magnetic field along the GOES 9 and 8 spacecraft orbits. To take into account the magnetic field of the interterrestrial sources, we used the International Geomagnetic Reference Field (IGRF95) model. The agreement of calculations with the measured magnetic field confirms the initial assumptions of the relative roles of the magnetospheric current systems in the course of magnetic storm.

7. Conclusion

The paraboloid model describes well the magnetic field variations on the Earth's surface and at the geosynchronous orbit during the interaction of a solar wind plasma cloud with the magnetosphere on January 9–12, 1997. The root mean square deviation between the model calculations and the measured field is equal to 8.7 nT.

During the main phase of a weak magnetic storm the magnetotail current and the ring current create disturbances of approximately equal intensities. The tail current contribution to the storm maximum disturbance is about −60 nT (for the Dst maximum equal to −78 nT).

An abrupt increase of the solar wind pressure during the recovery phase of the magnetic storm strongly influences the intensity of the magnetopause current; however, the magnetotail current system remains at the quiet level. The tail current enhancement at 1100 UT on January 11, 1997, is associated with the substorm activity and is controlled mainly by the parameters of magnetospheric origin. To describe the corresponding increase in the total magnetospheric magnetic field, both the direct action of the solar wind and the processes of energy accumulation and dissipation in the magnetosphere should be taken into account.

To determine the role of the tail current dynamics we compared our calculations with those made by *Turner et al.* [2000]. In contrast to the T96 model, the paraboloid one describes well the Dst profile not only during the storm maximum but also during the strong magnetospheric compression. The results obtained demonstrate the broader validity interval of the paraboloid model in comparison to the T96 model. The underestimation of the current sheet contribution to Dst made by *Turner et al.* [2000] is explained by their choice of a model of the current sheet with fixed earthward edge and by their neglect of the closure currents on the magnetopause, which form a joint tail current system and vary synchronously with the currents of the magnetotail. Unlike the empirical T96 model, the paraboloid one enables us to take into account the dynamics of all current systems. The submodels formulate the methods of calculation of each parameter of the large-scale current systems in the magnetosphere and allow us to take into account the significant differences in the processes of the formation of various current systems.

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