Time-dependent responses of the neutral mass density to magnetospheric energy inputs into the cusp region in the thermosphere: A high-resolution two-dimensional local modeling

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Title page:

Time-dependent responses of the neutral mass density to magnetospheric energy inputs into the cusp region in the thermosphere: A high-resolution two-dimensional local modeling

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Abstract

Remarkable enhancements of the thermospheric mass density around the 400-km altitude in the cusp region have been observed by the CHAllenging Minisatellite Payload (CHAMP) satellite. We employed a high-resolution two-dimensional local model to gain insights into the extent to which the neutral-ion drag process controls the mass density’s enhancements under the energy inputs typical of the cusp. We expressed those energy inputs by quasi-static electric fields and electron precipitation. We compared two cases and calculated the thermospheric dynamics with and without neutral-ion drags. We found that in the more realistic case containing the neutral-ion drag, the calculated mass density enhancement was 10% at most, which is dramatically smaller than the observations by the CHAMP satellite (33% on average). The results also showed that the neutral-ion drag process suppresses Joule heating and neutral mass density enhancements, as well as the chemical reaction process. The discrepancy between our modeling result and the satellite observation suggests the existence of additional energy sources, such as Alfvén waves propagating from the magnetosphere, which play an important role in the cusp’s density enhancement.

Keywords:
neutral mass density anomaly, neutral upwelling, cusp, Joule heating, neutral-ion drag

**Main Text**

1. **Introduction**

The cusp is typically located around 75° magnetic latitude between ~1000 and ~1400 magnetic local time in the altitudes of the ionosphere–thermosphere, where low energy electrons almost directly come from the dayside magnetosheath. The ionosphere–thermosphere dynamics in the cusp region are extremely complicated depending on inputs from the dayside magnetosheath (e.g., solar wind particles and interplanetary magnetic fields [IMFs]) and the condition of solar extreme ultraviolet (EUV) radiation. Recent CHAllenging Minisatellite Payload (CHAMP) satellite observations have shown that the neutral mass density around the 400-km altitude in the cusp is remarkably larger than that of ambient regions. After Lühr et al.’s (2004) discovery, the anomalous mass density structure and other related phenomena have been extensively investigated in observational and modeling studies. Kervalishvili and Lühr (2013) have shown that the mass density enhancement is, on average, 33%. The mass density anomaly is considered to be generated by thermospheric heating processes, such as Joule heating and particle heating, which drive neutral upwelling.
Joule heating is caused by Pedersen currents depending on Pedersen conductivities, perpendicular electric fields, and neutral winds. Electron precipitation enhances Pedersen conductivity and, thus, Joule heating by ionization. In addition, electron precipitation directly heats the neutral atmosphere.

Many modeling studies have been conducted to reproduce the mass density anomaly. Under geomagnetically disturbed conditions, previous studies have partially been successful in reproducing the mass density anomaly, while still facing difficulties in reproducing sufficient mass density enhancements under quiet conditions. Crowley et al. (2010) calculated mass density enhancements during strong IMF $B_Y$ (+20 nT) conditions and managed to generate mass density enhancements of over 200%. Wilder et al. (2012) also employed the Thermosphere-Ionosphere-Mesosphere-Electrodynamics General Circulation Model (TIME-GCM) (Roble et al. 1988; Roble and Ridley 1994) and created a density change of over 100% for a geomagnetic storm. Drawing on Ridley et al.’s (2006) Global Ionosphere–Thermosphere Model (GITM), Deng et al. (2013) imposed an intense Poynting flux of 75 mW/m$^2$ and increased mass density by 60%. Crowley et al. (2010), Wilder et al. (2012), and Deng et al. (2013) all assumed highly strong disturbances. Brinkman et al. (2016), who used the Aerospace Dynamical Model (ADM) (Walterscheid and Schubert 1990), obtained the result consistent with
observation as far as the model of moderate energy inputs is concerned. However, for the
strongest energy inputs arising from geomagnetic storms, their model’s density enhancements were well below the observations. Overall, the complete explanation of the mass density anomaly for various conditions remains to be established.

Many previous studies have used global models such as TIME-GCM and GITM, which have a horizontal resolution of around 100 km and a vertical resolution of one-half scale height. However, the density anomaly has small-scale features, such as kilometer-scale field-aligned currents and strong vertical dependencies of heating. Therefore, such global models’ spatial resolutions may be insufficient to describe the cusp’s density structures.

Furthermore, the ion density, temperature, and velocity are highly variable, and these high variabilities may considerably affect the neutral dynamics in the high-latitude ionosphere. Thus, the precise calculations of spatially dependent and time-dependent ions’ profiles are crucial to the study of such ionosphere–thermosphere dynamics.

In this study, we investigated how ionospheric–thermospheric processes, such as Joule heating, drag forces, and ion motion, contribute to the mass density anomaly by developing a two-dimensional local model. We also examined the importance of time-dependent features of ions for neutral dynamics. For this study, we compared two cases: one with and another without neutral-ion drags.
2. Model description

2.1. Neutral dynamics

We consider the neutrals to be composed of $N_2$, $O_2$, NO, N, O, and He. The continuity equation of neutrals is

$$\frac{\partial n_j}{\partial t} + \nabla \cdot (n_j u_n) = 0, \ (j = N_2, O_2, NO, N, O, He) \ (1),$$

where $n_j$ is the number density of neutral species $j$, and $u_n$ is the neutral flow velocity.

Including Coriolis force, pressure, collision to ions, gravity, and viscosity, the momentum equation of neutrals can be written as

$$\frac{\partial u_n}{\partial t} + (u_n \cdot \nabla) u_n + 2\Omega \times u_n = -\frac{1}{\rho_n} \nabla p_n - \nu_{ni}(u_n - u_i) + G + \frac{1}{\rho_n} \nabla \cdot (\eta \nabla u_n) \ (2),$$

where $\Omega$, $\rho_n$, $p_n$, $\nu_{ni}$, $G$, and $\eta$ are the angular velocity of the Earth’s rotation, the neutral mass density, the neutral pressure, the neutral-ion collision frequency, the gravitational acceleration, and the dynamic viscosity, respectively.

Considering adiabatic expansion, heat conduction, and external heating, the energy equation of neutrals is given by

$$\frac{\partial T_n}{\partial t} + u_n \cdot \nabla T_n = -\frac{RT_n}{c_v} \nabla \cdot u_n + \frac{1}{\rho_n c_v} \nabla \cdot (\kappa \nabla T_n) + \frac{Q}{\rho_n c_v} \ (3),$$

where $T_n$, $R$, $c_v$, $\kappa$, and $Q$ are the neutral temperature, the specific gas constant, the specific heat capacity at constant volume, the heat conductivity, and the volumetric...
heating rate, respectively. In the auroral region, the external heat sources are mainly Joule
heating and particle heating. The former $Q_j$ is given by
\[ Q_j = \sigma_p (E + u_n \times B)^2 \] (4).
where $\sigma_p$ is the Pedersen conductivity. The latter $Q_p$ will be described in 2.3.

2.2. Ion dynamics

We consider the ions to be composed of $O_2^+$, $N_2^+$, NO+, and O+. The continuity equation
of ions is
\[ \frac{\partial n_k}{\partial t} + \nabla \cdot (n_k u_i) = S_k, (k = O_2^+, N_2^+, NO^+, O^+) \] (5),
where $S_k$ is the source term by ionization, recombination, and other chemical reactions.
This term will be described again in 2.3.

Assuming time derivative, advection, Coriolis force, and viscosity to be zero, the
momentum equation of ions is
\[ 0 = -\frac{1}{\rho_i} \nabla p_i + \frac{e}{m_i} (E + u_i \times B) - \nu_i n (u_i - u_n) + G \] (6),
where $e$ is the elementary charge, and $m_i$ is the mean molecular mass of ions.

In the perpendicular component of (6), Lorenz and collisional forces are dominant. Thus,
we can derive the perpendicular component of $u_i$ (i.e., $u_{i\perp}$) as follows:
\[ u_{i\perp} = u_{n\perp} + \frac{k_i}{1 + k_i^2} \frac{E + u_n \times B}{B} + \frac{k_i^2}{1 + k_i^2} \frac{(E + u_n \times B) \times B}{B^2} \] (7),
where \( k_i = \Omega_i / \nu_{in} \) (\( \Omega_i = eB / m_i \) is the gyro frequency of ions).

The motion of ions to the parallel direction is determined by ambipolar diffusion. Therefore, \( u_{i\parallel} \) is given by

\[
u_{i\parallel} = \nu_{n\parallel} - D_a \left[ \frac{1}{n_iT_p} V_{i\parallel} (n_iT_p) + \frac{\sin I}{H_p B} \right] (8),
\]

where

\[
T_p = \frac{T_e + T_i}{2}, \quad D_a = \frac{2k_B T_p}{m_i \nu_{in}}, \quad H_p = \frac{2k_B T_p}{m_i G} (9).
\]

\( T_p, D_a, \) and \( H_p \) are the plasma temperature, the ambipolar diffusion coefficient, and the plasma scale height, respectively. \( T_e \) is the electron temperature, and \( T_i \) is the ion temperature. \( I \) is the geomagnetic inclination, which is set to be 90° in this study for convenience.

The ion temperature is approximated well by assuming a balance between the frictional heating and the heat exchange with neutrals as follows (St.-Maurice and Hanson 1982):

\[
T_i = T_n + \frac{m_n}{3k_B} (u_i - u_n)^2 \quad (10).
\]

### 2.3. Electron precipitation

To describe the effects of electron precipitation, we employed Fang et al.’s (2010) empirical model, which derives the altitude profile of the total ionization rate due to electron precipitation. We assumed the differential number flux of precipitating electrons
\( \phi(U) \) as a kappa distribution as follows:

\[
\phi(U) = \frac{Q_0}{2U_0^2} \cdot \frac{(\kappa-1)(\kappa-2)}{\kappa^2} U \left( 1 + \frac{U}{\kappa U_0} \right)^{-\kappa-1}, \quad (\kappa = 4.97) \quad (11),
\]

where \( Q_0 \) is the total energy flux, and \( U_0 \) is the characteristic energy. The peak altitude of the ionization increases for lower characteristic energies. In the cusp region, the electron precipitation is characterized by “soft” (~100 eV) electrons coming almost directly from the magnetosheath.

Another effect of electron precipitation is particle heating. Precipitating electrons collide with neutral molecules and transfer energy. Some energy is lost by dissociation and radiation, and the rest eventually heats the molecules. Using the total ionization rate \( P \) \( [m^{-3}s^{-1}] \), the particle heating rate \( Q_p \) \( [eV/m^3s] \) is given by

\[
Q_p = \Delta \epsilon P C_{eff} \quad (12),
\]

where \( \Delta \epsilon = 35 \text{ eV} \) is the mean ionization energy, and \( C_{eff} \) is the heating efficiency as an empirical function of height (Rees et al. 1983; Richards 2013).

### 2.4. Numerical implementation

This study develops a new two-dimensional local model based on Shinagawa and Oyama’s (2006) thermospheric neutral model. We set the x-axis, y-axis, and z-axis to be directed eastwardly, northwardly, and upwardly. All physical quantities were assumed to
be uniform in the x-direction. The numerical domain ranged from 0 to 700 km in altitude and from −3,000 to 3,000 km in meridional distance. We separate the domain into cells with a vertical size of Δz = 5 km and a horizontal size of Δy = 10 km. The time step Δt was set to be 1 ms. We employed the CIP (Cubic-Interpolated Pseudoparticle) method (Takewaki et al. 1985; Yabe et al. 1991; Yabe and Wang 1991) to obtain the time evolution. We set boundary conditions as follows: At y = −3,000, 3,000 km, \( \frac{\partial f}{\partial y} = 0 \) for any physical quantity \( f \). At z = 0 km, \( \mathbf{u}_n = 0, \frac{\partial T_n}{\partial z} = 0, \) and \( \frac{\partial n_n}{\partial z} = 0 \). At z = 700 km, \( \frac{\partial \mathbf{u}_n}{\partial z} = 0, \frac{\partial T_n}{\partial z} = 0, \frac{\partial n_n}{\partial z} = -\frac{n_n}{H_n} \), and \( \frac{\partial n_i}{\partial z} = -n_i/H_p \). The last two conditions mean diffusion equilibrium for neutrals and ions. The precipitating electron flux \( Q_0 \) and the northward electric field \( E_y \) were set to be Gaussian functions as follows:

\[
Q_0(y) = Q \exp \left[ -\left( \frac{y}{W/2} \right)^2 \right], \quad E_y(y) = E \exp \left[ -\left( \frac{y}{W/2} + \frac{1}{\sqrt{2}} \right)^2 \right] \tag{13}
\]

where \( W \) is the scale width and set to be 200 km as a typical meridional width of the cusp. The peak of electron precipitation is located at the center (\( y = 0 \) km). The electric field peak was shifted from the center to the south to maximize the meridional gradient of \( E_y \) and, thus, the upward field-aligned current at the center. In this study, we set the peak electric field \( E \) to be 60 mV/m. Electron precipitation was imposed with total energy flux \( Q \) of 1.6 mW/m² and characteristic energy \( U_0 \) of 100 eV, which indicates “soft”
electrons into the cusp.

The initial condition of neutrals was set by the NRLMSISE-00 model (Picone et al. 2002) with input parameters of $F_{10.7} = 100$ and $A_p = 10$. The ion profile was derived from the IRI-2016 model (Bilitza et al. 2017). Since the original profile given by IRI-2016 was not in equilibrium, we first ran the model for six hours without any external forcing. The resulting ion profile was used as the initial condition in the following calculations.

2.5. Modeling runs

We performed three modeling runs to investigate the contributions of neutral-ion drags to the neutral atmosphere. We calculated with neutral-ion drags in Case 1 and without them in Case 2. Specifically, the collisional term of (2) $-v_{ni}(u_n - u_i)$ was dropped in Case 2. All the modeling runs lasted 7,200 s (two hours).

3. Results

3.1. Comparing the contributions of various ionospheric processes

We define fractional density change as $\Delta \rho / \rho_0$, where $\rho_0$ is the initial neutral mass density, and $\Delta \rho$ is the difference of neutral mass density from $\rho_0$. Therefore, $\Delta \rho / \rho_0$ indicates the relative enhancement of mass density. For instance, $\Delta \rho / \rho_0 = 0.1$ means a
10% increase from the initial condition. Figure 1 shows the resulting north-south profiles around the center at $t = 7,200$ s. The right side (positive values) of the horizontal axis is the north. The contour maps in Figure 1a show the fractional density change, and vectors show the neutral flow velocity. Figures 1b and 1c show the neutral temperature change and specific heating rate, respectively. In altitudes of 200 to 400 km, the specific heating rate is maximized, and then neutral air heats, which causes neutral upwelling and mass density enhancements. Figure 1 shows that mass density enhancement, upward neutral velocity, and the specific heating rate of Case 1 are all smaller than those in Case 2. The peak values of mass density changes, neutral temperature changes, and vertical neutral velocity are summarized in Table 1. The peak of mass density is located north from the center in Case 1. When neutral-ion drags are present, the neutral air is pulled into the direction of the $E \times B$ drift (westward). After that, the Coriolis force pulls the neutrals northward, causing the large mass density in the northern region. The differences in peak locations between the electric field and electron precipitation also cause weak asymmetry.

Figure 2 shows the neutral atmosphere profiles at the 400-km altitude. Figures 2a, 2b, 2c, and 2d show the mass density enhancements, temperature changes, northward velocity, and upward velocity. Similar to Figure 1, the three neutral parameters in Case 1 are all
smaller than those in Case 2. The mass density in the north in Case 1 is larger than that in the south. Figure 2c shows that the Coriolis force suppresses the southward flow in the south region in Case 1. The peak values of the mass density changes at the 400-km altitude are 9.5% in Case 1 and 12.1% in Case 2. Considering that CHAMP’s mean mass density enhancements are 33% (Kervalishvili and Lühr 2013), as mentioned above, the peak values in our results are smaller than the observations. This will be discussed in Section 4.

3.2. Time evolution of neutral mass density and Joule heating rate

Figure 3 shows the time evolution of mass density changes at the 400-km altitude and the volumetric heating rate at the 300-km altitude, where Joule heating drives neutral upwelling most effectively. Figure 3a shows that the neutral mass density oscillates until about 50 min due to atmospheric gravity waves caused by sudden commencement of heating at 0 min (in our calculations, electric fields and electron precipitation rise as step functions at the beginning). After 50 min, the mass density increases very slowly in both cases.

Figure 3b shows the time evolution of the volumetric heating rate. In both cases, Joule heating initially increases by ionization and then decreases at several tens of minutes. The
volumetric heating rate at the 300-km altitude is initially 1.3 nW/m$^3$ and eventually grows to 2.0 nW/m$^3$ in Case 1 and 3.5 nW/m$^3$ in Case 2. In both cases, the Joule heating rate decreases with time, which is why mass density enhancements hardly enlarge for longer times of energy inputs. Although the difference between the two cases is not huge, the time-dependent ion-neutral coupling is important for calculating Joule heating and neutral mass density enhancements.

4. Discussion

4.1. Effects of each process on the time evolution of Joule heating

Figure 4 shows altitude profiles of the ion density, specific heating rate, ion temperature, and vertical ion velocity at the center at 40 and 120 min intervals in each case. Assuming the $E \times B$ drift flow as the ion, the Joule heating rate (4) can be written as follows:

$$ Q_J = \sigma_p[(u_n - u_i) \times B]^2 \quad (14). $$

Thus, larger velocity differences between neutrals and ions generate larger Joule heating rates. In Case 1, the horizontal neutral velocity is pulled into the $E \times B$ drift direction and finally reaches a value where the neutral-ion drag and viscous forces are balanced. (The Coriolis force is tiny in this direction.) Therefore, the neutral-ion drag reduces the Joule
heating, which is consistent with Billet et al.’s (2020) observations. Figures 4b and 4c show that both ion temperature and specific heating rate of Case 2 are larger than those of Case 1 since large velocity differences between neutrals and ions are maintained in Case 2.

In the $F$ layer, the major ion species is $O^+$, and the dominant chemical reactions are

\[
\begin{align*}
N_2^+ + O & \rightarrow O^+ + N_2 \\
O^+ + N_2 & \rightarrow NO^+ + N \\
O^+ + O_2 & \rightarrow O_2^+ + O
\end{align*}
\]

Neutral upwelling brings molecule-rich air to higher altitudes (Fuller-Rowell et al. 1996; Lu et al. 2016). Thus, the three chemical reactions above all act to decrease the $O^+$ density in the $F$ layer (Figure 4a). Figure 4d shows ion down-flow at 120 min, corresponding to the reduction of ions.

Both neutral-ion drags and chemical reactions in this model reduce Joule heating rates. This result crucially indicates that the cusp’s neutral mass density cannot be evaluated correctly in the fixed ionosphere condition.

### 4.2. Comparison with previous studies

Brinkman et al. (2016) have calculated mass density enhancements for various input parameters. Assuming that the electric field is $10 + 50$ mV/m (DC and AC components, respectively), the total energy flux is 1.6 mW/m², with a characteristic energy of 100 eV
and the cusp’s meridional width of 2°, Brinkman et al. (2016) have shown that the resulting mass density increase at the 400-km altitude is larger than 30%. In this calculation, Brinkman et al. (2016) used fully ionized and fixed ionospheric profiles. In contrast, our model solved ion density, temperature, and velocity dynamically, which were not included in Brinkman et al.’s (2016) study. In our study with almost the same conditions, the density increase was 10% in Case 1 and 12% in Case 2; a more realistic model cannot reproduce larger density enhancements. This indicates that energy sources other than those we considered crucial are needed to gain insights into the density enhancements.

Previous studies have reported that electric field variability by Alfvén waves can play important roles (Deng et al. 2009; Zhu et al. 2019). Since alternating electric fields keep velocity differences between neutrals and ions large, the mass density’s time evolution may differ from what we presented above. Lotko and Zhang (2018) have shown that Joule heating rates generated by Alfvén waves are maximized at $F$ layer altitudes, with the altitude profile depending on wavelength and frequency. In contrast, quasi-static electric fields maximize Joule heating rates at $E$ layer altitudes. We treated only quasi-static electric fields in this study. Alfvén waves propagating from the magnetosphere are candidates for the additional energy sources.
At present, we make a simple estimation of Alfvénic power to reproduce the observations. Oscillating electric fields, on average, result in no horizontal ion motion. Thus, we can estimate the average horizontal ion velocity $u'_i\perp$ as follows:

$$u'_i\perp = u_n\perp + \frac{k_i}{1+k_i^2} \frac{u_n \times B}{B} + \frac{k_i^2}{1+k_i^2} \frac{(u_n \times B) \times B}{B^2} \quad (16).$$

We used $u'_i\perp$ to calculate (2) and (5), but original $u_i\perp$ was used in (10). Additionally, the electric field peak was placed simply at the center rather than (13), since Alfvénic fluctuations were excluded in large-scale field-aligned currents expressed by the gradients of $E_y$ in (13). In this estimation, the mass density enhancement at the 400-km altitude became 31% when the electric field was 150 mV/m. This magnitude is too large as a typical value of quasi-static electric fields but not an unrealistic value of Alfvén waves amplitude. Swarm observations have shown that Alfvénic electric fields can exceed 100 mV/m during moderately active conditions (Pakhotin et al. 2020). For an in-depth discussion, it is essential to precisely calculate the height profile of Alfvén heating, which will be explored in our future works.

5. **Summary**

We used a high-resolution numerical model to investigate the neutral mass density’s time-dependent responses to magnetospheric energy inputs into the cusp region.
Contributions of neutral-ion drags were compared using two cases with and without neutral-ion drags. Neutral-ion drag forces decrease velocity differences between neutrals and ions. Chemical reactions reduce ions at $F$ layer altitudes in response to neutral upwelling. Both two processes suppress the Joule heating rate and mass density enhancements. The mass density enhancement in the calculation containing the neutral-ion drag process is 10% at most, which is remarkably smaller than the observations by the CHAMP satellite (33% on average). This non-negligible discrepancy indicates additional energy sources such as Alfvén waves propagating from the magnetosphere, which play an important role in the cusp’s density enhancement.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

List of abbreviations
Availability of data and materials

The output data in this study can be provided on request to Tomokazu Oigawa.

Competing interests

The authors declare that they have no competing interests.

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Authors’ contributions

TO implemented the simulation model, and prepared the manuscript. HS supervised its implementation. ST designed the study. HS and ST edited the manuscript.

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Preparing illustrations and figures

Figure legends

Figure 1
The resulting north–south profiles of the fractional density change and neutral velocity (top), neutral temperature change (middle), and specific heating rate (bottom) in each case. In the top, the contour maps show the fractional density change, and vectors show the neutral flow velocity. The right side (positive values) of the horizontal axis is the north. The peak of electron precipitation is located at the horizontal center.

Figure 2
The resulting profiles of the fractional density change (top), neutral temperature change (middle top), northward neutral velocity (middle bottom), and vertical neutral velocity (bottom) at the 400-km altitude in each case. Positive distance is directed to the northward. The peak of electron precipitation is located at the center.

Figure 3
The time evolution of the fractional density change (top) and volumetric heating rate (bottom) at the 400-km altitude in each case.

Figure 4
The resulting profiles of the ion density (left), specific heating rate (middle left), ion temperature (middle right), and vertical ion velocity (right) at 40 min (top) and 120 min (bottom) intervals in each case.

Preparing tables

Table 1 The resulting mass density enhancements, neutral temperature change, and vertical neutral velocity
The resulting north–south profiles of the fractional density change and neutral velocity (top), neutral temperature change (middle), and specific heating rate (bottom) in each case. In the top, the contour maps show the fractional density change, and vectors show the neutral flow velocity. The right side
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Figure 2

The resulting profiles of the fractional density change (top), neutral temperature change (middle top), northward neutral velocity (middle bottom), and vertical neutral velocity (bottom) at the 400-km altitude in
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**Figure 3**

The time evolution of the fractional density change (top) and volumetric heating rate (bottom) at the 400-km altitude in each case.
Figure 4

The resulting profiles of the ion density (left), specific heating rate (middle left), ion temperature (middle right), and vertical ion velocity (right) at 40 min (top) and 120 min (bottom) intervals in each case.

Supplementary Files

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- table1.xls
- graphicalabstract.png