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Artificial Beam Injection in the stratosphere for modifying Ozone depleted hazardous environment: A model approach

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Abstract

It is demonstrated in the paper that electron beam injection from high-altitude balloons could create local perturbations of ozone and some other minor atmospheric constituents, a novel approach specially for restoring depleted stratospheric ozone. Theoretical analysis of the problem and the results of numerical computations are presented, displaying noticeable increase of ozone concentration near balloon. Such exercise is of special significance as it is known that stratospheric ozone layer plays the main role in protection of the Earth's surface from hazardous UV radiation. The dynamics of ozone in this layer is very complicated and often significant depletion in ozone concentration (especially near poles) is detected. That is why to investigate various mechanisms suitable for ozone restoration in the stratosphere is of prime importance.

1. Introduction

Chemical processes in the middle atmosphere are too complicated and our knowledge of them is not sufficient. At the same time without understanding of such processes it is impossible to predict correctly the dynamics of ozone in the stratosphere and the influence of anthropogenic factor on it. Complicated numerical models are not able to give reliable forecast for extended time periods. Laboratory experiments also cannot reproduce the real situation in the stratosphere (chemical composition, atmospheric winds, and turbulent diffusion). That is why controlled experiment in the stratosphere is desirable. Recently it was suggested to use for such purpose microwave discharge in air [Gurevich et al, 1997; 2000]. Unfortunately, this method requires creation of a special

facility which is very expensive. Alternative possibility is the injection of short pulses of fast electrons from high-altitude balloon [Ruzhin et al, 1999]. Energetic electrons produce significant additional ionization. Nonelastic collisions of secondary electrons with oxygen and nitrogen molecules lead to their dissociation and excitation of different states ($O_2(a^1\Delta g)$), $N_2(A_3\Sigma_u^+$, ...). New born components actively interact with minor atmospheric constituents and cause local perturbations in their composition. Based on numerical computations we predict significant increase of artificially created atomic oxygen which serves as a main source of ozone generation [Borisov et al., 1993].

2. Mechanism of Ozone creation and possible enhancement of its Concentration through artificially injected sources

Ozone is created mainly in triple collisions of atomic oxygen with neutral molecules (Brasseur and Solomon, 1986), see reaction 1 in the Appendix. Atomic oxygen in our case appears due to dissociation of oxygen molecules by fast electrons. In order to exclude more efficient mechanism of atomic oxygen creation by UV radiation in daytime conditions, our experiment should be conducted at night. Let us give a crude estimate of ozone creation. Taking the energy concentrated in one pulse as $W_p = IU\tau_p$ (I is the electric current, U is the potential, τ_p is the pulse duration) ,we obtain an amount of ozone molecules created in one pulse $\Delta N_{O_3} = W_p/\delta\epsilon O_3$, where $\delta\epsilon O_3$ is the energy cost to produce one ozone molecule. The increase of ozone concentration in stationary conditions can be estimated as $\Delta n_{O_3} \approx \frac{Wp}{\delta\epsilon O_3} \frac{f_p}{\pi D_T L_p}$, where D_T is the coefficient of turbulent diffusion and L_p is the relaxation length of the electron beam, f_p is the repetition frequency of electron pulses. Taking for estimate I = 1A, U = 40 keV, $\tau_p = 10^{-5}$ s, f_p = 200 Hz, $\Delta\epsilon O_3$= 50 eV, $D_T = 10^4$ cm^2/s, $L_p = 10^3$ cm we obtain for additional ozone concentration $\Delta n_{O_3} \approx 3.10^{11}$ cm^{-3}. This value is of the order of a background ozone concentration at the heights $h \approx 35 - 40$ km. It is seen that the effect is inversely proportional to the coefficient of turbulent diffusion D_T which is poorly known. It should be mentioned that in real conditions in the stratosphere not only ozone but also some other chemically active components like nitric oxides are created. Due to this the dynamics of ozone is more complicated and in order to find it a system of chemical reactions with the corresponding sources should be solved numerically.

2.1 Sources of Perturbation of minor atmospheric constituents

There is a wide spectrum of scientific interests for active experiments with energetic electron beam injection into the atmosphere. Some key items of interest include beam-plasma discharge and plasma chemistry, neutralization and dynamics of artificial plasma and radio wave propagation problems. Another aspect is the investigation of ozone generation and fission of freons or halogen components. Thus, the scientific topics which are potentially addressed with active experiments in the stratosphere include: different type (regime) air discharges in conditions which not are available in the laboratory; effects of secondary energetic electrons (artificially injected) in the stratosphere (ozone production/destruction); the regime of ozone dynamics during beam-plasma interaction and the role of some halogen reaction; influence of CFCs on ozone dynamics; beam-plasma discharge outside the laboratory, etc. Significant amount of problems mentioned above can be investigated with the help of high altitude balloons (30-45 km). Electron gun injects from balloon short pulses of energetic electrons. Each primary electron with the energy $U \approx 40$ keV gives rise to $\sim 10^3$ secondary electrons. These electrons play the main role in the creation of chemical perturbations near balloon. According to Green and Sawada (1972), the initial distribution function of secondary electrons in the stratosphere can be considered as Maxwellian with the temperature $T_e \approx 10$ eV. Due to nonelastic collisions secondary electrons loose their energy very quickly. This process is described by equation for the distribution function of secondary electrons $F_e^{(2)}(v, t)$

$$\partial F_e^{(2)} / \partial t = - v\sigma_{ne}(v) N_m F_e^{(2)}(v, t), \qquad (1)$$

where σ_{ne} is the total cross-section of nonelastic collisions, N_m is the concentration of neutrals, v is the speed of electron. The amount of oxygen atoms that appear due to dissociations of oxygen molecules in a unit volume during the period t after the creation of a secondary electron is determined by

$$N_O = 2N_{O_2} \int_0^{\Delta t} dt \int_{v_{th}^{(O)}}^{\infty} v^2 \frac{\sigma_{O_2}^{(d)}(v)}{\sigma_{ne}(v)} F_e^{(2)}(v, t)\, dv, \qquad (2)$$

Here $v_{th}^{(O)}$ is the is the threshold electron velocity for dissociation, $\sigma_{O_2}^{(d)}(v)$ is the cross-section of dissociation, N_{O_2} is the concentration of oxygen molecules. With the help of (1), (2) we find the amount of oxygen atoms produced in a unit volume in one second

$$Q_{\mathrm{O}}^{(0)} = 4\pi f_p \frac{N_{O_2}}{N_m} \int_{v_{th}^{(O)}}^{\infty} v^2 \frac{\sigma_{O_2}^{(d)}(v)}{\sigma_{ne}(v)} F_{\mathrm{e}}^{(2)}(v,t)\, d\, v, \qquad (3)$$

where

$$F_{\mathrm{e}}^{(2)}(v) = \frac{n^2}{(2\pi)^{3/2}\, v_{\mathrm{T}}^3} \exp\left(-\frac{v^2}{2v_{\mathrm{T}}^2}\right) \qquad (4)$$

is the initial distribution function of secondary electrons, $n_2 \approx 10^3 \frac{N_e}{\pi a^2 L_p}$ is the concentration of secondary electrons, N_e is the amount of primary electrons in one pulse, determined by the electric current I and the pulse duration τ_p, a is the radius of the beam. In the same manner we find the sources of atomic nitrogen $Q_{\mathrm{N}}^{(0)}$ excited nitrogen molecules $Q_{N_2^*}^{(0)}$ in the state $A_3\Sigma_u^+$, excited oxygen molecules $Q_{O_2^*}^{(0)}$ in the state $a^1\Delta_g$, positive ions $Q_{O_2^+}^{(0)}$, $Q_{N_2^+}^{(0)}$ and free electrons $Q_{\mathrm{e}}^{(0)}$. Only for these sources it should be inserted in (3) the corresponding reduced concentrations and the cross-sections related to the discussed processes.

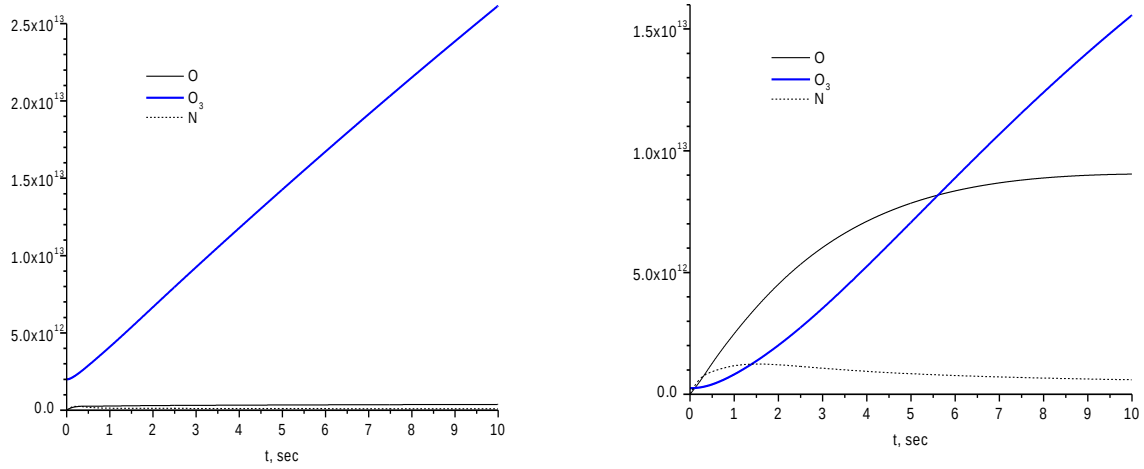

Figure 1: Growth of ozone concentration in time at the heights h = 35 km (Fig. 1a), h = 45 km (Fig. 1b) without turbulent diffusion. On the vertical axis concentrations of ozone, atomic oxygen and nitrogen in cm ^{3} are given.

3. Results of numerical computations

We are interested in the chemical perturbations of minor atmospheric constituents at the heights $h \approx 35-45$ km in nighttime conditions. As the characteristic diffusion time $\Delta t_D \sim a^2/D_T$ is of the order of a few seconds or less, we take into account only fast processes (here a is the radius of the electron beam). Due to this hydrogen components are not included in the scheme. We solve numerically the system of diffusion-type equations for different processes presented in Appendix with the corresponding sources. The sources have a Gaussian distribution $Q_i^{(0)}\exp(-r^2/a^2)$ in the plane orthogonal to the beam of primary electrons, where $Q_i^{(0)}$ are the values in the center of the beam. These values are calculated numerically with the help of the results obtained in the previous section (see (3)). In Figs.1a, 1b the concentration of ozone at the heights h = 35 km, h = 45 km is demonstrated.

Here we present the case when the diffusion is absent (D_T= 0). It is clearly seen the linear growth of ozone with time. The effect is significant even at rather small times $\Delta t_D \sim 1-5$ s. In real conditions the influence of the turbulent diffusion should be taken into account because the action on the stratosphere from the balloon exits only in a localized region across the beam of electrons. This action is rather weak. Due to diffusion the stationary level of perturbations appears at a characteristic time Δt_D. For $D_T = 10^3 \text{cm}^2/\text{s}$, a = 30 cm the diffusion time is of the order of $\Delta t_D \approx 1$ s. The perturbation achieves its maximum value in the center of the beam (r = 0) and decreases by power law for the distances $r > a$. The influence of the turbulent diffusion ($D_T = 10^3$ cm^2/s) on ozone concentration in the center of the beam for the same heights is presented in Figs.2a, 2b. To compare with the previous case when diffusion is absent, the perturbation of ozone concentration is smaller approximately one order of magnitude (at time interval Δt_D). With the growth of the diffusion coefficient D_T the increase of ozone concentration becomes smaller. This result is confirmed by numerical calculations. The perturbations of some other minor atmospheric constituents are presented in Figures.3a, 3b for the same heights and $D_T = 10^3$ cm^2/s.

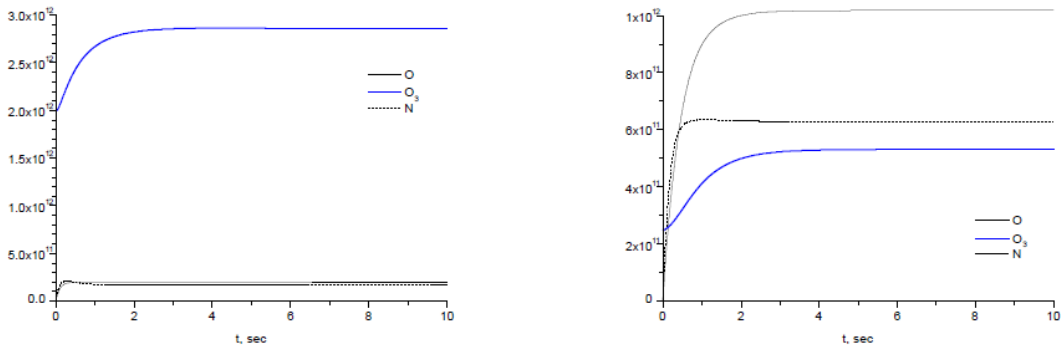

Figure 2: Growth of ozone concentration in time at the heights h = 35 km (Fig. 2a), h = 45 km (Fig. 2b) for the case $D_T = 10^3$ cm^2/s. On the vertical axis concentrations of ozone, atomic oxygen and nitrogen in cm^{-3} are given.

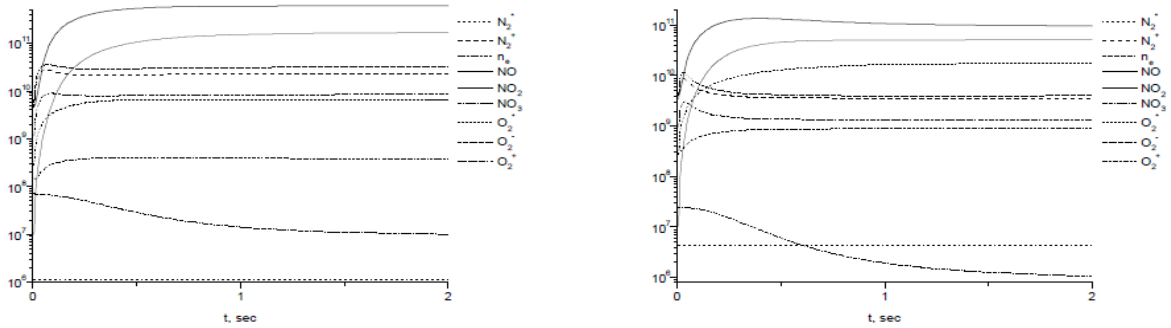

Figure 3: Growth of atomic oxygen O and nitric oxides NO, NO2 in time at the heights h = 35 km, (Fig. 3a), h = 45 km (Fig. 3b) for the case $D_T = 10^3$ cm^2/s. On the vertical axis concentrations of different species in cm^{-3} is given.

4. Conclusion

It is shown with the help of numerical computations that noticeable local changes of minor atmospheric constituents are created by short pulses of energetic electrons from high-altitude balloon at the heights $h\sim$ 35 − 45 km. According to our results ozone production rate up to $(2-5)10^{11}$cm^{-3} s^{-1} is expected in the center of the electron beam at the initial stage of the electron beam injection. Later on turbulent diffusion comes into play and causes significant decrease of the ozone production (compare Figs. 1 and 2). At smaller heights the background concentration of ozone is too large compared to the produced perturbations. At the heights $h \geq$ 50 km the chemical

reactions becomes rather slow to compare with the diffusion time due to the significant decrease of the N_2 and O_2 concentrations. Quantitative predictions based on numerical calculations for different components (O_3, O, N, NO, NO_2, N_2^*,O_2^*) at the heights $h \sim 35 - 45$ km and for different coefficients of turbulent diffusion are given. Our method makes it possible to investigate experimentally the influence on ozone of freons and some other harmful species released from balloon. The suggested experiment can be provided by accurate diagnostics of different types situated on balloon and near it [Ruzhin et al., 1999].

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