SOLAR WIND AND HIGH ENERGY PARTICLE EFFECTS IN THE MIDDLE ATMOSPHERE

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INTRODUCTION

The solar wind is very variable. There are many different solar wind and high-energy particle phenomena (often mutually related) and their variability, which may affect the Earth and its middle atmosphere: variability of v_{SW}; variability of the interplanetary magnetic field (IMF) B and of its components B_x (radial), B_y (azimuthal), B_z (north-south) - southward turning of B_z appears to be very geoactive; crossing the IMF sector boundary (current sheet in interplanetary space); modulation of galactic cosmic rays by solar wind and its IMF (especially Forbush decreases); relativistic electron events (REP); solar cosmic ray bursts (mainly protons with energies 100 keV - 10 GeV); highly relativistic electron events; high speed streams and shock fronts; interaction regions in solar wind; etc. The mechanisms of their effects often overlap each other.

Disturbances caused by solar wind and high energy particles have high preference to winter higher latitudes since most of the energy is focused into the auroral oval and its vicinity (higher latitudes) and because of the lack of solar UV energy (winter).

GEOMAGNETIC ACTIVITY EFFECTS

The high speed streams, shock fronts and changes in solar wind parameters (v_{SW}, B) enhance geomagnetic activity and generate magnetospheric substorms or geomagnetic storms depending on the magnitude of the solar wind energy input.

The penetration (= precipitation) of energetic particles appears to be the main factor responsible for the middle atmosphere response to geomagnetic storms. These particles consist almost exclusively of electrons (E > 20 keV) at middle latitudes. A local middle atmospheric reponse may be affected by transport from high latitudes.

The energy of the penetrating high-energy particles is lost under impact (collisions) or by X-ray bremsstrahlung production. The bremsstrahlung deposits energy at lower levels in the middle atmosphere than the impact does.

The lower ionosphere responds very dramatically to geomagnetic storms. The energy of the penetrating particles is lost, however, not only through ionization, but also through excitation, heating and dissociation processes. They result in effects of various intensities in the neutral middle atmosphere.

Excitation processes result in airglow. Auroral optical phenomena depend very much on the geomagnetic activity, of course. SHEFOV (1973) and RAPOPORT and SHEFOV (1976) found an aftereffect of the geomagnetic storm to exist in the mid- and low-latitude OH emission (night, h $\sim$ 90 km). The effect in midlatitudes begins a few days after the geomagnetic storm and may last as long as 3-4 weeks. It is an effect of transport from the auroral zone, not of local particle precipitation (especially at low latitudes).

Any energy deposition reflects itself in temperature. Therefore, a response of the middle atmosphere temperature to geomagnetic activity is expected to exist. The results of the "Sun-Atmosphere 1969, 1971, 1976" experiments performed at Volgograd and the Heiss Island, of some soundings at the Wallops Island and of some other experiments (KOKIN and MIKHNEVICH, 1974; BUTKO et al., 1974; IVANOVA et al., 1981; RAMAKRISHNA and HEATH, 1977; TULINOV et al., 1975) show that the strongest influence of geomagnetic activity on temperature is observed at high latitudes and make it possible to suggest the following scheme of geomagnetic activity (storms) influence on temperature:

- lower thermosphere and upper mesosphere - heating;
- middle mesosphere (70 km) - opposite variation, cooling;
- lower mesosphere (60 km) - moderate heating;
- upper stratosphere - positive but not much significant correlation.

Figure 1 shows the opposite course of temperature and geomagnetic activity-related corpuscular flux as measured in October 1971 over Volgograd (BUTKO et al., 1976). Results of the same rocket flights for 60 km provide a positive correlation of temperature with geomagnetic activity-related corpuscular flux.

The geomagnetic activity also affects both boundaries of the middle atmosphere, the turbopause and the tropopause. ZIMMERMANN et al. (1982) found a strong correlation of A_p with deviations of the turbopause height h_T from the mean diurnal variation (but not with h_T itself). BROWN and GRAVELLE (1985) reported a significant increase of the tropopause temperature and a decrease of the tropopause height two days after a flare-associated high speed stream incidence on the Earth, but not after recurrent streams.

Winds in the middle atmosphere are expected to respond to geomagnetic activity. Since this topic is treated in more detail by KAZIMIROVSKY (1989), we only mention the existence of an apparent difference between North American (weaker effect) and European (stronger effect) results (LAŠTOVIČKA, 1988a).

Turbulence is another important dynamical parameter in the middle atmosphere. It is not possible to determine whether or not there is a direct relation between the energy input during geomagnetic disturbances and the turbulent state of the high latitude mesosphere (THRANE et al., 1985).

Geomagnetic activity influences the chemical composition of the middle atmosphere, particularly that of minor constituents. The most important minor constituents are O_3 (heat balance) and NO (ionization of the lower ionosphere).

Energetic particles are able to produce NO through dissociative recombination of N_2 and reaction: $N + O_2 \rightarrow NO + O$. Due to the quasi-continuous particle penetration in the auroral zone as a result of magnetospheric substorm activity, the NO concentration in the auroral lower thermosphere is 2-3 times higher than in midlatitudes, and decreases towards low latitudes. The NO concentration at higher latitudes is organized according to geomagnetic rather than geographic coordinates. Similar trends also exist in mesospheric nitric oxide. All these characteristics are confirmed by rocket and satellite observations (e.g. references summarized by RUSCH and CLANCY (1987) and LAŠTOVIČKA (1988a).

Figure 2 gives an example of latitudinal dependence of NO

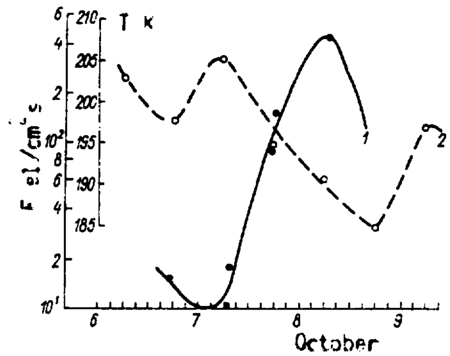

Fig. 1. The opposite course of corpuscular flux (1 - full line - electrons/cm^2s) and temperature (2 - dashed line - absolute temperature) on 6-9 October 1971 (BUTKO et al., 1974).

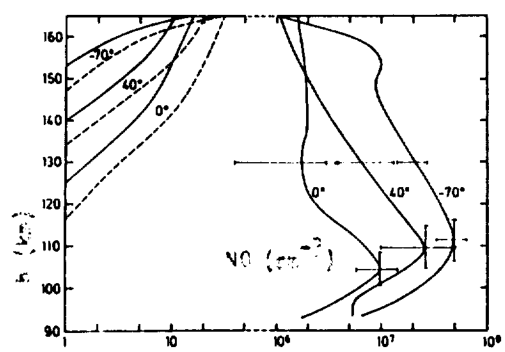

Fig. 2. Three NO-profiles averaged over 5° of latitude (GERARD and NOËL, 1986).

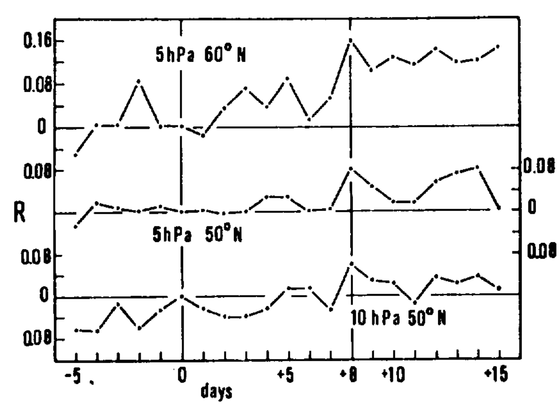

Fig. 3. Changes of stratospheric ozone mixing ratio (R -µg/g) during major geomagnetic storms (61 events, 1979-1983). 0 - day of storm maximum.

concentration in the lower thermosphere based on AE-D measurements. The NO concentration at 70°S is systematically higher than that at 40°N and the NO concentration at equator is again considerably lower.

Some results indicate an increase of NO concentration during post-storm events in middle latitudes, (MÄRCZ, 1983; SINGER et al., 1987). SINGER et al. (1987) suggest that the excess midlatitude NO is created dominantly in situ by local particle bombardment and not by transport.

Another important constituent is ozone. BEKORYUKOV et al. (1976) studied the response of total ozone to geomagnetic storms ($K_p \geq 4$, 1960-70). They found a deep narrow depression in the total ozone in the auroral zone 1 day after the onset of a geomagnetic storm. A considerably weaker but still detectable effect was observed for subauroral zone stations. BEKORYUKOV et al. (1976) try to explain the observed effects in terms of redistribution of stratospheric baric fields. On the other hand, DUHAU and FAVETTO (1989) found a positive correlation between the total ozone concetration observed at the Antarctic Syowa station (1969-85) and the geomagnetic index A_p.

Figure 3 shows our results of investigation of stratospheric ozone response to isolated and major geomagnetic storms (1979-1983). We use the SBUV Nimbus 7 ozone data at 5 and 10 hPa levels and at 40°, 50° and 60°N. Even if we use a "tolerant" criterion of statistical significance - the difference between extreme data points is statistically significant at the 0.05 confidence level - we obtained no statistically significant results for isolated storms and for major storms, 40°N 5 and 10 hPa, 60°N 10 hPa. All "statistically significant" results are given in Figure 4. The maximum is observed on the +8 day, minimum on the -5 day (-4 at 10 hPa). However, in general, we do not observe any well-pronounced effect of geomagnetic storms in the stratospheric ozone.

HIGH-ENERGY PARTICLES

We deal here with 3 types of events: variability of galactic cosmic rays, solar proton events (= solar cosmic rays = solar particle events) and relativistic electron precipitation events. They represent the high-energy part of the spectrum of energetic particles influencing the middle atmosphere. Their effects in the middle atmosphere were reviewed by THORNE (1980).

Galactic cosmic rays are responsible for the ionization of the lowest part of the lower ionosphere and of the stratosphere. They also affect the chemical composition of the middle atmosphere belonging among others to sources of odd nitrogen in the lower stratosphere (THORNE, 1980). The strongest effect in the galactic cosmic ray flux is its Forbush decrease. Some Forbush decrease effects in the mesosphere are treated by SATORI (1989).

The solar proton events (SPE) cause the polar cap absorption (PCA) events in the lower ionosphere, they produce odd nitrogen and odd hydrogen at high latitudes and, consequently, they cause some increase of the nitric oxide concentration above about 50 km and the well-known ozone depletion. The SPE effects in the middle atmosphere are treated in more detail by JACKMAN et al. (1989).

The relativistic electron precipitation (REP) events occur in auroral and subauroral latitudes. Their duration is typically

1-3 h. REP events are associated with magnetospheric substorms. They contribute to the effects of geomagnetic activity in the auroral and subauroral lower ionosphere. The REP events are considered to be the dominant in situ source of nitric oxide in subauroral latitudes in the mesosphere, being important also in the upper stratosphere (THORNE, 1980).

HIGHLY RELATIVISTIC ELECTRONS

BAKER et al. (1987) found an important role of highly relativistic electrons (2-15 MeV) in the middle atmosphere at L-shells about 3-8. Such electrons are largely absent near solar cycle maximum, while they are prominent during the approach to solar minimum. They closely parallel the presence of high-speed solar wind streams (electrons occur on their declining edges), which result from solar coronal hole structures during the approach to solar minimum. Typical rise time of events is 2-3 days with similar decay time (BAKER et al., 1987).

The energy deposition profile of these electrons is shown in Figure 4. The upper part of the "electron" curve represents impact energy deposition, the lower part the bremsstrahlung effect. The highly relativistic electrons dominate during the peak of electron precipitation event between 40-80 (35-85) km with a maximum energy deposition rate between 50-60 km.

The highly relativistic electrons produce odd nitrogen and odd hydrogen. CALLIS et al. (1988) found the production of high levels of odd nitrogen just above the stratosphere and a significant wintertime transport of this odd nitrogen to the stratosphere. This increase of odd nitrogen is expected to decrease ozone concentration. Thus highly relativistic electrons can significantly influence the strato-mesospheric chemistry.

SHELDON (1988) suggested the following chain of phenomena, which leads to the influence of highly relativistic electrons on Antarctic ozone hole formation: enhanced ionization bremstrahlung) in the stratosphere stimulates droplet formation in supersaturated air → formation of polar stratospheric clouds → low stratospheric temperature and ozone depletion.

EFFECTS OF INTERPLANETARY MAGNETIC FIELD

Another factor of solar origin is the interplanetary magnetic field (IMF). There are several possible effects of IMF: those of its components B_z, B_y and B_x, and those of the crossing of the IMF sector boundary. The effects of the changes of IMF components in the lower ionosphere (and probably in the neutral middle atmosphere, if there are any) are essentially a response to the IMF-generated changes in geomagnetic activity. The situation is not so simple, however, when the IMF sector boundary crossing (SBC) effects are considered.

There are two basic types of responses to the IMF SBC, called geomagnetic and tropospheric, both of which are observed in the lower ionosphere. They differ in morphology as well as mechanism (LAŠTOVIČKA, 1979, 1988a).

There are several factors, which make the geoactivity of IMF SBCs variable:

a) The considerable seasonal variability of the ionospheric and atmospheric responses to IMF SBCs.
b) The dependence of the amplitude of effects on the degree of disturbance before the IMF SBC.

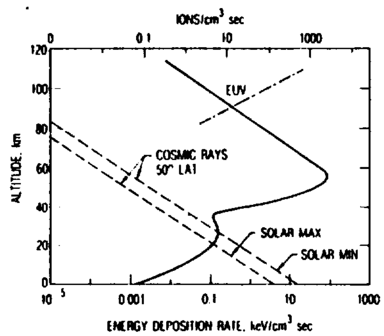

Fig. 4. Energy deposition rate profiles for highly relativistic electrons (full line - peak of an event), galactic cosmic rays and solar EUV radiation (BAKER et al., 1987).

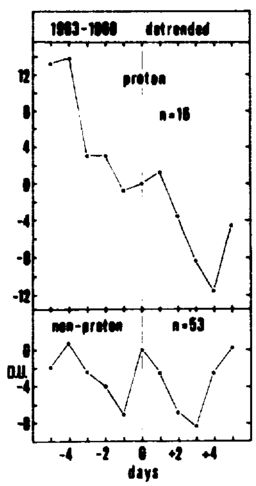

Fig. 5. The IMF SBC effect in the seasonally-detrended midlatitudinal European total ozone, winters 1963-69, for proton and non-proton sector boundaries (BREMER and LAŠTOVIČKA, 1989). Total ozone values in Dobson Units (D.U.) are expressed as a difference from the IMF SBC day value; n - number of IMF SBCs.

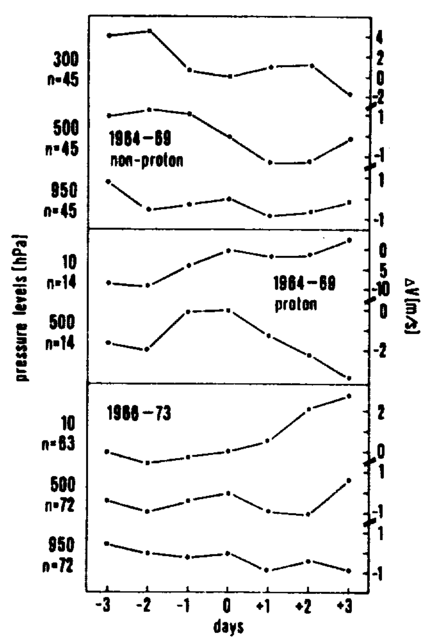

Fig. 6. The IMF SBC effect in wind speed for various pressure levels separately for proton and non-proton boundaries in 1964-69 and for all boundaries in 1966-73. $\Delta V = V - V_0$; n - number of IMF SBCs (LAŠTOVIČKA, 1988b).

c) A different effect of "pro-" and "anti-" sectors, which is important for the geomagnetic type effect.
d) Crossings of proton sector boundaries (the boundaries followed by enhanced streams of low-energy solar protons) evoke considerably stronger effects than crossings of non-proton sector boundaries.

The IMF SBC could influence the ozone concentration. The contradiction between the results of various authors concerning the IMF SBC effect in the total ozone (LAŠTOVIČKA, 1988b) was shown to be rather apparent by BREMER and LAŠTOVIČKA (1989) who found for midlatitude European stations the existence of a statistically significant effect only for proton sector boundaries while the effect of common sector boundaries was quite negligible (Figure 5).

With the use of winter data (December 1979 - December 1982) on the ozone mass mixing ratio between 40°-60°N form the SBUV experiment onboard Nimbus-7, it was found that there was no IMF SBC effect at 0.4, 1, 3 and 10 hPa levels (LAŠTOVIČKA, 1988b; LAŠTOVIČKA and GILL, 1988).

Data on temperature, wind speed and direction, and height of 7 isobaric levels between 1000-10 hPa (10, 30, 50, 100, 300, 500, 1000 or 950 hPa) above Berlin were analysed for winters 1964-73 by LAŠTOVIČKA (1988c). Figure 6 shows for wind speed all the curves, where the difference between mean maximum and mean minimum data points is statistically significant at the 0.1 level (very tolerant criterion). There is no effect in the lower stratosphere (50 and 100 hPa) and only a questionable effect in the middle stratosphere. Similar results were obtained for other parameters.

The observed IMF SBC effects are small. They are in no way a dominant channel of solar activity influence, but they are not negligible in some altitudinal regions.

We may outline the following pattern of the IMF SBC effects in winter at middle latitudes at heights of about 0-100 km (LAŠTOVIČKA, 1988b):

Lower ionosphere - two different effects, the day-time effect of the tropospheric type (quietening) and the night-time effect of the geomagnetic type (disturbance).
Lower mesosphere - no effect in ozone.
Upper stratosphere - no effect in ozone.
Middle stratosphere - no effect in ozone, wind direction and temperature; questionable (if any) effect in isobaric heights and wind speed.
Lower stratosphere - no effect in VAI, isobaric heights, temperature, wind speed and direction.
Troposphere - relatively well-developed effect in VAI and an effect in wind direction, both of the tropospheric type; questionable (if any) effects in isobaric heights, temperature and wind speed.

ENERGY BUDGET

Probably the best attempt to study the energy budget of the middle atmosphere at high latitudes was made in the Energy Budget Campaign (EBC) in Northern Europe in autumn 1980.

Table 1 shows the energy budget at 90 km for two salvoes of the EBC - salvo C (quiet conditions) and salvo A2 (fairly strong geomagnetic disturbance). Even though all the figures given in Table 1 are very rough estimates, there is no doubt that during salvo C the atmosphere at 90 km was strongly out of balance due to the peculiar turbulent structure of that day (OFFERMANN, 1985). As to the role of energetic particles in the energy budget, Table 1 shows that it increases with increasing magnetic activity, but dynamical, photochemical and radiative mechanisms together appear to play a more important role than the particle energy deposition. Nevertheless, the variability and uncertainty of various energy sources/sinks at high latitudes is high and the question of the role of energetic particle and geomagnetic activity influence in the high-latitude middle atmosphere has not been definitely solved yet.

Table 1
Energy budget at 90 km (heating and cooling per one day) for two salvoes of the Energy Budget Campaign after OFFERMANN (1985).

Energy source/sink	salvo C (quiet)	salvo A2 (disturbed)
Particle precipitation	≤ 1 K	≤ 2.5 K
Solar irradiation	5 K	5 K
IR cooling (15 μm)	− 4 K	− 7.5 K
Wave dissipation	< 1 K	1 K
Atomic oxygen recombination	16 K	5 K
Turbulent cooling	0 K	−10 K
Sum	+ 19 K	− 4 K

BE CAREFUL

Solar wind and high energy particle effects in the middle atmosphere are not usually dominant effects and may be often overlapped and masked by other effects. One must be very careful in selecting input data for studying statistical relations between various factors. It is necessary either to eliminate other influences, or to compensate for them, or to take their effects into account when the results are interpreted. The above presented factors, which make the geoactivity of the IMF sector boundaries variable, may serve as an example.

Some corelations or effects may be considerably modulated by quite unexpected factors, as e.g. the phase of the quasi-biennial oscillation, or the role of planetary waves in the middle atmosphere response to periodic solar UV forcing. Similar factors may influence also the middle atmosphere response to solar wind and high energy particle flux variability.

CONCLUSION

The solar wind variability and high-energy particle effects in the neutral middle atmosphere are not much known. These factors are important in the high-latitude upper mesosphere-lower thermosphere energy budget. They influence temperature, composition (minor constituents - nitric oxide, ozone), circulation (wind system) and airglow. The vertical and latitudinal structures of such effects, mechanisms of downward penetration of energy and questions of energy abundance (trigger mechanisms?) are largely to be solved.

The most important recent finding seems to be the discovery of the role of highly relativistic electrons in the middle atmosphere at L = 3 - 8 (BAKER et al., 1987).

The solar wind and high-energy particle flux variability appear to form a part of the chain of possible Sun-weather (climate) relationships. The importance of such studies in the nineties is emphasized by their role in big international programmes STEP and IGBP - Global Change.

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