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RELATION OF Kp INDEX TO SOLAR WIND PARAMETERS

M.Yu.Goncharova, Yu.P.Maltsev *(Polar Geophysical Institute, Apatity, Russia)*

Abstract. Substorm activity index Kp have been related to interplanetary media parameters: interplanetary magnetic field (IMF) B_z component and its variability, total IMF module, solar wind velocity and density, solar wind dynamic pressure, based upon OMNI multi-spacecraft measurements with 1 hr resolution for 28 years. The study has revealed B_s (B southward) component, solar wind velocity and density being the most contributing factors for geomagnetic activity variations. The independent input of all three factors has been shown. Empirical formula relating Kp to these parameters have been suggested.

Introduction

Three-hourly K_p index is commonly used as a measure of substorm activity. The relationship of the geomagnetic activity enhancements to the southward IMF component as a controlling factor was established by Fairfield and Cahill [1966] and explained in terms of reconnection of antiparallel magnetic fields on the dayside [Dungey, 1961] providing the energy transfer from the solar wind to the magnetosphere. However, the substorms happen also under northward IMF [e.g., Maltsev, 1998], and their origin is unclear. Their comparative effectiveness in relation to IMF B_z is one of the purposes of the actual study.

Earlier results of Shatten et al. [1967], in which K_p was plotted versus IMF B_z in GSM coordinate system, indicate that the southward IMF B_z is a controlling factor in a wide magnitude range. Average substorm occurs under IMF B_z = -2 nT [Caan et al., 1978]. However, the scattering in K_p occurrence rate tends to increase towards positive B_z values, and mean K_p to have its minimum near $B_z \approx 0$ that imply the substorm activity is strongly varying for IMF B_z northward and slowly grows with it. This tendency was confirmed by Vorobjev and Zverev [1982] who studied the dependence of AE index on Bz and By IMF components.

The linear relationship between K_p index and solar wind velocity was found by [Snyder et al., 1963; Wilcox et al., 1967], the non-linearity of the AE index under B_z northward was obtained by Vorobjev and Zverev [1982]. The solar wind number density variations were shown to be uneffective for substorm activity by [Wilcox et al., 1967] though they found linear correlation of mean Kp with total interplanetary magnetic field strength. Substorms occur in average under the solar wind dynamic pressure $P_{sw} \approx 4$ nPa and IMF modulus $|B| \approx 13$ nT [Maltsev, 1998]. Note that the average solar wind has $B_z = 0$ nT, $P_{sw} \approx 2.3$ nPa, and $|B| \approx 5$ nT.

Problem of solar wind-magnetosphere coupling and, particularly, substorm predictions was attempted to be solved with a method of coupling functions relating solar wind parameters to geomagnetic indices. Arnoldy [1971] found the linear response of the AE index to the IMF southward component B_s where $B_s = B_z$ for $B_z < 0$ and $B_s = 0$ for $B_z > 0$. Large variety of coupling functions as combinations of basic parameters (B_s, n, V) or (B_z, n, V), and sometimes the IMF variability σ, were tested by Murayama and Hakamada [1975], Murayama [1982], Gleisner and Lundstedt [1997]. It was found the best coupling functions include the product of B_s or B_z in power 1, solar wind velocity in power 1, 2 or 3, and dynamic pressure in 1/2, 1/3 power. Murayama [1982] reported the Bs V^2 coupling function to be surpassing all the others in predicting AL index. Gleisner and Lundstedt [1997] consider $B_s V^2 P^{1/2}$ to be a good predictor for AE index.

In this paper we try to study separate effects of different solar wind parameters to 3 hourly Kp index.

Data base and analysis technique

We use 1-hour data from OMNI program data set for 1963-1991 years from WDC. The variables were as follows: IMF |B|, B_z in GSM coordinate system (nT), its variance $\sigma(B_z)$ in GSE, 3 hr K_p index, solar wind velocity V, km/s and number density n, cm^{-3} and proton temperature T_i. We plotted all variables each versus other both as two- and three-dimensional plots under other parameters being free-varying or fixed. Total of ~20 modifications of contributing factors were considered, some of them have revealed no effect to K_p and were removed from further consideration. The rest of variables were related by empiric formula.

Results

To determine the response of average K_p index to the chosen factor we used the technique of sequential exception of other factors. First, the K_p data were binned according to bins of the chosen factors and mean K_p as well as mean factor values were assigned to each bin together with K_p occurrence probability (or, the same, data amount inside bin). The bin of maximum K_p data amount was binned again by other factor and the operation was repeated unless the averaging inside bins becomes unreliable. When the four principle contributing factors have been determined, three-dimensional plots of average K_p versus two other factors under the third fixed one have been built using two-dimensional bin technique.

The factors revealing weak effect to the K_p index were found as follows: total magnetic field strength |B|, IMF B_z variance $\sigma(B_z)$, proton temperature and kinetic-to-magnetic pressure ratio for protons. These factors were not included into the further analysis and were let to vary free. K_p index was shown to be related mostly to the IMF B_z, the IMF southward component B_s ($B_s = B_z$ under $B_z < 0$ and $B_s = 0$ under $B_z > 0$), solar wind dynamic pressure, solar wind velocity, and proton number density.

The general behavior of K_p index versus IMF B_z in Fig. 1 is shown. Gray scale gives a decimal logarithm of data amount in each 5 nT bin of IMF B_z. The solid curve gives mean K_p as a function of IMF B_z. The tendency of mean K_p to increase with increasing both southward and northward B_z value is well recognized in spite of larger scattering of the data for B_z northward. This unexpected behavior can be caused by solar wind flow properties since low geoeffectiveness of IMF B_z northward have been evidently shown by Arnoldy [1971], Vorobjev and Zverev [1982], Kuznetsov and Sergeev [1983]. Figs. 2 and 3 demonstrate K_p as a function of IMF B_z inside narrow intervals of solar wind velocity V_{SW} and vice versa respectively (the proton number density was not fixed). The character of the $K_p(B_z)$ dependence remains the same in different V_{SW} intervals. The apparent discrepancy between mean K_p values for highest B_z northward is due to the lack of solar wind velocity data for these B_z. The same can be told about linear relationship between K_p and V_{SW} under various B_z conditions. Note that this linear relationship would cancel the interpretation of the geomagnetic activity enhancement under B_z northward due to pure dynamic pressure increase since in this case the dependence would have square power character.

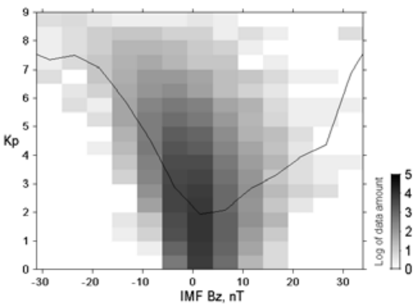

Fig. 1. $K_p$vs B_z, The gray scale is $\log_{10}$ of data amount per 5 nT bin. The solid line is the mean value.

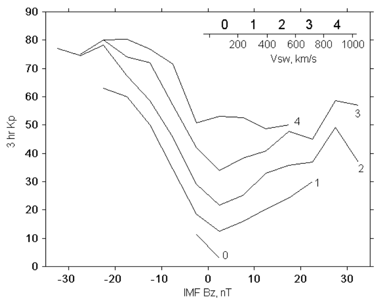

Fig. 2. Mean K_p×10 vs B_z for various V_{SW}.

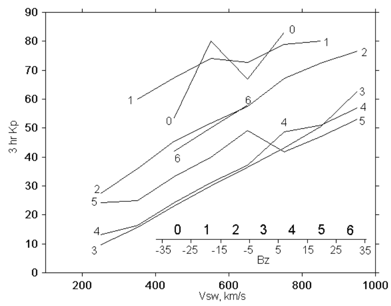

Fig. 3. Mean K_p×10 vs V_{SW} for various B_z.

Mean K_p has also been found to increase slowly with proton number density, which can be seen from Figs. 4, 5, and 6. These figures represent mean K_p (multiplied by 10) given by gray scale with isocontours as a function of proton number density n and solar wind velocity V_{SW} under essentially different IMF B_z conditions.

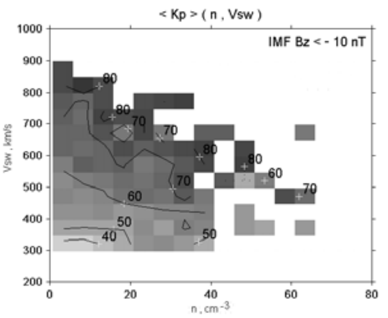

Fig.4. Mean $K_p(n,V_{SW})$ ×10, for B_z < -10 nT

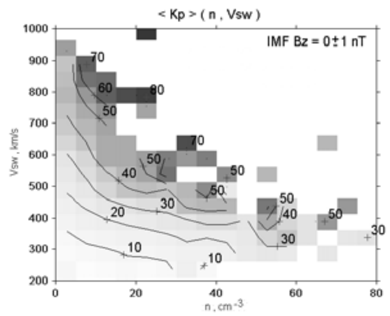

Fig.5. Mean $K_p(n,V_{SW})$ ×10 for $B_z \approx 0$ nT

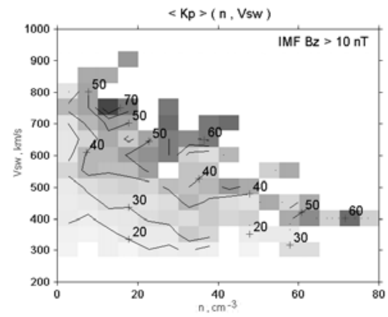

Fig.6. Mean $K_p(n,V_{SW})$×10, for B_z > 10 nT

As seen from Figs. 4, 5, and 6, the close mean K_p values are observed under both near-zeroth and essentially northward B_z conditions that would imply the geoeffectiveness of B_z northward is indeed low in comparison with B_z southward. Clear correspondence between solar wind velocity and proton density along K_p isocontours is also seen. To reveal it we have mutually changed the variables and plotted K_p versus proton number density under fixed and slightly varying IMF B_z conditions.

In Figs. 7, 8, 9 the mean Kp is plotted versus proton number density for fixed solar wind velocity given by gray scale with isocontours. The IMF B_z is chosen to vary inside 3 narrow ranges: -6.5±1.5, 0±1 and 6.5±1.5 nT. The isocontours would show the power character of relationship between K_p and n, providing V and Bz are constant. This character gets clearer under $B_z \approx 0$ and $B_z > 0$. The close likelihood of K_p behavior under $B_z \approx 0$ and $B_z > 0$ would indicate the geoeffectiveness of the IMF B_z is almost the same under these conditions and therefore the best coupling function would contain B_s factor rather than B_z. The same evidence would be confirmed by plot in Fig. 7 which differs strongly from those of Figs. 8, 9. As seen, under B_z=-6.5±1.5 nT large K_p are observed even for extremely low proton number densities whereas under $B_z \approx 0$ and $B_z > 0$ K_p closes to 0 as well as the number density does.

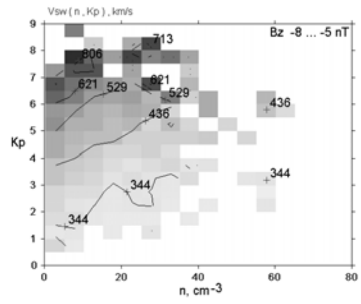

Fig. 7. Mean K_p vs n for fixed V_{SW},· -8 < B_z < -5 nT.

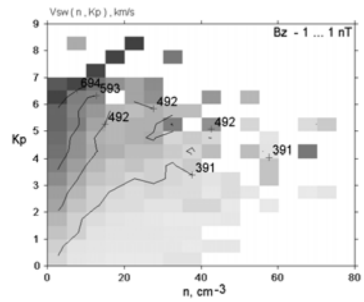

Fig. 8. Mean K_p vs n for fixed V_{SW},· -1 < B_z < 1 nT.

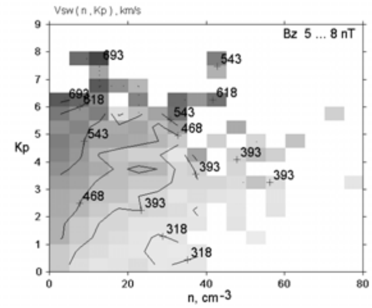

Fig. 9. Mean K_p vs n for fixed V_{SW},· 5 < B_z < 8 nT.

Figs. 10, 11, 12 demonstrate mean K_p behavior versus solar wind velocity V_{SW} under fixed proton number density n. K_p tends to grow linearly with increasing solar wind velocity under $B_z \approx 0$ and $B_z > 0$ though some curvature of $K_p(V_{SW})$ lines for IMF $B_z < 0$ is also observed.

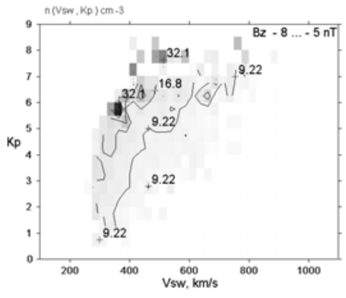

Fig. 10. Mean K_p vs V_{SW} for fixed n,· -8 < B_z < -5 nT

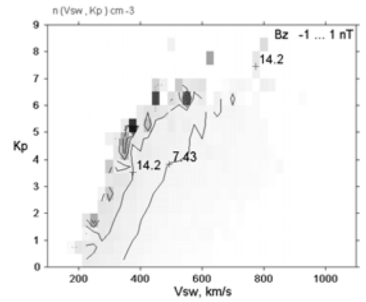

Fig. 11. Mean K_p vs V_{SW} for fixed n,· -1 < B_z < 1 nT

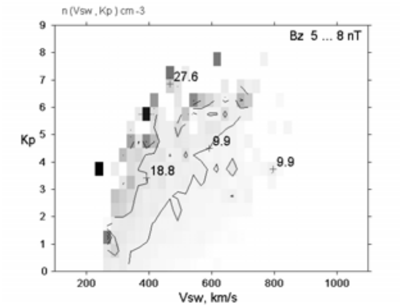

Fig. 12. Mean K_p vs V_{SW} for fixed n,· 5 < B_z < 8 nT

Modeling efforts

Previous authors [Murayama, 1982; Gleisner and Lundstedt, 1997] have studied the correlation of temporal sequences of factors which could be responsible for the geomagnetic activity variations with time. They proposed a number of coupling functions relating the geomagnetic activity indices to a product of solar wind parameters in a certain power. For example, Gleisner and Lundstedt [1997] found $B_sV^2P^{1/2}$ as the best coupling function with AE. Here $B_s = B_z$ under $B_z < 0$ and $B_s = 0$ under $B_z > 0$, V is the solar wind velocity, $P = m_p n_pV^2$ is the solar wind dynamic pressure, m_p and n_p are proton mass and number density respectively. Our results would support the linear proportionality between geomagnetic activity enhancement with solar wind velocity increase as well as the choice in favor of B_s parameter of the IMF. However, functions of this kind are unable to explain the magnetic activity enhancement with B_z northward increase, which is shown in Figs. 1 and 2. They suggest the presence of additive contribution of other solar wind parameters. The most reasonable one is the solar wind velocity as follows from the K_p behavior presented in Figs. 10-12. As seen from Fig. 3, the derivative dK_p/dV does not practically depend on the IMF orientation.

Results in Figs. 4, 5, and 6 can be approximated as follows

$$Kp = \frac{n+70}{8000}V - 2\left(1 + \frac{B_S}{8}\right) \quad (1)$$

where B_s is the IMF southward component ($B_s = B_z$ under $B_z < 0$ and $B_s = 0$ under $B_z > 0$).

Discussion

According to (1), K_p linearly grows with the IMF southward component B_s and does not depend on B_z under $B_z >$ 0. At the first glance, this contradicts to Fig. 1 where K_p grows under both southward and northward IMF. We think Fig. 1 may be explained by intercorrelation of solar wind parameters. Rezhenov and Maltsev [1998] obtained strong correlation of V and n to B_z. The correlation in the -15 nT < B_z < 15 nT range can be expressed approximately as follows: $V = 440 + 40\times(B_z/15)^2$, $n = 7 + 10\times|B_z|/15$. Substituting these expressions into (1) we obtain K_p growing with both the southward and northward IMF. Fig. 13 shows the behavior of the modeled K_p (the dashed line) calculated from expression (1) by using experimental data for n and V associated to corresponding values of B_z. The experimental

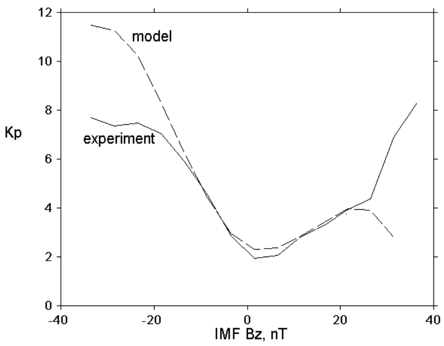

Fig. 13. The experimental and modeled $K_p(B_z)$.

dependence (the solid line reproduced from Fig. 1) agrees well with the modeled dependence in the -20 nT < B_z < 20 nT range.

Murayama [1982] suggested the B_sV^2 as the coupling function for predicting AL index. Gleisner and Lundstedt [1997] using the neural network suggested the dependence AE ~ $n^{1/2}$ V^3 B_s, The both functions predict the zero geomagnetic activity under the northward IMF. However one can see from Figs. 1-3, 5, and 6, that K_p index may be rather large under B_z > 0, hence our approximation (1) is more accurate.

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