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Geomagnetic activity threshold for *F*2-layer negative storms onset: Seasonal dependence

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[1] Geomagnetic activity threshold expressed in *ap* index units for $F2$-layer negative storms onset at middle latitudes exhibits seasonal (winter/summer) variation with summer thresholds being larger than winter ones. That is, for a given magnitude of the ionospheric disturbance, the associated magnetic activity must be larger in summer than in winter. There are also relative minima (or plateau) in the threshold annual variation during equinoctial periods. An analysis has shown that seasonal effect is due to seasonal difference in the thermosphere (O/N_2 ratio) reaction to geomagnetic disturbances, while the equinoctial plateau in the threshold annual variations may be related to the thermospheric circulation and atomic oxygen abundance changes during the equinoctial transition periods. *INDEX TERMS:* 2435 Ionosphere: Ionospheric disturbances; 2788 Magnetospheric Physics: Magnetic storms and substorms; 2431 Ionosphere: Ionosphere/magnetosphere interactions; *KEYWORDS:* Ionosphere-atmosphere interaction; Ionospheric disturbances; magnetic activity.

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1. Introduction

[2] Usual $F2$-layer storms are related to geomagnetic disturbances which are characterized by various indices of geomagnetic activity. It is well known that the correlation between relative δf_oF2 deviations and various indices of geomagnetic activity is not very high [e.g., *Araujo-Pradere et al.*, 2002; *Wrenn,* 1987; *Wu and Wilkinson*, 1957; *Zevakina et al.*, 1990]; however, needs of practice force researchers to develop methods for ionospheric f_oF2 short-term prediction based on indices of geomagnetic activity [e.g., *Araujo-Pradere et al.*, 2002; *Cander and Mihajlovic*, 1998; *Cander et al.*, 1998; *Chan and Cannon,* 2002; *Francis et al.*, 2000, 2001; *Kutiev and Muhtarov*, 2001; *Kutiev et al.*, 1999; *Marin et al.*, 2000; *Mikhailov*, 1990; *Muhtarov and Kutiev*, 1999; *Muhtarov et al.*, 1998; *Wintoft and Cander,* 2000; *Wu and Wilkinson*, 1995; *Zevakina et al.*, 1990]. Planetary geomagnetic activity indices may serve as an indicator of an average (in a statistical sense) disturbance level over the globe, while $F2$-layer perturbation picture is individual for each particular storm and depends on the geomagnetic storm intensity, season, latitude and longitude, UT and LT of storm onset etc. Ionospheric $F2$-layer storms at middle latitudes mainly reflect the state of the disturbed thermosphere (winds, neutral temperature and composition) resulted from high-latitude energy deposition via magnetospheric electric fields and particle precipitation. On one hand, this energy input spatially is not uniform during a geomagnetic storm and different longitudinal sectors turn out to be in different situations, on the other hand the thermosphere reaction to one and the same external impact is different and depends on its current state and prehistory. Unfortunately, the latter is not known in principle and hardly any thermosphere monitoring will be implemented in observable future. All these complexities do not allow to produce a deliberate f_oF2 forecast with an acceptable accuracy for periods of geomagnetic storms [e.g., *Wintoft and Cander*, 2000] which are the most interesting and important from practical point of view. Because of a complex and indirect relationship between $F2$-layer storm effects and the level of geomagnetic activity there is a wide range of estimates for the time delay between geomagnetic and ionospheric storm onsets: 0–6 hours for positive disturbances [*Zevakina and Kiseleva*, 1978], 12 hours [*Wrenn et al.*, 1987], 15 hours [*Wu and Wilkinson*, 1995], 6–12 hours [*Forbes et al.*, 2000]; 16–18 hours [*Kutiev and Muhtarov,* 2001], and 8–20 hours depending on season [*Pant and Sridharan,* 2001].

[3] However, researchers are working in this direction and any empirical regularities revealed in the $F2$-layer storm

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Table 1. List of Stations, Geodetic Coordinates, and Invariant Latitudes of the Stations, Periods of Observations Available, and Total Number of Storms Analyzed

Station	Latitude	Longitude	Invariant Latitude	Period, years	Number of Storms
Slough	51.5	−0.6	49.8	1949–1996	1147
Poitiers	46.6	0.3	45.1	1957–1998	619
Dourbes	50.1	4.6	47.8	1957–1990	642
Juliusruh	54.6	13.4	51.6	1957–1999	917
Uppsala	59.8	17.6	56.6	1957–1999	845
Kaliningrad	54.7	20.6	51.2	1964–1994	616
Kiev	50.7	30.3	46.5	1964–1992	498
St. Petersburg	59.9	30.7	55.9	1957–1998	842
Moscow	55.5	37.3	50.8	1957–1997	947
Nizhny Novgorod	56.1	44.3	51.4	1958–1989	559
Ekaterinburg	56.7	61.1	51.4	1957–1995	797
Tomsk	56.5	84.9	50.9	1957–1997	647
Irkutsk	52.5	104.0	45.6	1957–1997	452
Magadan	60.1	151.0	52.8	1969–1999	749

morphology are important for creating the methods of f_oF2 short-term prediction. Apart from this practical aspect of the problem, physical interpretation of the revealed regularities in storm features help understand $F2$-layer storm formation mechanisms and this is important for ionospheric physics. This paper is devoted to analysis of the seasonal variations in the geomagnetic activity threshold for the ionospheric $F2$-layer negative storms onset. The results of statistical analysis based on f_oF2 ionosonde observations are interpreted in the framework of the $F2$-layer formation mechanism.

2. Data Analysis

[4] An analysis of the $F2$-layer storms at middle latitudes indicates the existence of a threshold for the ionospheric storm onset expressed in ap index units, the threshold being seasonal-dependent. The following analysis aims to clarify the question. As the effect is expected to depend on latitude, only midlatitude stations with close invariant latitudes ($\Phi_{\text{inv}} \approx 50 \pm 5°$) were considered (Table 1). The initial experimental material, available hourly f_oF2 observations at

Table 2. Annual Variations of the Threshold in *ap* Units

Station	Unit											
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Slough	7.17	8.60	5.80	7.72	9.70	13.25	12.52	11.15	8.30	7.85	7.17	6.77
Poitiers	9.85	12.22	6.15	9.02	10.67	13.92	18.20	11.05	9.15	11.00	10.35	7.22
Dourbes	9.50	10.97	4.70	12.35	10.75	14.47	15.60	13.45	8.87	7.95	9.50	6.57
Juliusruh	9.27	8.45	10.10	9.45	10.22	12.45	16.77	13.07	7.70	8.02	7.67	8.00
Uppsala	7.45	12.45	9.52	11.82	10.07	11.30	12.95	14.32	7.70	8.10	11.35	12.30
Kaliningrad	8.65	9.87	11.65	8.90	8.52	10.57	12.15	10.20	8.17	8.90	9.55	9.57
Kiev	10.32	8.47	10.17	10.05	9.90	13.30	13.75	9.97	10.45	10.85	15.12	9.60
St. Petersburg	11.90	11.57	10.57	10.30	7.72	8.85	11.77	11.05	7.37	6.40	11.00	10.15
Moscow	6.22	5.60	7.47	9.05	9.77	10.47	13.30	9.37	9.47	6.40	6.45	6.70
Nizhny Novgorod	9.32	11.02	9.25	9.62	9.72	12.07	11.97	10.62	12.17	9.42	11.65	6.47
Ekaterinburg	8.47	7.37	8.05	8.37	7.90	10.80	11.25	9.10	11.32	9.15	6.10	6.60
Tomsk	8.67	9.00	8.75	7.40	8.12	11.67	12.57	13.10	10.12	8.87	4.75	7.57
Irkutsk	8.35	8.12	10.57	7.55	7.15	10.65	14.27	11.37	10.70	6.82	8.77	7.75
Magadan	6.50	8.15	8.90	8.40	8.00	11.70	11.90	8.77	8.95	7.07	8.95	7.02

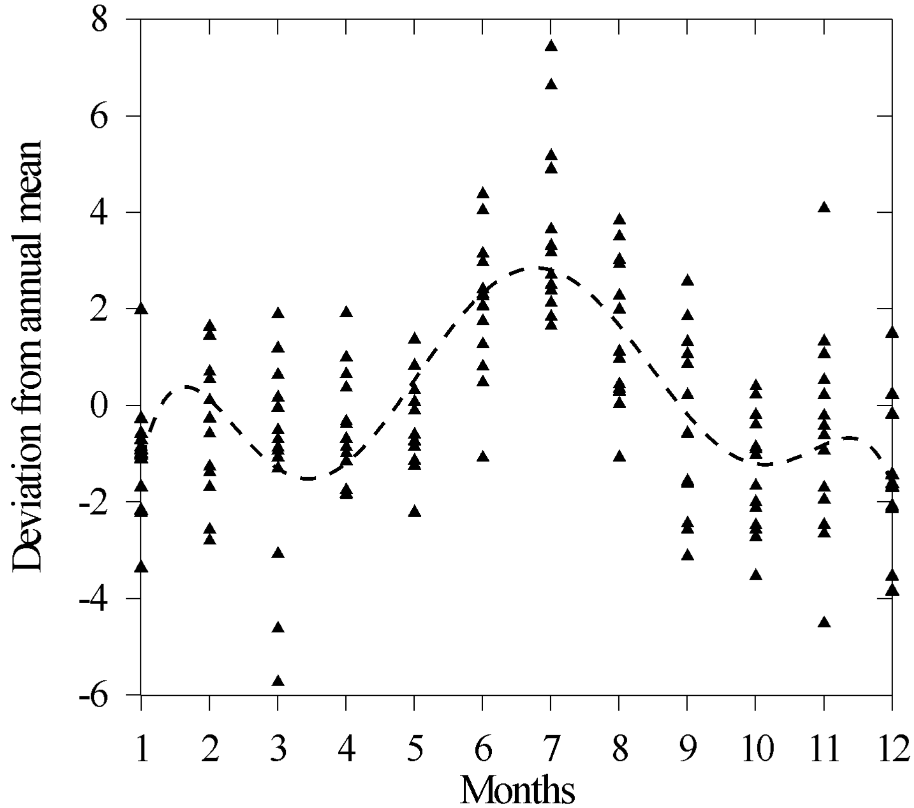

Figure 1. Annual variations of the threshold calculated with respect to the annual mean values (see the text). Dashes indicate the approximating sixth-order polynomial.

the stations listed in Table 1. A 27-day f_oF2 running median centered to the day in question rather than usual monthly median was used in the analysis. The advantages of using such median were discussed by *Mikhailov et al.* [2004]. Only long-duration ($\geq$ 6 hours) negative disturbances with $\delta = (N_mF2/N_mF2_{\rm med} - 1) \times 100\%$ more than 40% were analyzed. Such ionospheric disturbances may be considered to be related to changes in the thermospheric composition and temperature. The ionospheric storm is supposed to begin if $\delta > 40\%$ takes place during 4 successive hours at least. If this requirement is fulfilled, 3-hour *ap* indices for the previous 24 hour period were analyzed. To separate geomagnetic activity induced $F2$-layer disturbances from quiet time ones (Q disturbances [*Mikhailov et al.*, 2004]), at least one of eight ap indices for the previous 24-hour period should be larger than 15. This choice is used in accordance with *Kutiev and Muhtarov's* [2001, and references therein] results which show that the most probable state of the ionosphere corresponds to $kp \approx 3_0$ ($ap = 15$) and on average negative disturbances correspond to geomagnetic activity level higher than $ap = 15$. The threshold was calculated as an average over 8 *ap* indices for the 24-hour period prior the ionospheric storm onset. The choice of 24-hour period is based on the empirical estimations of the ionosphere reaction to the forcing geomagnetic activity (see earlier). The thresholds for all the storms at each station were ordered, and an average of over 5 of the smallest values was referred as a threshold for a given month. The same analysis was applied for 10 the smallest thresholds as well, but the results turned out to be about the same: Only the absolute values of the threshold were larger as cases for more disturbed conditions turned out to be included into the consideration. No separation on solar activity level was made for two reasons. On one hand, no pronounced and systematic dependence of the effect on solar activity has been revealed; on the other hand, analyzing the thresholds distribution over 12 months, the number of cases may turn out to be statistically insufficient in some bins for a particular month if solar activity gradation is applied.

[5] The results of our analysis over 14 stations are given in Table 2. A well-pronounced seasonal (winter/summer) variation is seen for all the stations. The threshold is low in winter and much higher in summer. There is also a pronounced tendency for complementary minima to appear during equinoctial periods. To present these annual variations in a more explicit way, monthly deviations of the thresholds relative to the annual mean values were found for each station and the results are given in Figure 1.

[6] This result implies that the level of geomagnetic disturbances should be higher in summer than in winter to result in the same $F2$-layer negative storm effect. A decrease in

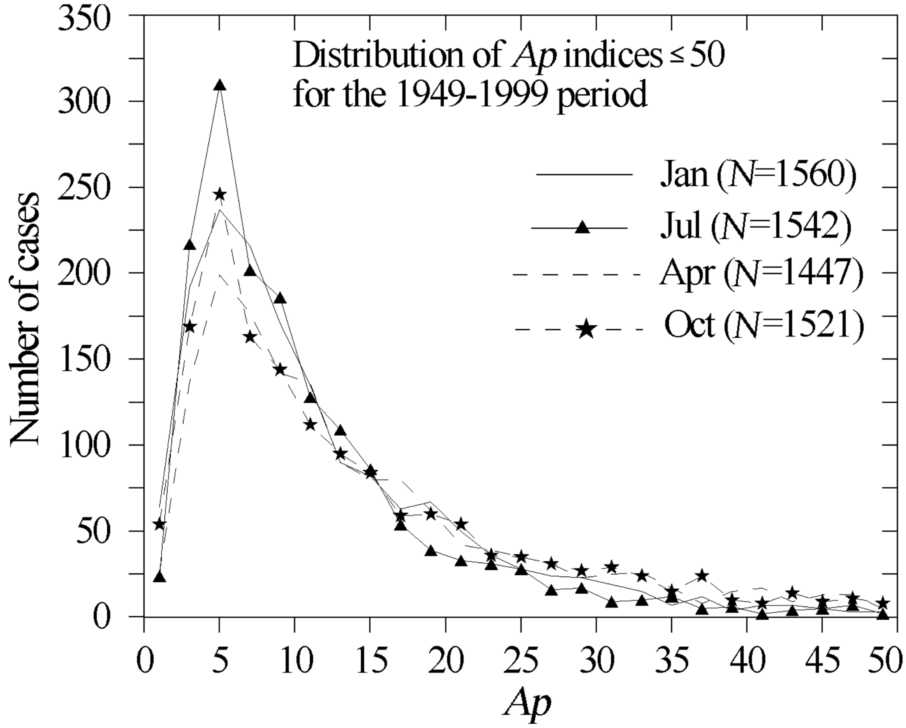

Figure 2. A comparison of daily Ap index distributions for four seasons. Only $Ap \leq 50$ indices for the 1949–1999 period were considered.

the threshold during equinoxes is also an interesting result of our analysis. Let us consider possible explanations for the variations revealed.

3. Interpretation

[7] No systematic seasonal differences in the $Ap \leq 50$ index distribution exist (Figure 2). The Ap distributions are peaking at $Ap \approx 5$ regardless the season; therefore the revealed annual threshold variations cannot be related to a peculiarity in the Ap index distribution. A well-known experimental fact that running average Ap indices exhibit a pronounced equinoctial maximum [e.g., *Roosen*, 1966] does not explain the threshold decrease during equinoxes (Figure 1); moreover, we consider the five smallest thresholds corresponding to low level of geomagnetic activity.

[8] Negative long-duration $F2$-layer storms are known to result from thermospheric neutral composition variations, namely, O/N_2 decrease [e.g., *Prölss*, 1980, 1995]. Therefore there should exist some seasonal difference in the thermosphere reaction to geomagnetic disturbances. The MSIS 86 model [*Hedin*, 1987] gives very small seasonal differences in $\Delta[O/N_2]$ at the $F2$ region heights at moderate high latitudes ($\varphi = 55°$) both for daytime and nighttime disturbances, with summer O/N_2 perturbations being larger than winter ones. This contradicts the European Space Research Organization (ESRO 4) observations by *Prölss and von Zahn* [1977], who found a pronounced seasonal difference in $\Delta(N_2/O)$ at 280 km for middle and high latitudes. The most important for present analysis result of *Prölss and von Zahn* [1977],observations is that "During summer the perturbations are of moderate magnitude compared with the larger disturbance effects commonly seen in the winter hemisphere". This seasonal disturbance effect is also present in the disturbed thermosphere composition model by *Zuzic et al.* [1997] based on the ESRO 4 observations. Figure 3, which can be obtained from the *Zuzic et al.* [1997] model,

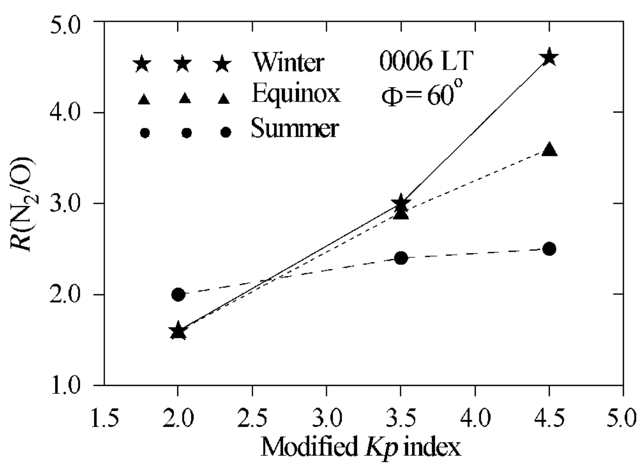

Figure 3. Seasonal difference in the thermosphere reaction to geomagnetic activity obtained from the model by *Zuzic et al.* [1997]. The geomagnetic activity level is presented by modified Kp index used in the model.

gives the $R(N_2/O) = (N_2/O)_{dist}/(N_2/O)_{quiet}$ dependence on geomagnetic activity. The postmidnight (0000–0600) LT sector where negative $F2$-layer disturbances are known to be the most frequent and pronounced was chosen for this illustration. Seasonal difference in the thermosphere reaction to geomagnetic activity is well presented in this model for enhanced geomagnetic activity. The ESRO 4 observed seasonal N_2/O disturbance variations can explain the revealed threshold seasonal changes (Table 2 and Figure 1). Indeed, large winter and equinoctial N_2/O disturbance effect (steep dependence on Kp) needs lower level of geomagnetic activity to overcome the same δN_mF2 disturbance threshold (40% in our case). In summer when N_2/O perturbations are small (gently sloping dependence on Kp), higher geomagnetic activity level is needed to obtain the same $F2$-layer negative storm effect.

[9] The seasonal (winter/summer) threshold variations seem to comprise two parts. The first one reflects seasonal changes of neutral temperature. For the sake of simplicity we may suppose that the thermosphere is isothermal and neutral species [O] and [N_2] are distributed in accordance with the barometric law: $[O] = [O]_0 \exp(-h/H)$ and $[N_2] = [N_2]_0\times \exp(-1.75h/H)$, where $H = kT_n/mg$ is the atomic oxygen scale height. This gives $[O]/[N_2] \propto \exp(0.75h/H)$. Neutral temperature, T_n increases during disturbed periods, so we can write down $d(O/N_2)/dH \propto -\exp(0.75h/H)/H^2$. This expression tells the higher the background neutral temperature T_n (and corresponding H), the smaller the $[O]/[N_2]$ storm-induced changes. Neutral temperature is maximal in summer and minimal in winter (e.g., MSIS 86); therefore summer storm-induced $[O]/[N_2]$ variations should be less compared to winter ones, and this is in line with the ESRO 4 observations.

[10] The second part of the seasonal effect may be attributed to the seasonal difference in the spatial distribution of the perturbed neutral composition [*Prölss and von Zahn*, 1977]. In summer the $[O]/[N_2]$ disturbance zone may extend all the way from the polar to the low latitudes, while in winter it is restricted to high latitudes only. This means that the same energy deposited in the auroral zone during a geomagnetic storm and resulted in the thermosphere perturbation is smeared over the whole hemisphere in summer, but it is localized only at higher latitudes in winter. The effect is known to be due the interaction of seasonal (background) and storm-induced thermospheric circulation [*Duncan*, 1969; *Field et al.*, 1998; *Forbes et al.*, 1996; *Mayr and Volland*, 1972]. This needs stronger geomagnetic disturbances (higher threshold) in summer compared to winter to have the same perturbation effect in neutral composition.

4. Discussion

[11] The calculated thresholds for a given month vary in a wide range so the standard deviations exceed mean values, therefore we were forced to consider 5 (or 10) the smallest values to specify the threshold. However, these (the smallest thresholds) turn out to be relatively low (Table 2), and this looks rather surprising. Some explanations for this effect may be proposed. During our analysis the storms were not distinguished by local time of their onsets. However, the dependence of negative storm onsets on local time is well known. The disturbances most frequently begin in the night–early morning LT sectors, and they are rare during daytime hours [*Mednikova*, 1957; *Prölss and von Zahn*, 1978]. This is due to the interaction of background and storm induced thermospheric circulation [e.g.,*Prölss*, 1995, and references therein]. Therefore the ionospheric effect of morning-daytime geomagnetic disturbances may be delayed until nighttime hours when the direction of the background meridional wind changes for the equatorward one, while nighttime geomagnetic disturbances appear in the $F2$ layer with much shorter time delay. This is one of the reasons for large scatter in time delay between geomagnetic and ionospheric storm onsets (see earlier). Analysis of the smallest thresholds (Table 2) (for instance, 4.70 (Dourbes, March), 4.75 (Tomsk, November), 5.80 (Slough, March), 5.60 (Moscow, February)) has shown that they are due to the following. First, the ionospheric storm may begin with a small ($\geq$3 hours, the span for ap index determination) delay with respect to the geomagnetic one, the previous 24-hour period being very quiet (small *ap* indices). Second, the geomagnetic disturbance may have taken place during the previous day, but because of poleward thermospheric circulation the disturbed neutral composition was restricted to high latitudes [*Prölss and von Zahn*, 1977] and the ionospheric storm did not begin until the nighttime hours, as mentioned earlier; again the previous 24-hour period was very quiet. In fact, this implies that once the composition perturbation (the disturbance bulge) has been generated, it is pushed around by winds and may move back and forth in latitude [*Prölss*, 1995]. This effect was confirmed by the storm simulation of *Fuller-Rowell et al.* [1994] as well as by ESRO 4 data analysis [*Skoblin and Forster*, 1993]. So, the ionospheric disturbance (of course, with smaller magnitude) may appear at the same location in 24 hours under magnetically quiet conditions. Such a case seems took place at Moscow on 16 February 1963 when the ionospheric disturbance occurred practically under quiet conditions (low threshold of 5.2) but after a preceding prolonged geomagnetic disturbance. The effect of an increase in the interhour correlation coefficients for deviations δf_oF2 separated by 24-hour interval was mentioned earlier [*Mikhailov*, 1990].

[12] It may seem that small calculated disturbance thresholds (Table 2) present exotic cases of ionospheric storms, therefore the analysis was repeated for strong storms corresponding to daily $Ap \geq 30$. Seasonal (winter/summer) difference in the thresholds takes place in this case as well. For instance, at Moscow the winter thresholds are 17.9 for December and 14.5 for January, while in summer they are 26.9 for June, 24.4 for July, and 26.5 for August. Similar seasonal difference takes place if the thresholds are calculated over 10 (rather than 5) the smallest values. Therefore seasonal (winter/summer) difference in the disturbance thresholds is a real feature of the $F2$-layer negative storms which may be explained by seasonal variations of neutral temperature and thermospheric circulation leading to changes in neutral composition.

[13] Another interesting result of our analysis is the equi-

noctial relative minimum or plateau in the threshold annual variations (Figure 1). In fact, one should speak about a plateau if to delete the extreme low points in March which present special storm cases discussed earlier. This equinoctial plateau may be related with the winter/summer transition in the thermosphere manifested by day-to-day changes of the meridional wind at the $F2$-region heights [*Mikhailov and Schlegel*, 2001] as well as with equinoctial transitions observed in the lower thermosphere [*Shepherd et al.*, 1999; *Shiokawa and Kiyama*, 2000]. Both analyses revealed day-to-day changes in the atomic oxygen abundance during the transition periods, and this may help understand the threshold lowering effect during the equinoxes. General increase of the thermospheric neural temperature from winter to equinox and further to summer provides a steady increase of the threshold as discussed earlier. However, if a geomagnetic storm occurs under summer-type thermospheric circulation accompanied by a decrease in the atomic oxygen [O] abundance, this should decrease the geomagnetic threshold. Indeed, in this case, less O/N_2 decrease is needed to overcome the same N_mF2 disturbance threshold (40% in our case), and this corresponds to lower level of geomagnetic activity. Days with winter-type thermospheric circulation correspond to increased atomic oxygen [O] abundance and positive N_mF2 disturbances [*Mikhailov and Schlegel*, 2001] are not considered in this paper.

5. Conclusions

[14] The main results of our analysis can be summarized as following:

[15] 1. Geomagnetic activity thresholds expressed in *ap* index units for $F2$-layer negative storms onset calculated for 14 midlatitude ionosonde stations exhibit a pronounced seasonal (winter/summer) variation with summer thresholds being larger than winter ones. There are also relative minima (or plateau) in the threshold during equinoctial periods.

[16] 2. Seasonal difference in the thresholds is due to seasonal difference in the thermosphere reaction to geomagnetic disturbances: a steep dependence of $\Delta(O/N_2)$ on geomagnetic activity in winter but gently sloping dependence in summer. This needs higher geomagnetic disturbance level (higher threshold) in summer compared to winter to have the same perturbation effect in the thermospheric parameters.

[17] 3. A proposed explanation for the threshold seasonal variations is based on seasonal changes in neutral temperature and on seasonal difference in the spatial distribution of the perturbed neutral composition. Higher background T_n in summer needs stronger disturbance level (larger threshold) to have the same changes in O/N_2 compared to winter when T_n is lower. The other effect is due to the interaction of seasonal (background) and storm induced thermospheric circulation. In summer the $[O]/[N_2]$ disturbance zone is known to extend over the whole hemisphere all the way from the polar to the low latitudes while in winter it is restricted to high latitudes only. Therefore more energy should be deposited in the auroral zone during a geomagnetic storm in summer compared to winter to have the same perturbation effect in the thermospheric parameters.

[18] 4. The equinoctial plateau in the threshold annual variations may be related to day-to-day changes in the thermospheric circulation and atomic oxygen abundance during the equinoctial transition periods.

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References

Araujo-Pradere, E. A., T. J. Fuller-Rowell, and M. V. Codrescu (2002), STORM: An empirical storm-time ionospheric correction model: 1. Model description, *Radio Sci., 37*(5), 1070, doi:10.1029/2001RS002467.

Cander, Lj. R., and S. J. Mihajlovic (1998), Forecasting ionospheric structure during the great geomagnetic storms, *J. Geophys. Res., 103,* 391.

Cander, Lj. R., M. M. Milosavljevic, S. S. Stankovic, and S. Tomasevic (1998), Ionospheric forecasting technique by artificial neural network, *Electron. Lett., 34,* 1573.

Chan, A. H. Y., and P. S. Cannon (2002), Nonlinear forecast of f_oF2: Variation of model prediction accuracy over time, *Ann. Geophys., 20,* 1031.

Duncan, R. A. (1969), F-region seasonal and magnetic storm behaviour, *J. Atmos. Terr. Phys., 31,* 59.

Field, P. R., H. Rishbeth, R. J. Moffett, D. W. Idenden, T. J. Fuller-Rowell, G. H. Millward, and A. D. Aylward (1998), Modelling composition changes in F-layer storms, *J. Atmos. Sol. Terr. Phys., 60,* 523.

Forbes, J. M., R. Gonzalez, F. A. Marcos, D. Revelle, and H. Parish (1996), Magnetic storm response of lower thermospheric density, *J. Geophys. Res., 101,* 2313.

Forbes, J. M., S. E. Palo, and X. Zhang (2000), Variability of the ionosphere, *J. Atmos. Sol. Terr. Phys., 62,* 685.

Francis, N. M., P. S. Cannon, A. G. Brown, and D. S. Broomhead (2000), Nonlinear prediction of the ionospheric parameter f_oF2 on hourly, daily, and monthly timescales, *J. Geophys. Res., 105,* 12,839.

Francis, N. M., A. G. Brown, P. S. Cannon, and D. S. Broomhead (2001), Prediction of the hourly ionospheric parameter f_oF2 using a novel nonlinear interpolation technique to cope with missing data points, *J. Geophys. Res., 106,* 30,077.

Fuller-Rowell, T. J., M. V. Codrescu, R. J. Moffett, and S. Quegan (1994), Response of the thermosphere and ionosphere to geomagnetic storm, *J. Geophys. Res., 99,* 3893.

Hedin, A. E. (1987), MSIS 86 thermospheric model, *J. Geophys. Res., 92,* 4649.

Kutiev, I., and P. Muhtarov (2001), Modeling of midlatitude F region response to geomagnetic activity, *J. Geophys. Res., 106,* 15,501.

Kutiev, I., P. Muhtarov, L. R. Cander, and M. F. Levy (1999), Short-term prediction of ionospheric parameters based on autocorrelation analysis, *Ann. Geophys., 42,* 121.

Marin, D., G. Miro, and A. V. Mikhailov (2000), A method for f_oF2 short-term prediction, *Phys. Chem. Earth C, 25,* 327.

Mayr, H. G., and H. Volland (1972), Magnetic storm dynamics of the thermosphere, *J. Atmos. Terr. Phys., 36,* 2025.

Mednikova, N. B. (1957), Mid-latitude ionospheric disturbances, in *Physics of Solar Corpuscular Fluxes and Their Impact on the Upper Atmosphere of the Earth* (in Russian), p. 183, Acad. Press of USSR, Moscow.

Mikhailov, A. V. (1990), A method for short-term prediction of f_oF2 using observational data, *Geomagn. Aeron.* (in Russian), *30,* 808.

Mikhailov, A. V., and K. Schlegel (2001), Equinoctial transitions in the ionosphere and thermosphere, *Ann. Geophys., 19,* 783.

Mikhailov, A. V., A. Kh. Depueva, and T. Yu. Leschinskaya (2004), Observations of neutral winds and electric fields using backscatter from field-aligned irregularities, *Int. J. Geomagn. Aeron., 5,* GI1006, doi:10.1029/2003GI000058.

Muhtarov, P., and I. Kutiev (1999), Autocorrelation method for temporal interpolation and short-term prediction of ionospheric data, *Radio Sci., 34,* 459.

Muhtarov, P., L. Cander, M. Levy, and I. Kutiev (1998), Application of the geomagnetically correlated statistical model to short-term forecast of f_oF2, 2nd COST 251 Workshop, European Cooperation in the field of Science and Technological Research (COST), Side, Turkey, 30–31 March 1998.

Pant, T. K., and R. Sridharan (2001), Seasonal dependence of the response of the low latitude thermosphere for external forcing, *J. Atmos. Sol. Terr. Phys., 63,* 987.

Prölss, G. W. (1980), Magnetic storm associated perturbations of the upper atmosphere: recent results obtained by satellite-borne gas analyzers, *Rev. Geophys., 18,* 183.

Prölss, G. W. (1995), Ionospheric F-region storms, in *Handbook of Atmospheric Electrodynamics, vol. 2, edited by H. Volland,* p. 195, CRC Press, Boca Raton, Fla.

Prölss, G. W., and U. von Zahn (1977), Seasonal variations in the latitudinal structure of atmospheric disturbances, *J. Geophys. Res., 82,* 5629.

Prölss, G. W., and U. von Zahn (1978), On the local time variation of atmospheric-ionospheric disturbances, *Space Res., 18,* 159.

Roosen, J. (1966), The seasonal variation of geomagnetic disturbance amplitudes, *Bull. Astron. Inst. Neth., 18,* 295.

Shepherd, G. G., J. Stegman, Espy P., C. McLandress, G. Thuillier, and R. H. Wiens (1999), Springtime transition in lower thermospheric atomic oxygen, *J. Geophys. Res., 104,* 213.

Shiokawa, K., and Y. Kiyama (2000), A search for the springtime transition of lower thermospheric atomic oxygen using long-term midlatitude airglow data, *J. Atmos. Sol. Terr. Phys, 62,* 1215.

Skoblin, M. G., and M. Förster (1993), An alternative explanation of ionization depletions in the winter night-time storm perturbed $F2$-layer, *Ann. Geophys., 11,* 1026.

Wintoft, P., and L. R. Cander (2000), Twenty-four hour predictions of f_oF2 using time delay neural networks, *Radio Sci., 35,* 395.

Wrenn, G. L. (1987), Time-weighted accumulations $ap(\tau)$ and $Kp(\tau)$, *J. Geophys. Res., 92,* 10,125.

Wrenn, G. L., A. S. Rodger, and H. Rishbeth (1987), Geomagnetic storms in the Antarctic F-region. I. Diurnal and seasonal patterns for main phase effects, *J. Atmos. Terr. Phys., 49,* 901.

Wu, J., and P. J. Wilkinson (1995), Time-weighted magnetic indices as predictors of ionospheric behaviour, *J. Atmos. Terr. Phys., 57,* 1763.

Zevakina, R. A., and M. V. Kiseleva (1978), $F2$-region parameter variations during positive disturbances related to phenomena in the magnetosphere and interplanetary medium, in *The Diagnostics and Modelling of the Ionospheric Disturbances* (in Russian), p. 151, Nauka, Moscow.

Zevakina, R. A., E. M. Zhulina, G. N. Nosova, and N. P. Sergeenko (1990), *Short-Term Prediction Manual, Materials* (in Russian), 71 pp., World Data Cent. B, Moscow.

Zuzic, M., L. Scherliess, and G. W. Prölss (1997), Latitudinal structure of thermospheric composition perturbations, *J. Atmos. Sol. Terr. Phys., 59,* 711.

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