Forecasting geomagnetic activity three hours in advance for ionospheric applications

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Abstract
An attempt at forecasting the magnetic activity index three hours in advance is presented. This approach is based on a suitable treatment of time-weighted accumulations of the three-hourly magnetic index *Kp*. The statistical analysis of impact of magnetic activity on the positive and negative disturbances of the F_2 layer peak electron density NmF_2 is made for 25 ionosondes in Europe and Russia during 1997 to 2001. It is shown that the response of positive and negative ionosphere disturbances to peak of magnetic activity *Kp*max delays by 1 to 48 h. Two peaks of occurrence of positive and negative ionospheric disturbed periods are found referring to *Kp*max equal to 3 and 4 for $DNmF_{2+}$ and *Kp*max equal to 4 and 5 for $DNmF_{2-}$ shifted regarding similar distribution of forecasted *Kpm* indices depicting two maxima at *Kp* equal to 1.7 and 2.7. Comparisons are made with observations and IRI-2001 model predictions.

Key words *geomagnetic activity – ionospheric disturbances – forecasting*

1. Introduction

Advanced models for forecasting the ionosphere response to geomagnetic storm should take into account the dependence of the ionospheric f_0F_2 critical frequency on the past history of the magnetic activity (Wu and Wilkinson, 1995; Perrone and De Franceschi, 1999; Fuller-Rowell *et al.*, 2001; Muhtarov *et al.*, 2001). In particular, the European ionospheric forecast and mapping technique, EIFM (Muhtarov *et al.*, 2001) provides the short-term forecast of f_0F_2 depending on availability of the measured ionospheric data and predicted *Kp* values. We present here a modification of the time-weighted accumulation of magnetic indices (Wrenn, 1987) to provide forecast of magnetic activity *Kpm* index 3 h in advance to serve as predictor of ionospheric behaviour.

2. Forecasting procedure

One of the proposed time series accumulations of a selected geomagnetic index, *e.g. kp*, starts from the *kp* value for the current time bin and also includes a number of instantaneous indices for the preceding time bins (Wrenn, 1987)

$$kp(\tau) = (1-\tau)\,(kp + (\tau)kp_{-1} + (\tau)^2\,kp_{-2} + \ldots) \qquad (2.1)$$

kp is the index value for the current 3-h UT bin

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of time, kp_{-1}, kp_{-2}... are the kp values for −3 h, −6 h... etc. The *persistence factor* τ ($0 \le \tau < 1$) determines how $kp(\tau)$ will depend on the history of the kp index. τ is function of the magnetic index used and of the characteristic response recovery time of the ionosphere to the magnetic perturbation. The *persistence time* t_p (in hours) is approximately given by the relation $t_p = t_s/(1-\tau)$ where t_s is the time scale or temporal interval (expressed in hours) for which the magnetic index is defined (*e.g.*, t_s = 3 h for kp). The persistence time can be also considered as the time required for 1/e decay of $kp(\tau)$.

The normalising factor $S_\tau = (1-\tau)$ is valid for infinite (or very long) series of terms included in the sum of eq. (2.1). In practice, the best correlation between $ap(\tau)$ (proportional to kp) and the NmF_2 variations (Wu and Wilkinson, 1995; Perrone and De Franceschi, 1999) was obtained using just five terms in eq. (2.1). This led to the evaluation of the best persistence factor $\tau = 0.8$. So by using a limited number of terms (n) in eq. (2.1), the normalising factor S_τ should be modified as

$$S_\tau = (1-\tau)/(1-\tau^n). \tag{2.2}$$

Then eq. (2.1) become

$$kp(\tau) = (1-\tau)/(1-\tau^n)\,(kp + (\tau)kp_{-1} + (\tau)^2\, kp_{-2} + \ldots + (\tau)^{n-1}\, kp_{-n+1}). \tag{2.3}$$

With the above modification, the greatest weight (equal to 1) is still given to the kp value for the current 3 h UT bin. Equations (2.1)-(2.3) can be used for retrospective studies as kp value for the current time t is not available until the full 3 h UT bin is over. For ionospheric forecasting purposes based on magnetic indices, a modification of eq. (2.3) is proposed. Earlier investigations employed the maximum kp' value for the 12 preceding hours to reveal effect of delay of the plasma response to magnetic storm (Chappel, 1972; Kozyra *et al.*, 1986; Kutiev *et al.*, 1995). To combine this within a scheme like (2.3), *e.g.*, to use geomagnetic indices only for the times *before* any given time, and to put the greatest weight on maximum value for n preceding hours, we changed the accumulation procedure as follows. Using only kp indices during n preceding hours, eq. (2.3) transforms to

$$Kpm = S_\tau(kp'_1 + (\tau)kp'_2 + (\tau)^2\, kp'_3 + \ldots (\tau)^{n-1}kp'_n) \tag{2.4}$$

where the kp'_s are the kp values for n preceding hours ranked by decreasing order

$$kp'_1 \ge kp'_2 \ge \ldots \ge kp'_n. \tag{2.5}$$

So, the greatest weight (= 1) is given to $kp'_1 = kp(\max)$ of n preceding values, and the least weight (τ^{n-1}) is given to $kp'_n = kp(\min)$ of the n preceding values. The advantage of ranking the kp values by decreasing order is that the greatest index kp'_1 yields the greatest Kpm of all possible combinations, that leads to the best fit of the instantaneous index value for the peak of a magnetic storm. The elimination of the kp value for the current time of observation makes eq. (2.4) able to forecast Kpm 3 h in advance. The series of Kpm based on kp indices for 12 preceding hours are produced for the total period of observations 1932 up-to-date. Permanent forecast of the Kpm indices is based on preliminary k-indices updated every three hours at the Internet page of SEC, NOAA, Boulder, CO, U.S.A.

According to Shubin *et al.* (1998), the persistence factor τ can be obtained from t_p and t_s

$$\tau = \exp(-t_s/t_p). \tag{2.6}$$

Table I gives parameters τ, S_τ, t_s for different magnetic indices for a fixed t_p = 12 h. It is evident from eq. (2.6) and table I that, for a given persistence time, τ grows with decreasing t_s compensated by reduced normalizing factor due to an increased number of terms n.

Table I. The persistence factor τ and normalising factor S_τ for persistence time t_p = 12 h for the different magnetic indices.

t_s	n	τ	S_τ	Index
3 h	4	0.7788	0.3499	*kp, ap, aa*
1 h	12	0.9200	0.1265	*AE, Dst*
0.25 h	48	0.9794	0.0326	*PC*

Equations (2.1)-(2.4) represent a smoothing filter for the *instantaneous* magnetic indices. Though different magnetic indices (*ap*, *kp*, *aa*, *AE*, *AL*, *AU*, *PC*, *Dst*, etc.) characterize different physical processes in the magnetosphere-ionosphere system, the above procedure discloses a close correlation between the different storm signatures supposed to take into account the integral effect of their accumulation.

3. Database of the ionospheric disturbed periods

The ground-based ionosonde observations and geomagnetic activity indices available via Internet were employed in this study. The observation sites with their geodetic and magnetic coordinates and the period of observation are given in table II. Since 1997, the ionospheric disturbed periods for selected ionosondes in Europe and Russia have been permanently calculated by one of co-authors (TLG) for an Internet page of the Ionospheric Despatch Centre in Europe, IDCE, Warsaw (Stanislawska *et al.*, 1999). The $DNmF_2$ disturbed periods are specified for the positive and negative ionospheric disturbances at least of 3 h duration. Criteria for the selection of the said periods are for the mean relative deviation of NmF_2 greater than ± 40% of the monthly median during the disturbed period which corresponds to requirement for

Table II. The ionosonde locations and period of observation used for the analysis of the ionospheric disturbed periods.

Station	Latitude	Longitude	Mlatitude	Mlongitude	Years
1 Kiruna	67.8N	020.4E	65.1N	116.4E	1997-2000
2 Sodankyla	67.4N	026.6E	63.6N	120.8E	1998-2001
3 Salekhard	66.5N	066.5E	57.4N	149.7E	1997-2001
4 Lycksele	64.6N	018.8E	62.5N	111.7E	1997-2000
5 Podkamennaya	61.6N	090.0E	50.8N	165.4E	1999-2001
6 Sankt Petersburg	60.0N	030.7E	56.1N	118.3E	1997-2001
7 Magadan	60.0N	151.0E	50.9N	211.6E	2001
8 Uppsala	59.8N	017.6E	58.3N	106.9E	1997-2000
9 Sverdlovsk	56.4N	058.6E	48.5N	139.6E	1999-2001
10 Moscow	55.5N	037.3E	50.4N	123.2E	1997-2001
11 Juliusruh/Rugen	54.6N	013.4E	54.3N	099.7E	1997-2001
12 Novosibirsk	54.6N	083.2E	44.2N	158.9E	1998-2001
13 Warsaw	52.2N	021.2E	50.5N	105.7E	1997-2000
14 Fairford	51.7N	358.2E	54.3N	082.8E	2001
15 Chilton	51.5N	359.4E	54.0N	084.4E	1999-2001
16 Pruhonice	50.0N	014.6E	49.7N	098.5E	1998-2001
17 Lannion	48.5N	356.7E	52.0N	080.1E	1998-2001
18 Rostov	47.2N	039.7E	42.4N	120.3E	1997-2001
19 Poitiers	46.6N	000.3E	49.2N	083.0E	1997-1998
20 Sofia	42.7N	023.4E	41.0N	103.9E	1997-2001
21 Rome	41.8N	012.5E	42.3N	093.2E	1997-2001
22 Tashkent	41.3N	069.6E	32.3N	145.2E	2000-2001
23 Tortosa	40.4N	000.3E	43.6N	080.9E	1997-2001
24 Athens	38.0N	023.6E	36.4N	102.5E	2001
25 El Arenosillo	37.1N	353.3E	41.4N	072.3E	1998-2001

f_0F_2 deviation exceeding the monthly median by ± 20% (Kouris *et al.*, 1998). The total data set of the ionospheric disturbed periods consists of more than 10000 events for 1997 to 2001 at 25 locations (table II) including 5000 negative $DNmF_{2-}$ events and 5700 positive $DNmF_{2+}$ events.

The relation between 3 h *kp* indices and $DNmF_2$ events has been analysed in the present study. To make them comparable with hourly ionosonde observations, the 3-h *kp* values were linearly interpolated to obtain its values at every hour.

4. Results

First of all, the time lag (difference) between moment of observed peak of *kp* indices, *Kp*max, during 48 h preceding start of $DNmF_2$, and the start-time of $DNmF_2$ period was calculated. The *Kp*max is characteristic of intensity of magnetic storm, and the time lag is important parameter for forecasting a start of the ionospheric response to magnetic storm. Results are shown in fig. 1 for the positive and negative ionospheric disturbed periods. Here we see that distribution of the time lag for the negative disturbances is

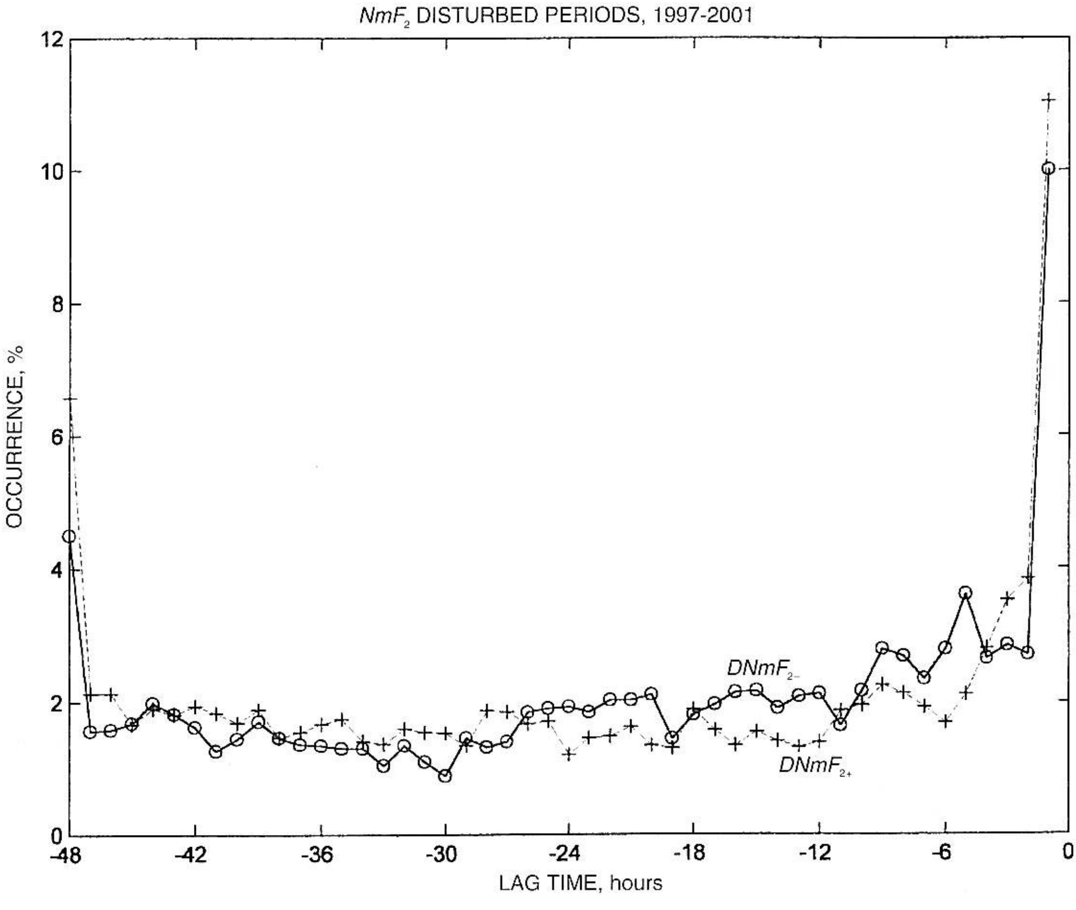

Fig. 1. Time lag between peak of *Kp* index during 48 h preceding positive and negative ionosphere disturbance and start of the ionosphere disturbed period.

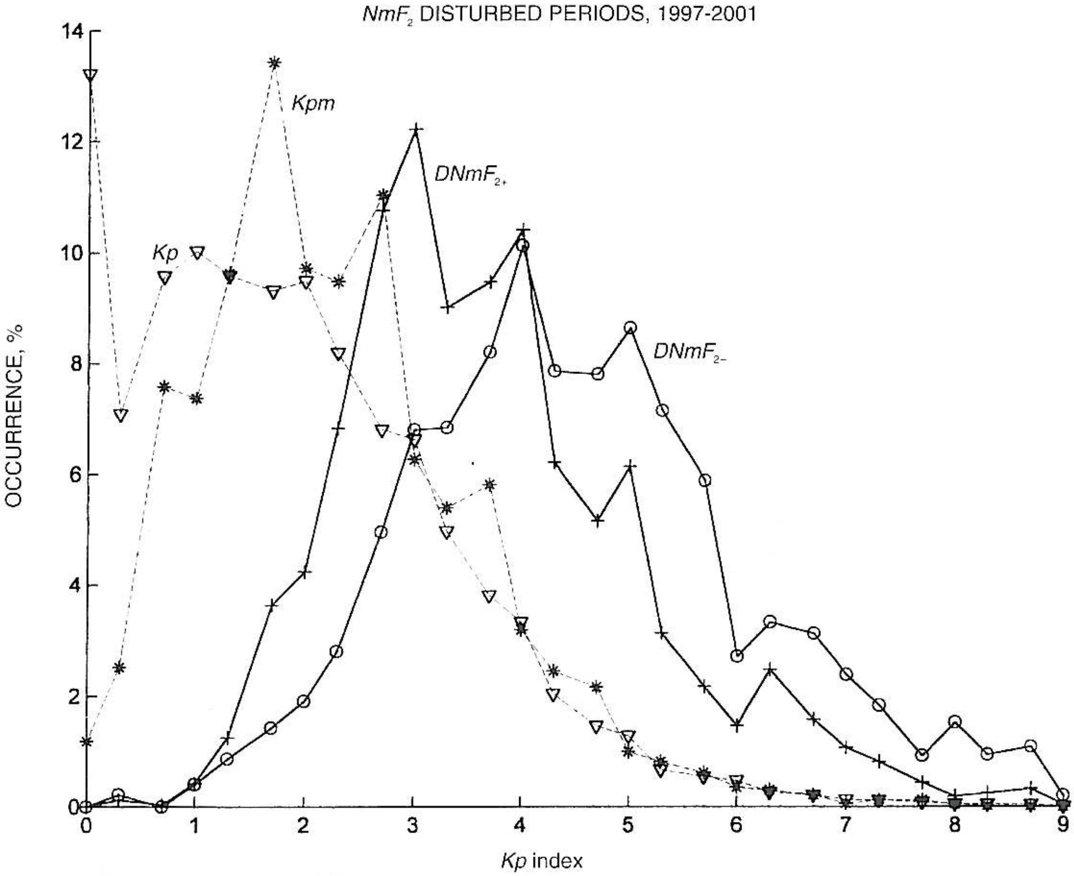

Fig. 2. Percentage occurrence frequency of the positive and negative ionosphere disturbances for the full range of peak *Kp* observed during 48 h before $DNmF_2$ period, along with distribution of original *Kp* indices and forecasted *Kpm* indices occurrence for the period of 1997 to 2001.

very similar to the time lag for the positive disturbances. In many cases successive combination of $DNmF_{2+}$ and $DNmF_{2-}$ are driven by the same *Kp*max during the 48 preceding hours but the time lag for such events is different due to the shifted start of the two opposite deviations of NmF_2. 10% of events occur 1 h later than *Kp*max. As follows from fig. 1, about 25% of events refer to a time lag of – 1 to – 6 h, 40% of events refer to a time lag of – 1 to – 12 h (see table I), 50% of events refer to – 1 to – 18 h (Kutiev and Muhtarov, 2001), 75% of events refer to – 1 to – 33 h (Fuller-Rowell *et al.*, 2001). About 5% of results show time lag equal to – 48 h which could mean some cases when the ionospheric response to *Kp*max is greater than 48 h. From fig. 1 we conclude that forecast of the ionospheric response to magnetic activity is more reliable if the relevant model takes into account the time lag between the peak of the magnetic activity index and the start of the ionospheric disturbance (Deminova *et al.*, 1998).

Figure 2 presents the percentage occurrence of $DNmF_{2+}$ and $DNmF_{2-}$ events in each *Kp*max bin (three bins per unit) inferred for 48 h preceding an ionospheric disturbance. Also percentage occurrence of original *kp* and predicted *Kpm* indices is shown for each *Kp* bin during 1997 to 2001. We note the double peaks of occurrence of *Kpm* (at $Kp = 1.7$ and 2.7), $DNmF_{2+}$ (*Kp*max = 3 and 4) and $DNmF_{2-}$ (*Kp*max = 4 and 5) shifted one after another towards the greater *Kp* bins. Unlike *Kpm* occurrence, the original *Kp* indices do not show such distribution. So we conclude that the level of *Kp*max greater or equal to 3 is the most likely source for the positive ionospheric disturbance, whereas if *Kp*max is equal to or greater than 4 the negative disturbance should be expected. With this result, the earlier finding by Kutiev and Muhtarov (2001) referring positive ionospheric disturbances to *Kp* values less than 3 while *Kp* greater than 3 are assumed to be a source of only negative ionospheric disturbances should be reconsidered.

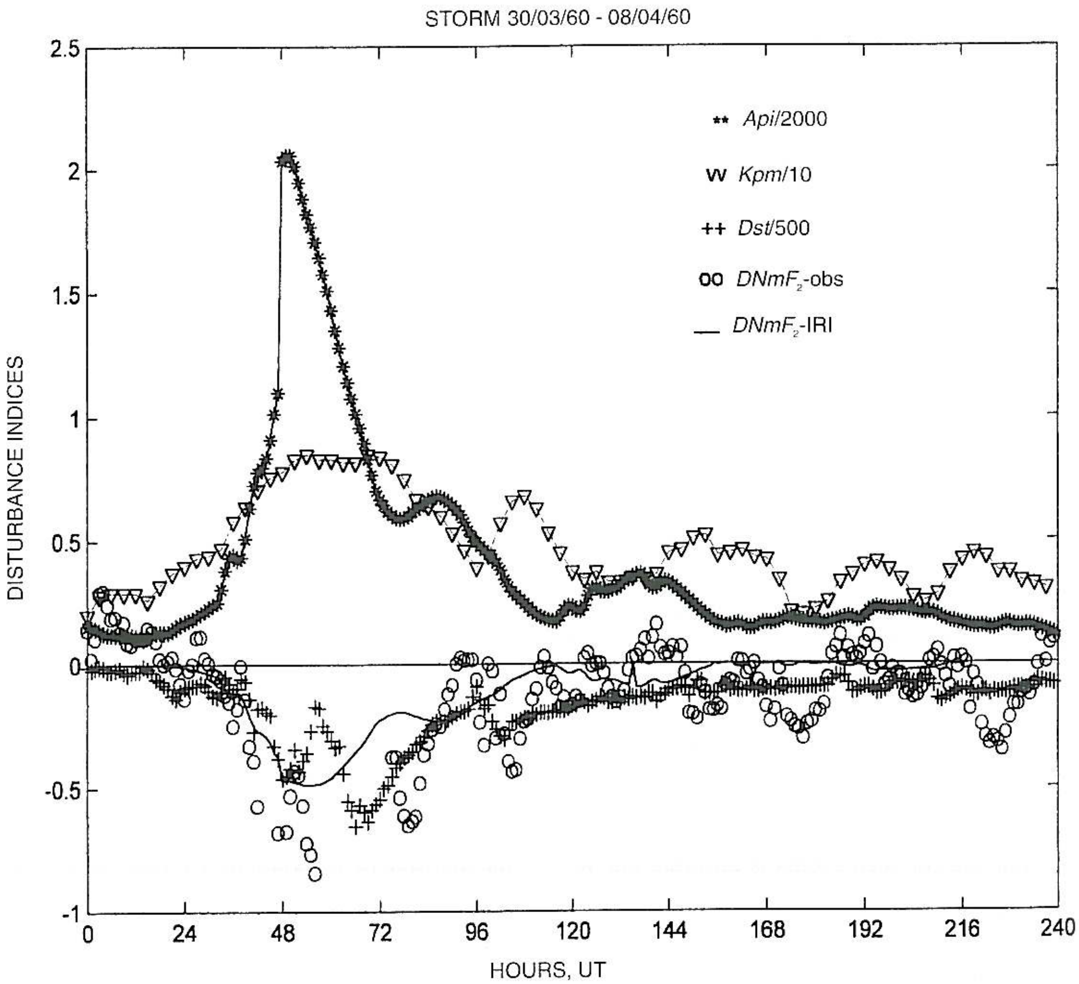

Fig. 3. Observation and modeling of intense magnetic storm during 10 days of March-April 1960. $DNmF_2$ observed at Moscow (circles) are compared with IRI-2001 model (solid line). Observed equatorial *Dst* index is compared with proposed 3-h in advance forecast of *Kpm* indices and integrated *Api* index used for IRI, storm predictions.

The next important conclusion following from fig. 2 suggests that a certain amount of the positive disturbances (27%) and negative ionospheric disturbances (12.5%) occurred while *Kp*max was less than 3 during the 48 h preceding start of the ionosphere disturbance. In such cases, the ionosphere was disturbed but the magnetic field was quiet. Note that only disturbances lasting 3 h or more hours are considered in our analysis. So these cannot be incidental deviations of observed NmF_2 from the monthly median, but may be local appreciable perturbations of the ionosphere around the F_2 layer peak. Such cases cannot be forecasted using the history and forecast of magnetic activity. Other sources of natural or artificial origin should be looked for in such cases.

However, for the strong magnetic disturbances specified as geomagnetic storm or substorm significant progress has been reached lately in modeling the ionization depletion based on the history of magnetic activity. In particular, a recent modification of the International Reference Ionosphere, IRI-2001 (Bilitza, 2001) provides an option of storm-time updating of the ionospheric F_2 layer peak density depletion based on integrated *ap*-indices, *Api* (Fuller-Rowell *et al.*, 2001). An example is given in fig. 3 where 10 days of intense magnetic storm in March-April 1960 are illustrated with magnetic and ionospheric disturbance indices. Circles present a logarithm of the ratio of observed NmF_2 at Moscow to the median calculated by using a sliding window of 27 days preceding given day of observation (Gulyaeva, 1996). Solid curve shows IRI storm-time prediction expressed as logarithm of the storm-model NmF_2 to IRI-CCIR prediction of the quiet conditions. The observed equatorial *Dst* index (crosses) was equal to – 327 nT on 1st April, 1960, when the global storm reached the equator. The upper part of fig. 3 presents the integrated *Api* index based on *ap* indices for the past 33 h driving the ionospheric storm model. Triangles show a forecast of *Kpm* indices which resemble many details of original *kp* indices, particularly during the recovery phase of the stormy days which are also seen in $DNmF_2$ indices observed with ionosonde at Moscow.

5. Conclusions

A forecasting scheme is proposed in the present paper to produce planetary magnetic *Kpm*-index three hours in advance based on the history of magnetic *kp*-indices. The technique presents a modified filter of Wrenn (1987) including instantaneous *kp*-indices ranked by decreasing order for 12 h preceding given time for forecasting. The relation of magnetic activity with ionospheric disturbances is explored using database of the positive and negative ionospheric disturbed periods of 3 h or longer duration for 25 ionospheric stations in Europe and Russia during 1997 to 2001. The delay of ionospheric response to peak of magnetic activity can range from 1 to 48 h; a special time lag parameter should be included in the forecast of impact of magnetic storm on the ionosphere.

Positive ionosphere disturbances reveal dominant values of *Kp*max equal to 3 and 4 inducing positive disturbed periods. Negative ionospheric disturbances are observed more frequently after *Kp*max reached 4 or 5 thus more intense energy input from the magnetosphere is a source of a ionospheric plasma depletion during the storm. There is a certain percentage (12 to 25%) of the ionosphere disturbances occurring independently of magnetospheric storminess under quiet magnetic conditions. These cases cannot be forecast using magnetic activity indices.

Recent advances in modeling of the storm-time update of the ionosphere peak density based on the history of magnetic activity indices are promising. The proposed technique for forecasting the magnetic activity indices three hours in advance can be used in advanced procedures of ionosphere forecasting.

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