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Universal variation of the F_2-layer critical frequency and solar activity

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Regular variations of the F_2-layer in the quiet ionosphere are studied using the universal variation of the F_2-layer critical frequency, i.e. the dependence of the instantaneous mean-longitudinal value of foF_2 at a fixed latitude on universal time (UT). Algorithms for the universal variation calculation have been developed and are used to process the ionospheric vertical sounding data for 1957–1990. It is shown that the foF_2-universal variation forms are essentially different for solar minima and maxima years. In the solar minima years, the foF_2-universal variation is similar to the known universal variation of the atmospheric electric field near the Earth's surface which has a maximum at 19 UT. There is no foF_2-universal variation seasonal change in solar minimum years. The foF_2-universal variation form changes for solar maximum years have a minimum of foF_2, at 16–17 UT, and there are small seasonal changes in the foF_2-universal variation. Such behaviour of the foF_2-universal variation suggests that under the quiet conditions in solar minimum years the electric field penetrates from the lower atmospheric layers up to the F_2 layer of the ionosphere.

1. Introduction

The dependence of ionospheric characteristics on solar activity was ascertained in the early regular ionospheric observations (see, for example, Appleton, 1950). Now there are many data to show the connection between the foF_2-variations are solar activity. The physical nature and dependence of the ionospheric characteristics on solar activity remain the subject of investigation. Michailov *et al.* (1990a, b) have sought an index which would best approximate the dependence of foF_2 on the solar activity level. Rao and Rao (1969), Smith and King (1981) have studied the problem about the uniqueness of the connection between foF_2 and solar activity during the growth and decay phase of the solar cycle.

In earlier papers the seasonal, longitudinal and solar cycle variations of the ionospheric characteristics were studied for fixed local time (LT), i.e. they were analysed for the day or night (Yonezawa, 1972), sunset or sunrise. As was noted (Besprosvanaya and Kozina, 1988), when only one station was analysed for a single period of the day (midday or midnight), ambiguous conclusions could be drawn about the foF_2 solar cycle behaviour. Different physical mechanisms are used to explain observations at different LT, for various latitudes and longitudes for changing solar activity (Torr and Torr, 1973). Earlier studies sought to identify dominant processes acting at different times. For example, in the daytime, such a mechanism could be changes in ionization and recombination; at night dynamic processes may be the governing factor. In the modern theory of the F_2-layer it is assumed that its quiet state is conditioned by the combined action of all these mechanisms (see, for example, Bryunelli and Namgaladze, 1988).

Therefore, to describe ionospheric behaviour quantitatively, it is necessary to have not only a model containing all of these physical processes, but also observations that describe their simultaneous occurrence. The universal variation can be used as such a characteristic. It is introduced by analogy with this characteristic in atmospheric electric field investigations (for example Reiter, 1992). The existence of the universal variation in the vertical electric current and the field created by it in the atmosphere, was first shown by the famous measurements of the research vessel Carnegie (Parkinson and Torreson, 1931). The seasonal presentation of the Carnegie data is shown in Fig. 1 (taken from Dolezalek (1972)). Historically, such diurnal variations were derived by averaging individual measurements. It has been demonstrated by Paramonov (1950, 1972) in a series of publications that, if arranged in a suitable way, even the regular local time variations at land stations cancel each other when one averages the readings from stations around the globe.

Therefore, the universal variation of geophysical characteristics such as foF_2 is defined here as the diurnal variation of the instantaneous mean-longitudinal value of this characteristic with UT for a fixed latitude (Kuznetsov *et al.*, 1990). It would be possible to study the variations in the mean-diurnal values of the characteristic, but then the value would be different for stations with the same latitude. The characteristic depends on the longitude and does not reflect the relationship between the physical processes during the day at a given latitude. The universal variation was suggested by us earlier as a characteristic of the quiet state of the global ionosphere (Plotkin *et al.*, 1992). Its amplitude is not large, therefore it is only possible to detect this variation in the absence of any disturbances. From the above reasoning, in this paper the universal variation is used to study the regular variations of the ionosphere in quiet conditions. This permits us to study the seasonal and solar cycle characteristics of the F_2-layer from a different perspective and to assess in future the combined action of several physical processes and the relationship among their contributions.

2. Method and Data Analysis

The methods for obtaining the universal variation are described by Kuznetsov *et al.* (1990, 1993). The first method is based on the small difference in the diurnal

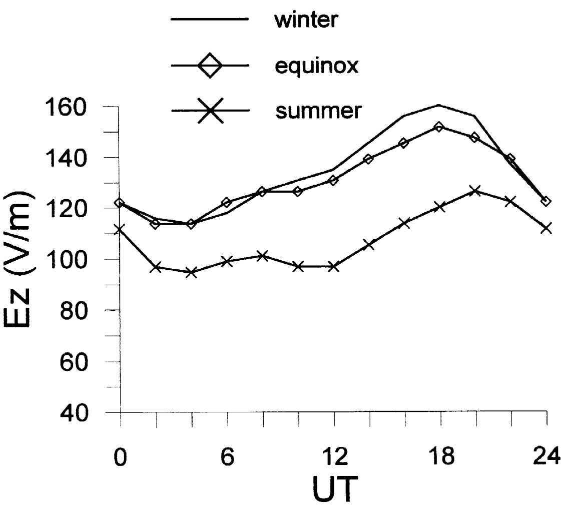

Fig. 1. Seasonal curves of diurnal universal variation of atmospheric electric field.

behaviour of foF_2 observed at stations with approximately identical geographic latitude (Kuznetsov *et al.*, 1990). The input foF_2 data are usually presented depending on local time of the observation station. The ionosonde stations are nonuniformly distributed. There are several stations within some time zones and there are no stations within another zones. It is necessary for every time zone to have the dependence foF_2 on LT which would be typical for this time zone. When there are several stations within any time zone, data averaging was used. If stations are absent within any time zone, a linear interpolation of foF_2 was used between these values for near-by time zones. Such a method was first used to obtain the universal variation of the vertical atmospheric electric field Ez near Earth's surface (Paramonov, 1950). Therefore a similar analysis is used by us to estimate the universal variation of foF_2. This method is suitable for both cases since both Ez and foF_2 changes depend on LT and we have excluded this dependence by averaging over geographic longitudes.

The other method to obtain the universal variation of foF_2 uses the spectral analysis of the observed data in the form of temporal Fourier-harmonics (Kuznetsov *et al.*, 1993). The expansion of the spectral components on the parts controlled by LT and UT is produced by the method of least squares. The simultaneous use of both methods increases the reliability of the foF_2-universal variation determination.

Additional tests were fulfilled to establish whether the

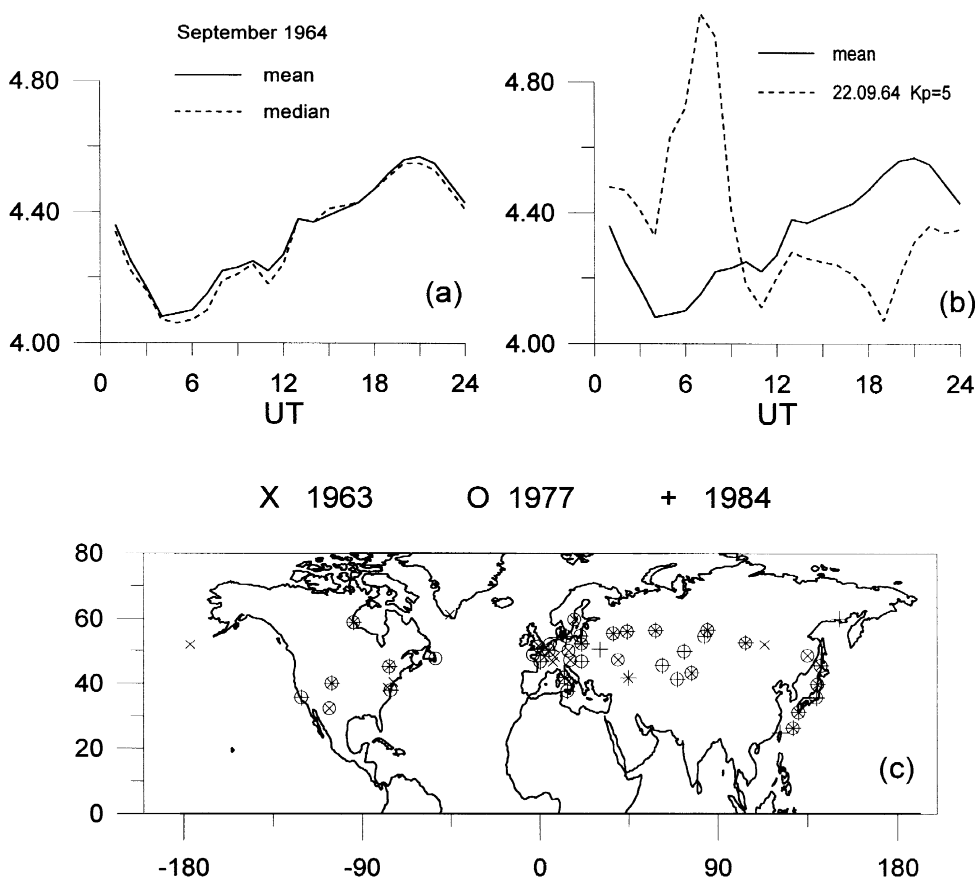

Fig. 2. The mean-monthly universal variation of foF_2 (solid curve) and the universal variation calculated from the foF_2 medians (dashed curve) (a). Form of the foF_2-universal variation for the day with a sharp increase in the Kp-index (dashed curve) (b). The observation stations used for calculations in different years (c).

poorly dispersed hemispheric ionosonde station distribution affects the results. Firstly, instead of real data, model input data were used for the sum of two regular variations; one controlled by LT and the other by UT, and geophysical noise. The UT-variation was given by an arbitrary form (it need not have a 19 UT maximum). Then these two variations were recovered by our methods for the available station distribution. Since this operation was successful, we then processed the real data. Secondly, the validity of our methods is confirmed because for the same geophysical conditions the station distribution changed (for example, for different years, as it is seen from Fig. 2(c)) and the results did not change, as it will be presented in next section.

We have used for analysis the vertical ionospheric sounding data contained on the CD-ROM Dataset produced by the National Geophysical Data Center (Boulder, USA) in 1994 in cooperation with the World Data Centers. The two disks contain the observational results of 130 stations of the world ionosonde network for 1957–1990. They contain the hourly values of the standard ionospheric characteristics scaled by the same method at all the stations. The F_2-layer critical frequency, foF_2, is used here. If the values of foF_2 were absent for some hour, the median for this month at this station was used: it was found during this investigation (see Fig. 2(a)) that the diurnal universal variation for monthly averages (i.e. mean-month universal variation) are similar to the variation obtained from foF_2 medians. In such a manner we have obtained the starting material and have then calculated the diurnal foF_2-universal variation for all of the years of the observed period (1957–1990). Here, the universal variation of foF_2 is defined as the instantaneous mean-longitudinal value of foF_2 for the ionospheric stations located close to the given geographic latitude. The available data for the world ionosonde network was used to determine a reliable characteristic for latitudes around 50°N. For different years the data were analysed for 28 to 33 stations (Fig. 2(c)). In the Southern hemisphere there are large distances between ionospheric stations, so we cannot determine the universal variation of foF_2 there.

3. Results of Experimental Data Analysis

The diurnal values of the foF_2-universal variation were used to calculate the mean universal variation for different periods and to estimate the dispersion of these values. The small difference between the mean-monthly universal variation of foF_2 and the universal variation calculated from the foF_2 medians (Fig. 2(a)) confirms the regular character of the universal variation as typical of the variation of the quiet ionosphere state and the consistency of its calculation method.

Forms of the foF_2-universal variation for days with different levels of magnetic disturbance were analysed. The form of the foF_2-universal variation shows marked changes on days with a sharp increase in the Kp-index (Fig. 2(b)). Moreover, when the disturbed days were taken into account, the dispersion of the mean-monthly foF_2-universal variation

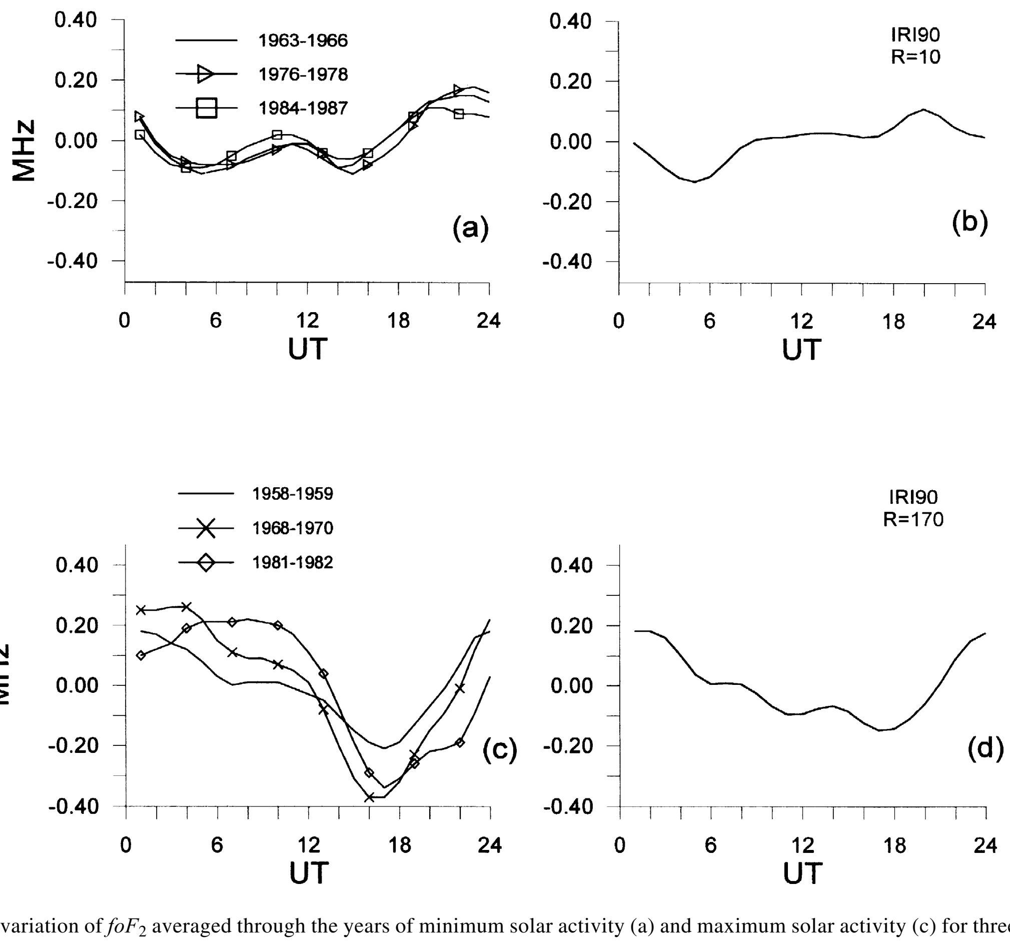

Fig. 3. Universal variation of foF_2 averaged through the years of minimum solar activity (a) and maximum solar activity (c) for three cycles of solar activity and calculated by IRI-90 model for R = 10 (b) and for R = 170 (d).

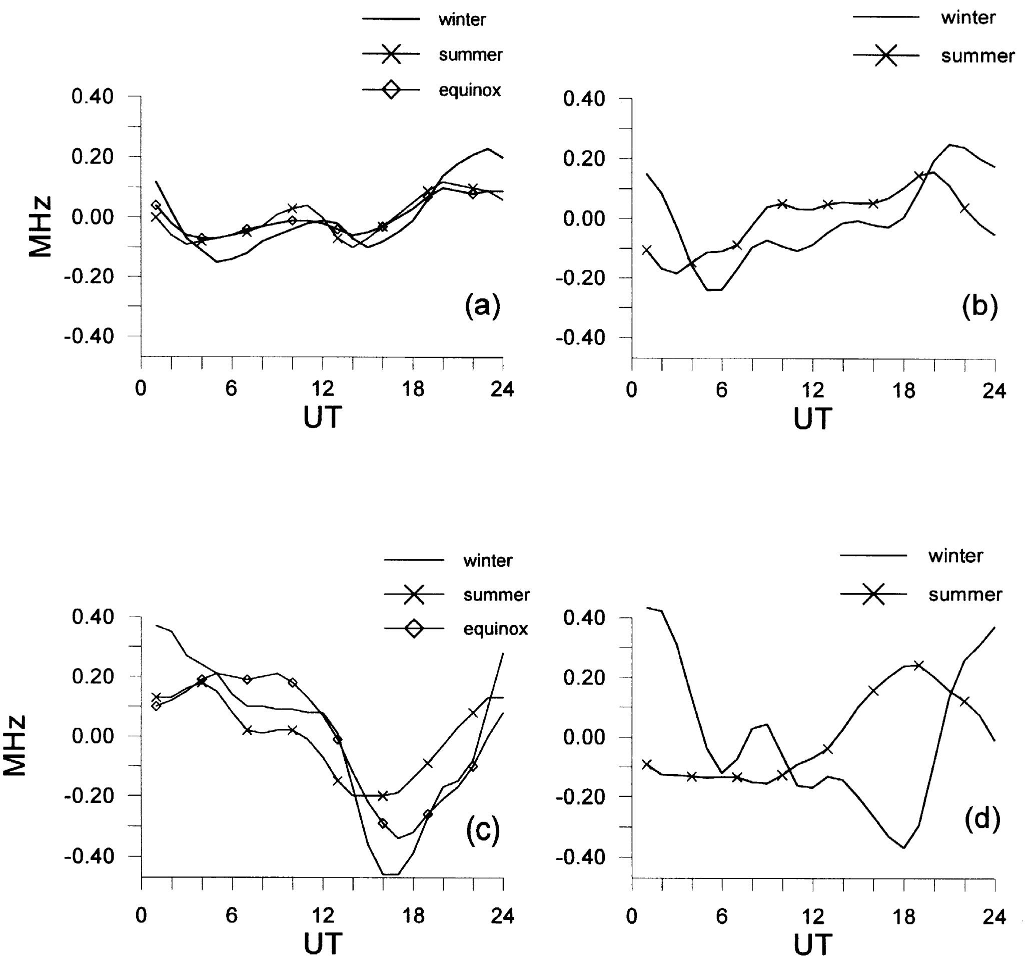

Fig. 4. Universal variation of foF_2 averaged through the seasons for all years of minimum solar activity (a) and maximum solar activity (c) for cycles of solar activity studied by us and calculated by IRI-90 model for R = 10 (b) and for R = 170 (d) for two seasons.

changes substantially. This confirms our approach of using the universal variation of foF_2 as a characteristic of the global quiet ionospheric condition (Plotkin *et al.*, 1992; Kuznetsov *et al.*, 1993).

Therefore, the foF_2-universal variation can be used to study the prolonged variations of the quiet ionosphere, in particular, solar cycle and seasonal variations. For this it is better to use the universal variations obtained from the monthly foF_2 medians at the stations (the median universal foF_2 variations), than diurnal values of the foF_2-universal variations.

The annual and seasonal dispersion of the median universal foF_2 variation for all LT is small when its mean-diurnal value was subtracted during calculation (such a mean foF_2-universal variation has a known seasonal behaviour with a maximum during the equinoxes). This permits us to use the median universal foF_2 variation with zero mean value as the independent characteristic. The form of this universal variation changes during several solar cycles; the results are shown in Figs. 3 and 4. It is seen from Fig. 3 that the shape of the foF_2-universal variation differs essentially during years of minimum and maximum solar activity.

This proves that several physical processes controlling the diurnal F_2-layer trend exhibit regular changes during the solar cycle. The shape of the foF_2-universal variation can be used as an empirical characteristic for the influence of solar activity on the ionosphere and it can also show the relationship of contributions from different physical mechanisms by its changes. Moreover, it should be obtained from the available numerical models and used as a measure of their representation of real processes.

Kuznetsov *et al.* (1990) have noted that the foF_2-universal variation calculated from 1964 data is a close match to the known universal variation of the atmospheric electric field near the Earth's surface. As it is seen from Fig. 3(a), the foF_2-universal variation has a similar form during solar minima for the three available cycles. Moreover, it has a very small seasonal trend during these years (see Fig. 4(a)). The curves for different years are obtained from data for several sets of observation stations (see Fig. 2(c)). Good agreement of curves for similar geophysical situations confirms that the observed UT-effect is not a result of a poor station distribution nor a defect of the data process methods used.

During the solar activity maximum, the foF_2-universal variation form is distinctly different: a very deep minimum exist at 16–17 UT. The universal variations for the different solar activity maxima also differ appreciably (see Fig. 3(c)). Moreover, during high solar activity the seasonal changes of foF_2-universal variation are more pronounced (Fig. 4(c)).

Figure 4 shows the seasonal behaviour of the foF_2-universal variation obtained by averaging the diurnal variations over each month of every season for all solar minima and maxima.

A referee suggested investigating the foF_2 universal variation using the empirical ionospheric model, IRI-90 (Bilitza, 1990). The results of such calculations for similar geophysical situations are shown in Figs. 3(b), 3(d), 4(b), and 4(d). The calculations were made for geographic latitude 55°N. In Figs. 3(b) and 3(d) variations are averaged through the whole year, in Figs. 4(b) and 4(d) curves are presented for summer (June, July, August) and winter (November, December, January). Low solar activity was given by Solar Sunspot Number $R = 10$ and high solar activity by $R = 170$. The curves calculated using the IRI-90 model reproduce adequately the calculations for experimental data, except for summer, high solar activity. From this the conclusion can be made that, firstly, the methods used by us determine reliably the universal variation and, secondly, the IRI model reproduces the ionospheric characteristics changes rather well except for one case which has to be explained in future. Therefore we intend to study in detail the global characteristics of ionospheric universal variation using IRI-90 model.

4. Conclusion

The foF_2 universal variation form differs for solar minima and maxima years. This indicates that F_2-layer behaviour is controlled by the joint action of several physical mechanisms, and the relationship changes with increasing or decreasing solar activity. The universal variation of foF_2 is a real characteristic of the ionosphere and has to be taken into account when ionospheric numerical and empirical models are produced. This is important in studies of the relationship in the ionosphere between photochemical and the transfer processes, the heat regime and neutral atmosphere variations influence, geomagnetic and electric fields influence and so on.

The results about the dependence of the foF_2-universal variation on the solar activity confirm the assumption made by us earlier (Kuznetsov *et al.*, 1990) that the electric field can penetrate from the atmospheric layer near the Earth's surface up to heights of the F_2-layer. However, as this effect is small, it is observed only in the solar minima years and not visible with increasing solar activity, when the influence of other physical mechanisms increases.

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References

Appleton, E. V., Studies of the F_2 layer in the ionosphere, *J. Atmos. Terr. Phys.*, **1**, 106–113, 1950.

Besprosvanaya, A. S. and P. E. Kozina, Variations of the electron density in the F_2-layer maximum in the solar activity cycle, *Geomagn. Aeron.*, **28**, 639–643, 1988 (in Russian).

Bilitza, D., International Reference Ionosphere 1990, National Space Science Data Center, NSSDC/WDC-A-R&S 90-22, Greenbelt, Maryland, 1990.

Bryunelli, B. E. and A. A. Namgaladze, *Physics of the Ionosphere*, 528 pp., Nauka, Moscow, 1988 (in Russian).

Dolezalek, H., Discussion of the fundamental problem of atmospheric electricity, *Pure Appl. Geophys.*, **100**, 8–43, 1972.

Kuznetsov, V. V., V. V. Plotkin, I. I. Nesterova, and M. S. Pozdeeva, Universal diurnal variation of F_2-layer critical frequency, *J. Geomag. Geoelectr.*, **42**, 1237–1240, 1990.

Kuznetsov, V. V., V. V. Plotkin, I. I. Nesterova, and N. I. Izraileva, Universal diurnal variation of F_2-layer critical frequency as characteristic of global ionospheric condition, *J. Geomag. Geoelectr.*, **45**, 1175–1179, 1993.

Michailov, A. V., S. D. Buldenkova, V. V. Michailov, and Ju. L. Terechin, Comparison of the solar activity indices for the modelling of foF_2 median value, *Geomagn. Aeron.*, **30**, 113–120 1990a (in Russian).

Michailov, A. V., Ju. L. Terechin, and V. V. Michailov, Regional effective index of the solar activity for the prediction of the monthly median values of foF_2, *Geomagn. Aeron.*, **30**, 624–636, 1990b (in Russian).

Paramonov, N. A., On the universal variation of the atmospheric electric potential gradient, *Doklady AN USSR*, **70**, 37–38, 1950 (in Russian).

Paramonov, N. A., Determination of the global diurnal variation of the potential gradient of the electric field in the atmosphere and the vertical conduction current, National Service for Technical Information, Springfield, Virginia, 22151, U.S.A., N JRPA 55331, *Meteorology and Hydrology*, No. 12, 89–94, 1972.

Parkinson, W. C. and O. W. Torreson, The diurnal variation of the electric potential of the atmosphere over the oceans, *UGGI (Sect. Terr. Magn. Elec.) Bull.* No. 8, 340–341, 1931.

Plotkin, V. V., I. I. Nesterova, and N. I. Izraileva, Universal variation of F_2-layer critical frequency as characteristics of global ionospheric state, *Geomagn. Aeron.*, **32**, 195–197, 1992 (in Russian).

Rao, M. S. J. G. and R. S. Rao, The hysteresis variation in F_2-layer parameters, *J. Atmos. Terr. Phys.*, **31**, 1119–1125, 1969.

Reiter, R., *Phenomena in Atmospheric and Environmental Electricity*, Elsevier, 1992.

Smith, P. A. and J. W. King, Long-term relationship between sunspots, solar faculae and the ionosphere, *J. Atmos. Terr. Phys.*, **43**, 1057–1063, 1981.

Torr M. R. and D. G. Torr, The seasonal behaviour of the F_2-layer of the ionosphere, *J. Atmos. Terr. Phys.*, **35**, 2237–2251, 1973.

Yonezawa, T., Semi-annual variations in the peak electrons densities of the F_2- and E-layers, *J. Radio Res. Lab.*, **19**, 1–22, 1972.

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