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G.I. Gordiyenko, A.F. Yakovets, Yu.G. Litvinov

«Institute of Ionosphere» JSC «NCSRT», Almaty, Kazakhstan,
ggordiyenko@mail.ru, artyak40@mail.ru, yurii-litvinov@mail.ru

LONG - TERM VARIATIONS IN THE F- AND D-REGIONS OF IONOSPHERE

Abstract. The long-term changes in the near-noon, diurnal, and midnight critical frequencies of the ionosphere F2 layer (foF2) and near-noon minimum reflection frequencies (fmin) were studied using ground-based vertical radio sounding of the ionosphere at Alma-Ata station [43.25N, 76.92E] for the period 1957-2017. The data on solar and geomagnetic activity were used as factors affecting the state of the ionosphere.

It was taken into account that the minimum reflection frequency depends both on the absorption of the probe signal in the lower ionosphere, and on the noise level and technical characteristics of the ionosonde. Therefore, it seems problematic to estimate the absolute value of signal absorption in this way. However, as a qualitative characteristic, as an indicator of the absorption level of the probe signal, the parameter fmin can be used.

Arithmetic average values of median foF2 for near noon (10-14 LT), near midnight (23-01 LT) hours and average diurnal values for this period of ionosphere observation are considered as initial data. The variability of the lower ionosphere was studied using fmin data for daylight hours. The monthly average values of the solar radio emission flux F10.7 and the Ap index are considered as characteristics of solar and geomagnetic activity. The geomagnetic (Ap) indexes, the near-noon, near-midnight, diurnal averaged foF2, and near-noon fmin variations are found to be in strong dependence from the solar activity; all of them show a dominant pattern of variation with a period of ~34-36 years and linear negative trend. The correlation coefficient between the foF2 and F10.7 long-term variations is very high, up to 0. 99 that permit us to believe that the solar activity can be considered to be the main driver for the long-term variations in the ionospheric F2-region.

The geomagnetic (Ap) index, the near-noon, near-midnight, daily averaged foF2, and near-noon fmin variations are found to be in strong dependence from solar activity; all of them show a dominant pattern of variation with a period of ~34-36 years and linear negative trend. The correlation coefficient between the foF2 and F10.7 long-term variations is very high, up to 0. 99, that permits us to believe that the solar activity can be considered as a main driver for the long-term variations in the ionospheric F2-region.

The long-term course of fmin is similar to those found in F10.7, Ap, and foF2, i.e. the periodicity of 34-36 years is also evident in the fmin variations. However, in contrast to the F2-layer parameters, the fmin variation clear demonstrates an upward (positive) linear trend that is opposite in sign to the trend found in F10.7. This means relatively high sensitivity of the fmin values to the solar activity changes and significant influence of other trend drivers on them, one of which is the possible impact of anthropogenic factors on the state of the lower ionosphere.

Key words: midlatitude ionosphere; upper and lower ionosphere; D-region, F2-region, long-term trends.

Introduction. In our previous work we investigated the long-term variations in the near-noon (10-14 LT) critical frequency of the ionospheric F2-layer (foF2) measured at the mid-latitude station Alma-Ata [43.25N, 76.92E] over the period from 1957 to 2012 [1]. The purpose of this paper is to provide further analyses of the F2-layer variations and study long-term trends (a long-term linear change) in the near-noon, near-midnight and daily averaged F2-layer critical frequencies measured at the Alma-Ata station in more extended time period, from 1957 to 2017 including the period of very deep minimum in solar activity observed in 2008-2009. In addition to the F2-layer parameters the minimum frequency of reflection fmin is also used as a climatic characteristic of the upper atmosphere/low ionosphere (D region) to do the trend analyses in the ionospheric absorption. The fmin value depends, apart from the absorption of radio waves in the ionosphere, on technical characteristics of ionosondes that does not give us any opportunity to use this ionosphere parameter to determine the absolute values of the absorption of radio waves. However, as a qualitative characteristic, as an indicator of absorption of radio waves, the fmin value is widely used ([2-3] and references therein).

For the present trend analyses, monthly median foF2 and fmin values routinely measured at the Alma-Ata station have been used. The arithmetic means of the foF2 values at the near-noon (10-14 LT), near-midnight (23-01 LT) hours, and daily means foF2 are calculated for the analyses, the fmin values are taken only for the near-noon hours: $foF2_{10\text{-}14}$, $foF2_{23\text{-}01}$, $foF2_{av}$, and $fmin_{11\text{-}13}$ correspondingly. The monthly mean solar flux F10.7 and geomagnetic index Ap are also used as the indexes for solar and geomagnetic activities (available at htt://ww.swpc.noaa.gov) to illustrate their long-term variations.

Description of the data, and observation results *Trends in the ionospheric F-region.* As an example, median mean values $foF2_{10\text{-}14}$, $foF2_{23\text{-}01}$, $foF2_{d.av}$ together with the corresponding data of solar and geomagnetic activity is shown in figure 1a-e. The dots represent observed data, the thick lines show the fitting curves. It should be also noted, the statistical processing of the ionospheric data series requires their continuity that is not always possible because of different reasons (ionosonde repair and other technical problems).

The regression dependences between the selected ionospheric parameters and F10.7 (figure 1f-h) have been analyzed to define the missing data. Thick lines represent the linear regression lines for these data; dashed lines correspond to the polynomial functions of the second degree that better fit the given F2-layer parameters ($R^2_{polinomial}$>R^2_{linear}) where R^2 is the coefficient of determination that provides a measure of how well the least-square curve fits the observational data, r is the correlation coefficient. Assuming the second-order polynomial dependence with F10.7 the missing foF2 values have been defined from the regression equations to fill available gaps in the data sets. Two things are evident in the figure, firstly the variations of all parameters are strictly modulated by cyclic 11-year variations of solar activity and secondly the foF2 data are much scattered relatively to the smoothed lines that can be attributed to various sources other than solar activity, including planetary waves and seasonal variations. As an example, the great part of seasonal variations is evident in Figure 1e where large deviations of the $foF2_{23\text{-}01}$ values from the smoothed line is caused by the fact that summer nighttime foF2 values are much higher than winter ones. Since this intraseasonal variability has to be taken into consideration in the trend analyses, annual averages of the parameters considered were calculated. Figure 2a-e demonstrates temporal variations of the calculated annual averages (denoted by symbol*) of the $F10.7^*$, Ap^* indexes, and the F2-layer parameters ($foF2^*_{10\text{-}14}$, $foF2^*_{23\text{-}01}$, and $foF2^*_{av}$) for whole period of observations; variations of the ionospheric parameters with $F10.7^*$ are presented in Figure 2f-h.

The main feature of the variations is their similarity (figure 2a-e) and close connection between the ionospheric parameters and solar activity (figure 2f-h). The coefficients of determination R^2 (the coefficients R2 and derived regression equations are shown in the figure fields) are found to be very high, from 0.97 to 0.99 it means that from 97% to 99% of the annual foF2 variations can be explained by their relationship with the 11-year cycle of solar activity.

According to our previous work [1], the 11-year (132 months) running mean values of the annual averages of the ionospheric parameters ($foF2^*_{10\text{-}14}(132)$, $foF2^*_{23\text{-}01}(132)$, and $foF2^*_{av}(132)$ were calculated to obtained an independent picture of long-term trends in the upper ionosphere; the 11-year smoothing technique was also applied to the F10.7 and Ap data sets ($F10.7^*(132)$, $Ap^*(132)$); Figure 3 presents these calculated values and shows that geomagnetic activity is strongly controlled by the solar activity, both show a dominant pattern of variations with the period ~34-36 years that is also reflected in all ionospheric parameters considered.

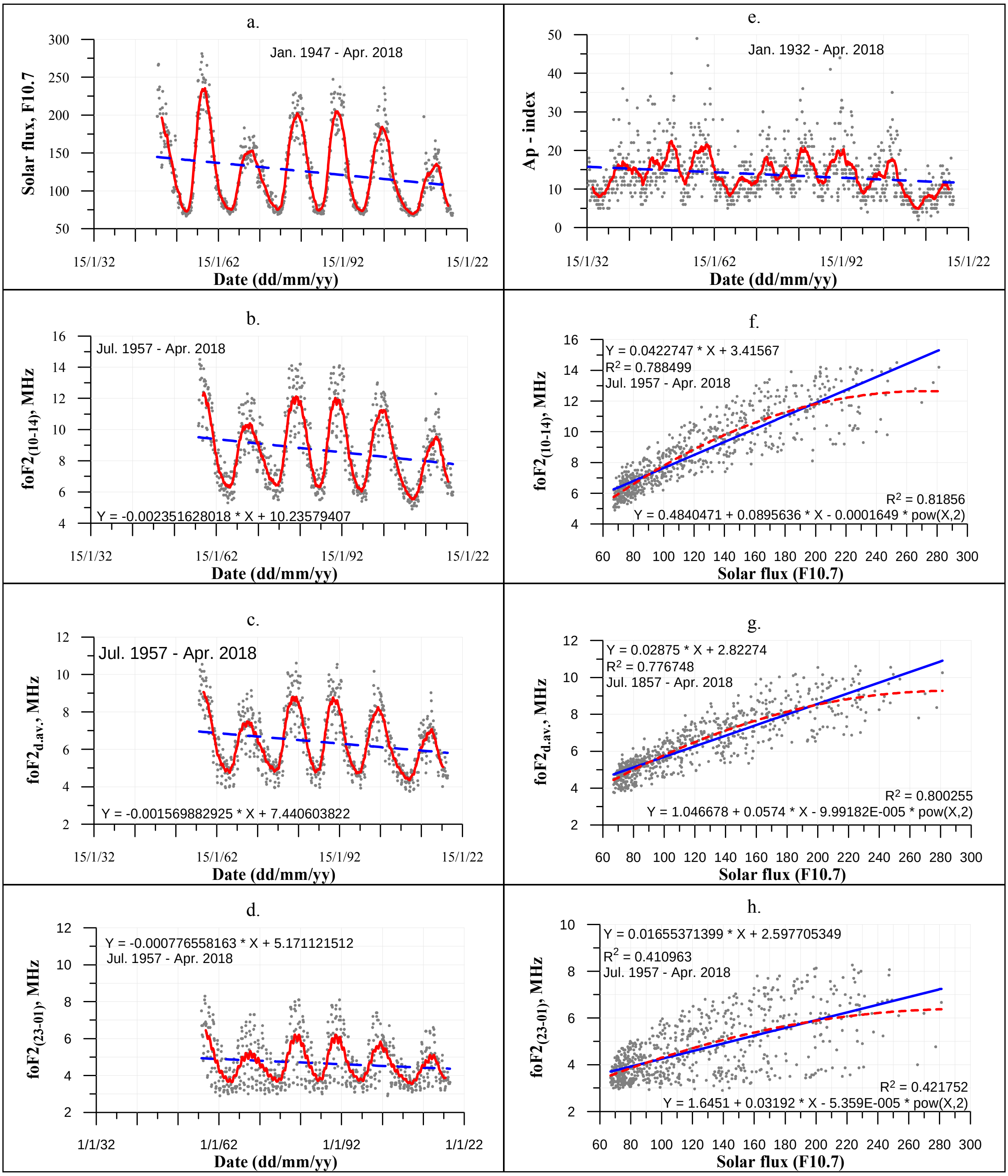

Figure 1 - The long-term variations of the near-noon(b), daily mean (c) and near-midnight (d) monthly median foF2 values in Alma-Ata [43.25^{0}N, 76.92^{0}E] in 1957-2017 together with the corresponding variations of solar flux F10.7 (a) and Ap index (c); solid dots – measured data, thick lines show the fitting lines, dashed lines – linear fits. Monthly median near-noon (f), daily mean (g), and near-midnight (h) foF2 values versus monthly mean F10.7; thick lines represent the linear regression lines for these data, dashed lines correspond to the polynomial functions of the second degree

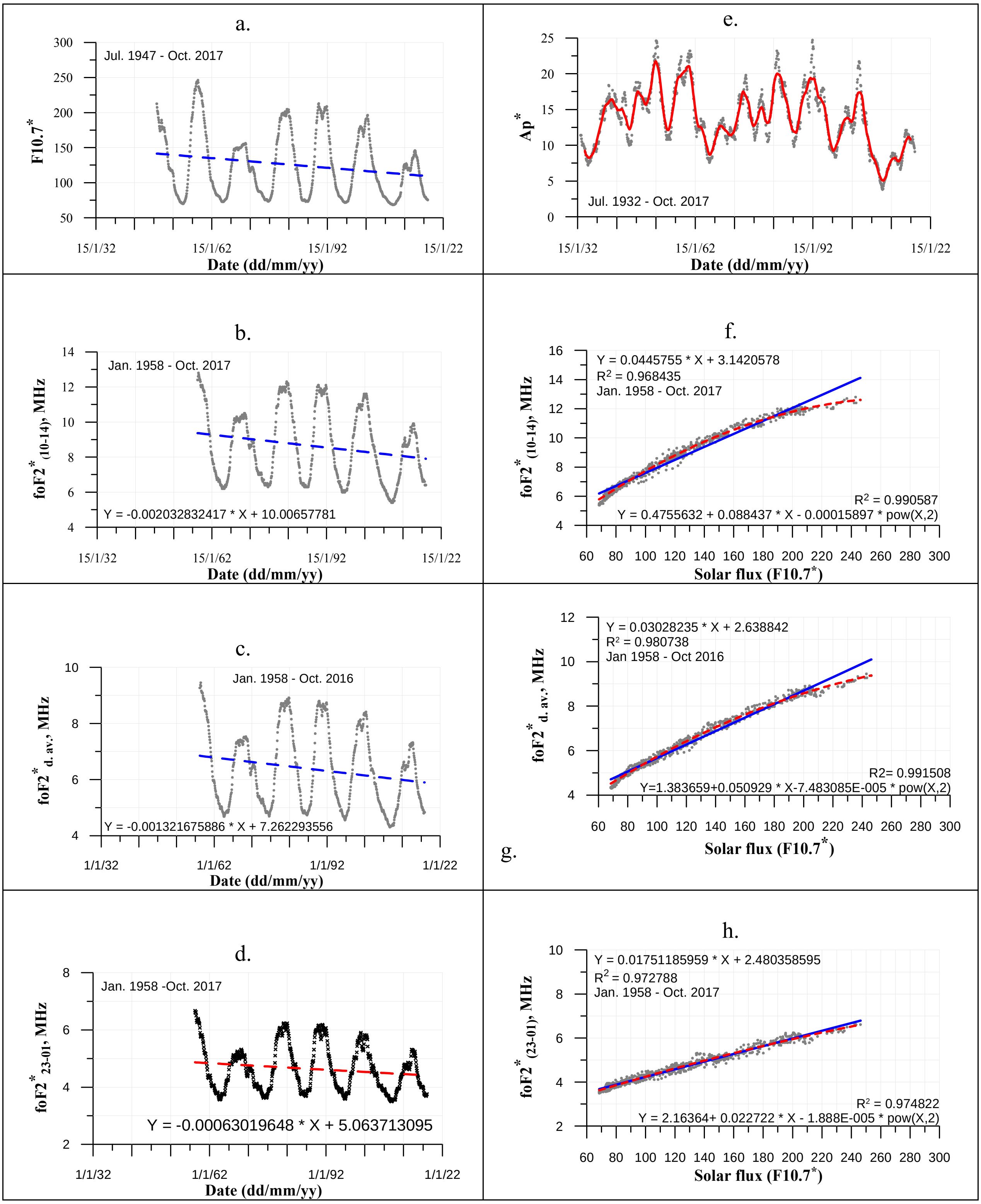

Figure 2 - As the Figure 1 but the annual averages of the F10.7, Ap, and foF2 values.

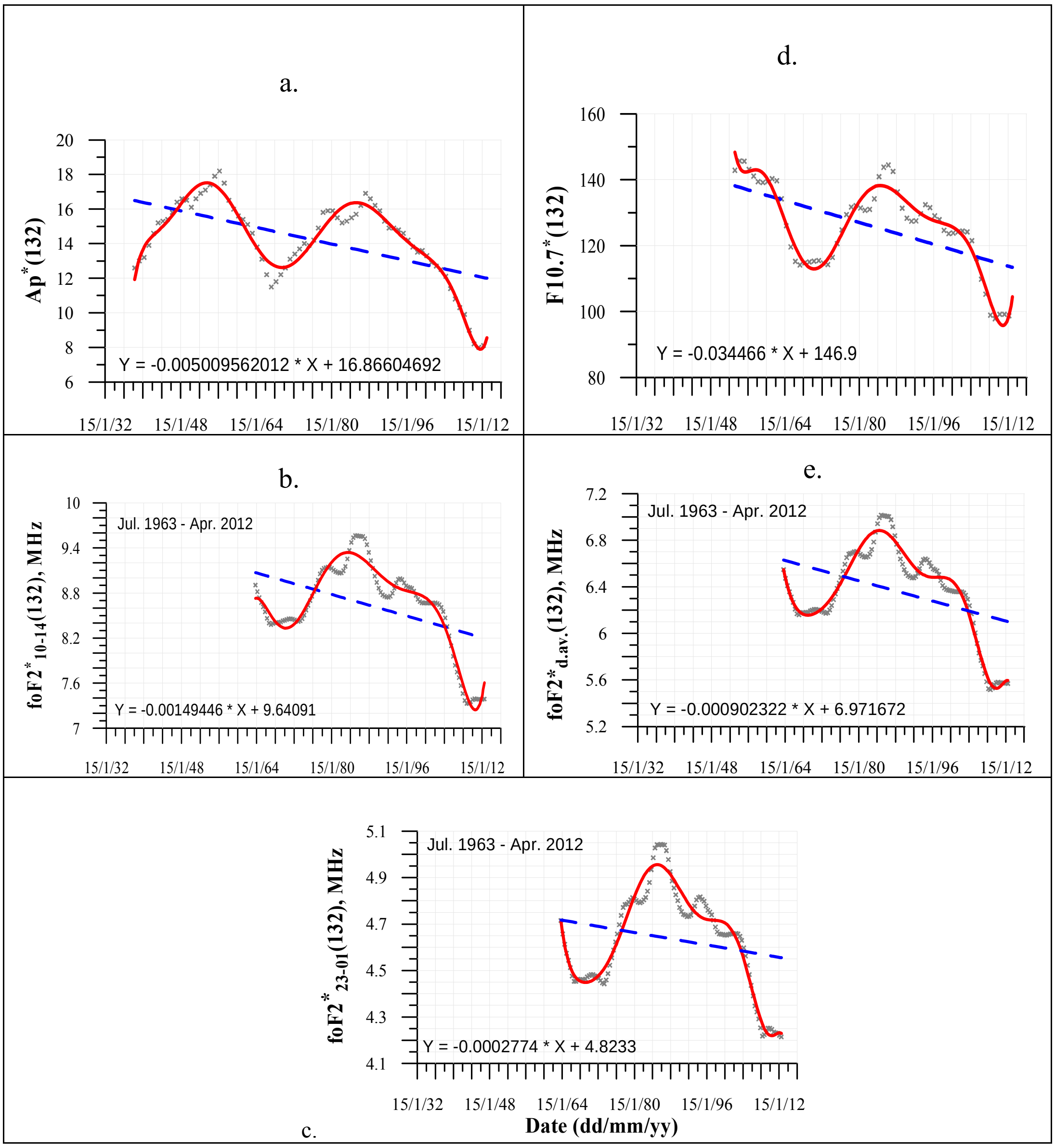

Figure 3 - The 132-month smoothed values of the annual averages of the ionospheric F2-layer parameters, F10.7, and Ap.

This period is slightly differs from our earlier finding [1] where the period was estimated to be in a range of 30-32 years. The extended data sets used in the study reveal the period more clearly. It should be mentioned that similar period (31-32 years) has been found in all the solar terrestrial parameters ([4-6], and references therein) and was interpreted as the 35-year Brutcher climatic periodicity. Note, the negative trend (dashed line), the lowering in the F2-layer critical frequency, is also seen in figure 3. The long-term trends found in different ionospheric characteristics (figures 1-3) are given in table.

Table

#	Parameter	Trend, MHz/year	Parameter	Trend, MHz/year	Parameter	Trend, MHz/year
1	$foF2_{10-14}$(med)	-0.02822	$foF2^*_{10-14}$	-0.02439	$foF2^*_{10-14}$ (132)	-0.01758
2	$foF2_{d.av}$ (med)	-0.01884	$foF2^*_{d.av}$	-0.01586	$foF2^*_{d.av}$ (132)	-0.01077
3	$foF2_{23-01}$ (med)	-0.00932	$foF2^*_{23-01}$	-0.00756	$foF2^*_{23-01}$ (132)	-0.00364

The regression dependences of foF2$^{*}_{10-14}$(132), foF2$^{*}_{23-01}$(132), foF2$^{*}_{d.av}$(132) on F10.7*(132) were studied for the period 1963-2012 (the 11-year smoothing technique that was applied to the foF2* data sets reduced the available period for study to between 1963 and 2012), the coefficients of determination (R^2) were found to be 0.96, 0.98, and 0.90 for near-noon, daily averaged and near-midnight data correspondingly figure 4a.

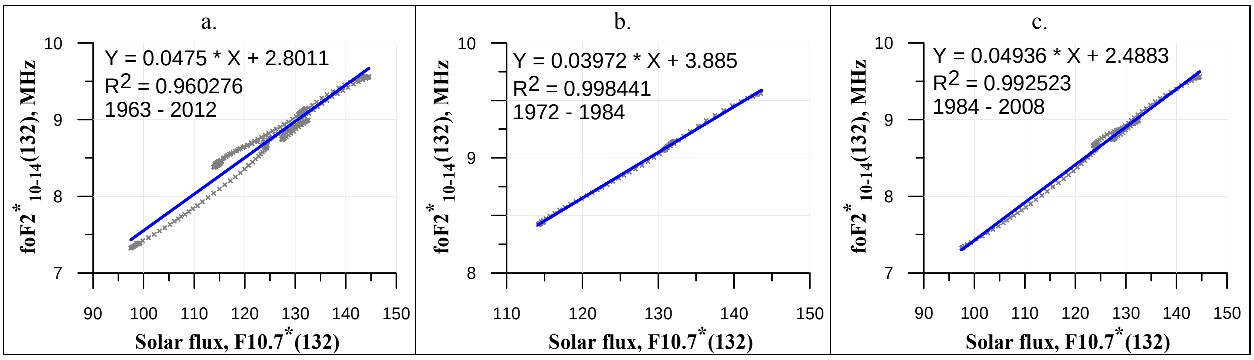

Figure 4 - The regression dependence between foF2*(132) and F10.7*(132) for the periods 1963-2012, (a), 1972-1984 (b) and 1984-2008 (c)

However, a combination of two groups of points was evident in figure 4 (upper panel) that assumed some different dependence between the parameters on different phases of the 34-36-years cycle (the period 1972-1984, and 1984-2008), when the foF2*(132) values increase to their maximum and then decrease to their minimum values. Examples of the regression dependences between foF2*(132) and F10.7*(132) for the two time periods are shown in figure 4a,b. It is distinctly seen in both cases that 99% of the variations in the ionospheric parameters can be explained by linear dependence between them and solar activity. So, the solar activity can be considered to be the main driver for the long-term variations in the ionospheric F2-region.

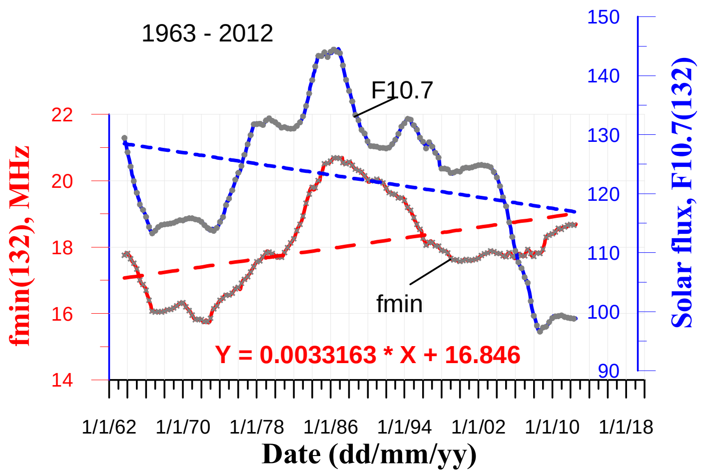

Figure 5 - The 132-month smoothed values of fmin and F10.7 where dashed lines represent their linear trends for the whole measuring interval

Trends in the D-region. A similar analysis, as that carried out for foF2, has been carried out for the fmin data observed at the Alma-Ata station in the years 1957-2017. As it has been already mentioned, the ionospheric parameter fmin is used as a qualitative characteristic of the ionospheric absorption in the D-region, and our interest "is there any trend in the fmin data, and if "yes" what is its sign?" For this purpose, we use the monthly median fmin values for near-noon interval of local time averaging the data over three hours, from 11:00 LT to 13:00 LT. Then, the fmin data were smoothed using the 11-year running mean smoothing to suppress effects of the 11-year solar cycle and obtain a picture of long-term variation in them. Figure 5 shows the fmin(132) and F10.7(132) variation together with the regression lines (dashed lines) and demonstrates that the long-time course of fmin(132) is similar to those found for F10.7 and foF2 (figures 1-3) in the event that the periodicity of 34-36 years is also evident in the fmin(132) variation which is found in variations of the F2-layer parameters. However, figure 5 clear illustrates a stable upward (positive) trend in fmin(132) values opposite in sign to the trends observed in variations F10.7 and foF2. It means relative high sensitivity of the fmin values to the solar activity changes and significant influence of other trend drivers on them that is very possible the impact of anthropogenic factors on the state of the lower ionosphere.

Conclusion. The F2-layer critical frequency (foF2) and lowest frequency (fmin) observed at the mid-latitude ionospheric station Alma-Ata [43.25N, 76.92E] in the period 1957-2017 were used to study long-term trends in the upper (F2-layer) and lower (D-region) ionosphere.

The geomagnetic indexes (Ap), the near-noon, near-midnight, daily averaged foF2 are found to be in strong dependence from the solar activity; all of them show a dominant pattern of variation with a period of ~34-36 years and linear negative trend.

The trend magnitudes are found to be of the same order independently of the fact whether the solar activity effects in the data sets are smoothed or not; the trends are statistically significant and lie within of -0.018 to -0.028, -0.011 to -0.019, -0.0036 to -0.0093 MHz/year for near-noon, daily averaged and near-midnight values correspondingly.

The long-term course of fmin is similar to those found in F10.7, Ap, and foF2, i.e. the periodicity of ~34-36 years is also evident in the fmin variation. However, in contrast to the F2-layer parameters, the fmin variation clear demonstrates an upward (positive) linear trend that is opposite in sign to the trend found in the F10.7. This means relatively high sensitivity of the fmin values to the solar activity changes and significant influence of other trend drivers on them, one of which is the possible impact of anthropogenic factors on the state of the lower ionosphere.

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А.Ф. Яковец, Г.И. Гордиенко, Ю.Г. Литвинов

ЕЖШС «Ионосфера институты» «ҰҒЗТО» АҚ, Алматы, Қазақстан

ИОНОСФЕРАНЫҢ F ЖӘНЕ D АЙМАҒЫНДАҒЫ ҰЗАҚ МЕРЗІМДІ ВАРИАЦИЯЛАРЫ

Аннотация. Алматы станциясындағы ионосфераның жер үсті тік радиозондауының деректері бойынша F2 Ионосфера қабатының (foF2) және жер маңындағы ең төменгі шағылысу жиіліктерінің (fmin) ұзақ мерзімді өзгерістері зерттелді [43.25 N, 76.92 E] 1957-2017 жж.

Сонымен қатар, ең аз шағылысу жиілігі төменгі ионосферада зондирлеуші сигналдың жұтылуына да, шу деңгейі мен ионозондтың техникалық сипаттамаларына да байланысты. Сондықтан сигналдың жұтылуының абсолюттік мәнін осындай жолмен бағалау проблемалы болып табылады. Алайда, қолшатыр сигналының жұту деңгейінің индикаторы ретінде сапалы сипаттама ретінде fmin параметрін пайдалануға болады.

Бастапқы деректер ретінде fof2 медиандық fof2 (10-14 LT), терек жанындағы (23-01 LT) сағат арифметикалық орташа мәндері және ионосфераның бақылауының қаралып отырған кезеңіндегі орташа тәуліктік мәндері қарастырылды. Төменгі ионосфераның өзгергіштігі күндізгі сағат үшін fmin деректерін пайдалану арқылы зерттелген. Күн радиосәулелендіру ағынының орташа айлық мәндері F10. 7 және Ap индексі күн және геомагниттік белсенділіктің сипаттамалары ретінде рассматрен.

Күн және геомагниттік белсенділігі бойынша деректер ионосфераның жағдайына әсер ететін факторлар ретінде тартылды. Ионосфера аймағының F2 параметрлері, сондай-ақ Ap геомагниттік белсенділіктің индексі T ≈ 35 жыл мерзімділігін және сызықтық теріс трендін анықтай отырып, күн белсенділігіне қатаң тәуелділікті сезінеді. FoF2 және F10.7 ұзақ мерзімді вариация арасындағы детерминация коэффициенттері 0.99 мәндеріне жетеді, бұл күн белсенділігі Ионосфера аймағының F2 ұзақ мерзімді өзгергіштігінің негізгі драйвері болып табылады деп болжайды.

Бұл нәтиже бір жағынан күн белсенділігіне жоғары тәуелділікті, екінші жағынан басқа факторлардың төменгі ионосфераның жағдайына, антропогендік факторларға әсерін болжайды.

Түйін сөздер: орташалықты ионосфера; жоғарғы және төменгі ионосфера; D-облыс; F2-облыс; ұзақ мерзімді трендтер.

А.Ф. Яковец, Г.И. Гордиенко, Ю.Г. Литвинов

ДТОО «Институт ионосферы» АО «НЦКИТ», Алматы, Казахстан

ДОЛГОВРЕМЕННЫЕ ВАРИАЦИИ В ОБЛАСТИ F И D ИОНОСФЕРЫ

Аннотация. Исследованы долговременные изменения околополуденных, среднесуточных и полуночных критических частот слоя F2 ионосферы (foF2) и околополуденных минимальных частот отражения (fmin) по данным наземного вертикального радиозондирования ионосферы на станции Алма-Ата [43.25N, 76.92E] за период 1957-2017 гг.

Принималось во внимание, что минимальная частота отражения зависит как от поглощения зондирующего сигнала в нижней ионосфере, так и от уровня шумов и технических характеристик ионозонда. Поэтому оценить абсолютное значение поглощения сигнала таким способом представляется проблематичным. Однако, как качественная характеристика, как индикатор уровня поглощения зондирующего сигнала, параметр fmin можно использовать.

В качестве исходных данных рассмотрены арифметически средние значения медианных foF2 для околополуденных (10-14 LT), околополуночных (23-01 LT) часов и среднесуточные значения за рассматриваемый период наблюдений ионосферы. Изменчивость нижней ионосферы исследована с использованием данных fmin для дневных часов. Среднемесячные значения потока радиоизлучения Солнца F10.7 и индекс Ap рассматрены как характеристики солнечной и геомагнитной активности.

Привлекались данные по солнечной и геомагнитной активности как факторы, оказывающие влияние на состояние ионосферы. Получено, что параметры F2 области ионосферы, а также индекс геомагнитной активности Ap испытывают строгую зависимость от солнечной активности, обнаруживая периодичность T ≈ 35 лет и линейный отрицательный тренд. Коэффициенты детерминации взаимосвязи долгопериодных вариаций foF2 и F10.7 достигают значений 0.99, это предполагает, что солнечная активность является основным драйвером долговременной изменчивости F2 области ионосферы.

Значения fmin, обнаруживая подобно параметрам F2 области ионосферы ~35-летнюю периодичность, демонстрируют положительный тренд в наблюдаемый период 1957-2017 гг. Данный результат предполагает с одной стороны высокую зависимость от солнечной активности, с другой стороны влияние других факторов на состояние нижней ионосферы, возможно факторов антропогенных.

Ключевые слова: среднеширотная ионосфера; верхняя и нижняя ионосфера; D-область; F2-область; долговременные тренды.

Information about authors:

Gordienko Galina Ivanovna, Ph.D. mat. Sciences, ANS, Institute of the Ionosphere, JSC "NCSCIT", Almaty, ggordienko@mail.ru. 1) The author made a significant contribution to the research concept, obtaining data and interpretation, 2) the author wrote the first version of the article 3) the author approved the final version of the article before submitting it for publication. https://orcid.org/0000-0002-9337-206X;

Yakovets Arthur Fedorovich, Ph.D. mat. Sciences, VNS, Institute of the Ionosphere, JSC "NTSKIT", Almaty, artyak40@mail.ru. 1) The author made a significant contribution to the research concept, data analysis and interpretation, 2) the author wrote the first version of the article, 3) the author approved the final version of the article before submitting it for publication. https://orcid.org/0000-0002-3374-9507;

Litvinov Yuri Georgievich, Ph.D. mat. Sci., SSS, Institute of the Ionosphere, NCSCIT JSC, Almaty, yurii-litvinov@mail.ru. 1) The author made a significant contribution to obtaining the data and their analysis, 2) the author made a critical review of the article for important intellectual content, 3) the author approved the final version of the article before submitting it for publication. https://orcid.org/0000-0002-0600-0517

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