ISSN 0016-7932, Geomagnetism and Aeronomy, 2021, Vol. 61, No. 3, pp. 359–364. © Pleiades Publishing, Ltd., 2021.
Russian Text © The Author(s), 2021, published in Geomagnetizm i Aeronomiya, 2021, Vol. 61, No. 3, pp. 347–353.

Dependence of the Annual Asymmetry in *NmF*2 on Geomagnetic Latitude and Solar Activity

M. G. Deminov[a, *], **V. N. Shubin**[a], **and R. G. Deminov**[b]

[a] *Pushkov Institute of Terrestrial Magnetism, Ionosphere, and Radio Wave Propagation (IZMIRAN), Russian Academy of Sciences, Troitsk, Moscow, Russia*

[b] *Kazan Federal University, Kazan, Russia*

**e-mail: deminov@izmiran.ru*

Received November 23, 2020; revised November 27, 2020; accepted January 28, 2021

Abstract—The properties of the annual asymmetry in the electron density of the *F*2-layer maximum *NmF*2 at noon are analyzed based on the global empirical model of the *F*2-layer critical frequency median (SDMF2 model). As a characteristic of this asymmetry, we used the *R* index, i.e., the January/July ratio of the total (at a given and geomagnetically conjugate points) *NmF*2 density at noon averaged over all longitudes. It was found that the *R* index decreases with increasing solar activity at low geomagnetic latitudes ($\Phi < 31°–33°$). At higher latitudes, the *R* index increases with an increase in solar activity. During low solar activity, the main *R* maximum is located at latitude $\Phi = 22°–24°$. During high solar activity, this *R* maximum is located at $\Phi = 64°–66°$. At latitude $\Phi = 22°–24°$ in the Northern and Southern hemispheres, the longitudinal average *NmF*2 density in January is higher than that in July for any level of solar activity. At $\Phi = 64°–66°$, an increase in *R* with increasing solar activity is mainly caused by a January increase in *NmF*2 in the Northern Hemisphere. The global (average over all latitudes) *R* index increases with increasing solar activity. Additional analysis showed that the global *R* index decreases with increasing solar activity in the IRI model both with URSI option and, even more so, with CCIR option. This appears to be due to the limited amount of experimental data on the obtainment of the CCIR and URSI coefficients, especially over the oceans.

DOI: 10.1134/S0016793221030038

1. INTRODUCTION

The term "annual asymmetry" (annual anomaly, December anomaly) refers to ionospheric phenomena in which the globally averaged electron density at a given local time in January is greater than that in July (Rishbeth and Müller-Wodarg, 2006). This asymmetry is often identified with the use of the electron density of the *F*2-layer maximum *NmF*2 based on data from the network of ionospheric stations (Rishbeth and Müller-Wodarg, 2006; Mikhailov and Perrone, 2015; Brown et al., 2018), topside sounding of the ionosphere (Gulyaeva et al., 2014), or radio occultation measurements on the FORMOSAT-3/COSMIC satellites (Zeng et al., 2008; Sai Gowtam and Tulasi Ram, 2017a). In addition, the total electron content of the ionosphere (Mendillo et al., 2005; Zhao et al., 2007; Gulyaeva et al., 2014) or the altitudinal distribution of the electron density in the ionospheric *F* region (Sai Gowtam and Tulasi Ram, 2017b) are used. The asymmetry index (Rishbeth and Müller-Wodarg, 2006)

$$AI = (NmF2(\mathrm{N+S})_{\mathrm{Jan}} - NmF2(\mathrm{N+S})_{\mathrm{July}})/(NmF2(\mathrm{N+S})_{\mathrm{Jan}} + NmF2(\mathrm{N+S})_{\mathrm{July}}) \quad (1)$$

or the relation (Rishbeth and Müller-Wodarg, 2006; Mikhailov and Perrone, 2015)

$$R = NmF2(\mathrm{N+S})_{\mathrm{Jan}}/NmF2(\mathrm{N+S})_{\mathrm{July}}, \quad (2)$$

are used as a characteristic of this asymmetry, e.g., for *NmF*2. Here, $NmF2(\mathrm{N+S})_{\mathrm{Jan}}$ and $NmF2(\mathrm{N+S})_{\mathrm{July}}$ are the total (for the Northern and Southern hemispheres) *NmF*2 values in January and July at a fixed local time. These equations typically use *NmF*2 monthly means or monthly medians (Rishbeth and Müller-Wodarg, 2006; Mikhailov and Perrone, 2015; Brown et al., 2018). Below, for definiteness, we use the *R* index for the *NmF*2 monthly medians. The *AI* value can be estimated from the known *R* index with the ratio $AI = (R - 1)/(R + 1)$.

To analyze the properties of the global *R* index, it is necessary to know the regularities and properties of the $R(\Phi)$ index at a given geomagnetic latitude Φ. The $R(\Phi)$ index is defined by Eq. (2), in which $NmF2(\mathrm{N+S})_{\mathrm{Jan}}$ and $NmF2(\mathrm{N+S})_{\mathrm{July}}$ are the total average over all longitudes (at a given latitude Φ in the Northern Hemisphere and conjugate latitude $-\Phi$ in the Southern Hemisphere) *NmF*2 values in January and July at fixed local time and level of solar activity. For brevity, the $R(\Phi)$ index is called the local *R* index.

To obtain correct estimates of the global and local *R* indices for a given local time and level of solar activity, it is necessary to have the corresponding *NmF*2 data for January and July at all longitudes. The data from ionospheric stations do not meet this criterion, since the Southern Hemisphere has such stations only in certain longitudinal sectors. Nevertheless, some properties of the *R* or *AI* indices were studied based on data from ionospheric stations (Yonezawa, 1971; Rishbeth and Müller-Wodarg, 2006; Mikhailov and Perrone, 2015; Brown et al., 2018). For example, contrary to the previous conclusions (Yonezawa, 1971), an analysis of four pairs of stations with this method revealed that *AI* in the solar maximum is generally higher than that in the solar minimum (Rishbeth and Müller-Wodarg, 2006). Satellite data, primarily, data from radio occultation measurements of *NmF*2 by the COSMIC satellite (Constellation Observing System for Meteorology, Ionosphere, and Climate) make it possible to obtain a nearly global picture of *NmF*2 for specific geophysical conditions and, thus, to judge the regularities of the spatial distribution of the *R* or *AI* indices for these conditions (Zeng et al., 2008; Sai Gowtam and Tulasi Ram, 2017a). According to the COSMIC data centered on June 21 and December 21, 2006, in the interval of 90 days, a distinct peak of the *AI* index was identified at a geomagnetic latitude of approximately 25°, and it was shown that the globally averaged *NmF*2 value at noon is 30% higher in December than that in June (Zeng, 2008). These results were obtained for low solar activity (Zeng, 2008). Attempts to estimate the solar-activity dependence of the annual asymmetry in *NmF*2 (or in the altitude distribution of the electron density in the ionospheric *F* region) based on COSMIC data in the growth phase of solar cycle 24 made it possible to establish only the qualitative trend of this dependence (Sai Gowtam and Tulasi Ram, 2017b). This is due to the fact that, in order to obtain a correct *R* or *AI* estimate, it is required that the data for December (or January) and June (or July) correspond to a fixed level (or interval) of solar activity. This requirement is rarely met during the phases of growth and decline of the solar cycle, since the variations in the solar-activity index for a half-year interval are usually significant. For example, the highest and lowest values of the global *AI* index in the growth phase of solar cycle 24 in the interval 2008–2012 were observed in the adjacent years 2011 and 2012 due to the significant and opposite difference in solar activity indices in June and December during these years (Sai Gowtam and Tulasi Ram, 2017b). Therefore, the problem of regularities in the variations in the annual asymmetry in *NmF*2 with respect to geomagnetic activity and latitude cannot be considered solved.

One way to solve this problem is based on the use of the global model of the *NmF2* median, which takes into account the dependence of *NmF*2 on geophysical conditions, including the dependence of *NmF*2 on latitude and solar activity. The implementation of this method on the example of the analysis of data of *NmF*2 medians at noon with the SDMF2 (Satellite and Digisonde Data Model of the *F*2 layer) model (Shubin, 2017) was the main goal of this study. The SDMF2 model was chosen, because it is based on a large database of ionospheric stations and satellite radio occultation measurements of the *F*2-layer critical frequency *foF*2. This provided almost global coverage of the *foF*2 data (with a 15° step in longitude and 5° in latitude) for each month and a fixed hour UT at low and relatively high solar activity. In the construction of the SDMF2 model, the Legendre method was used for the spatial expansion of the *foF*2 monthly medians calculated from this database, and the Fourier method was then used to expand the obtained coefficients in UT. In addition, the *foF*2 moving medians for a given day of the month were obtained via linear interpolation of the *foF*2 medians for a given month and the nearest month. As a result, the input parameters of this model are the geographic coordinates, UT, day, month, year, and integral index $F10.7(\tau)$ of solar activity for the given day. The $F10.7(\tau)$ index is the weighted average *F*10.7 index (with a characteristic time $T = 27$ days or $\tau = \exp(-1/T) = 0.96$), reflecting the dependence of *foF*2 on the pre-history of variations in *F*10.7 (Shubin, 2017).

To solve the problem, we used a version of the SDMF2 model in which *foF*2 is not interpolated for a given day of the month. In this case, the input (specified) parameters of the model are the geographic coordinates, UT, month of the year, and solar-activity index *F*, i.e., the measured solar radio flux at 10.7 cm for a given month. The analysis of the annual asymmetry uses not geographic but geomagnetic (Mikhailov and Perrone, 2015) or magnetic (Rishbeth and Müller-Wodarg, 2006; Brown et al., 2018) coordinates. Here, for definiteness, we use geomagnetic coordinates Φ and Λ, when the Earth's magnetic field is approximated by a centered dipole for 2010; the geographic coordinates of its pole in the Northern Hemisphere are 80.01° N, 287.79° E (Koochak and Fraser-Smith, 2017).

Therefore, the more specific goal of this study was to analyze the dependence of the annual asymmetry index *R* at noon on geomagnetic latitude Φ and solar-activity index *F* with the SDMF2 model. The results of this analysis, as well as the analysis of the properties of the global *R* index based on the SDMF2 model and the basic model of the *foF*2 median in the IRI model (Bilitza, 2018) with the CCIR (International Radio Consultative Committee) coefficients (Jones and Gallet, 1962, 1965) and URSI (International Union of Radio Science) coefficients, (Rush et al., 1984, 1989) are sequentially presented below, along with a discussion of these results and the main conclusions of the study.

2. RESULTS OF ANALYSIS

To obtain the local index $R(\Phi)$ at noon at a given geomagnetic latitude Φ for a fixed index of solar activity *F*, we calculated the average *NmF*2 values over all longitudes at noon for January (and July) at latitude Φ

in the Northern Hemisphere (and conjugate latitude $-\Phi$ in the Southern Hemisphere) for this solar activity. The algorithm for this calculation of *NmF*2 at noon, e.g., for January at latitude Φ for a given solar-activity index F, is as follows. Let us set the geomagnetic longitudes $\Lambda(i)$ with a longitude step of 15° (24 values). For each point with geomagnetic coordinates Φ, $\Lambda(i)$, we sequentially calculate geographic coordinates $\varphi(i)$, $\lambda(i)$ and time UT(i), which corresponds to the local noon; we calculate *foF*2(i) (and therefore *NmF*2(i)) from the resulting $\varphi(i)$, $\lambda(i)$, UT(i), and F using the SDMF2 model. We further calculate $NmF2(\mathrm{N})_{\mathrm{Jan}}$, i.e., the average *NmF*2 over all longitudes in January at noon in the Northern Hemisphere at latitude Φ for a given solar-activity index F. Similarly, we calculate $NmF2(\mathrm{S})_{\mathrm{Jan}}$, $NmF2(\mathrm{N})_{\mathrm{Jul}}$, and $NmF2(\mathrm{S})_{\mathrm{Jul}}$, from which we then calculate the total values $NmF2(\mathrm{N + S})_{\mathrm{Jan}}$ and $NmF2(\mathrm{N + S})_{\mathrm{Jul}}$. Using Eq. (2), we determine the sought value of the local index of annual asymmetry $R = R(\Phi)$ at noon at a given geomagnetic latitude Φ for a given solar-activity level F. The average $R(\Phi)$ value over all latitudes gives the global index of annual asymmetry R_{G} at noon for a given level of solar activity F. The global R_{G} index was calculated with a latitude step of 1°. The same step was used in the analysis of the dependence of the local annual asymmetry index R on the geomagnetic latitude Φ.

Figure 1 shows the dependences of the local annual asymmetry index R at noon on the geomagnetic latitude for two solar-activity levels; the dependences were obtained with the SDMF2 model and the above algorithm. It can be seen that the main R maximum is clearly distinguished at low solar activity ($F = 75$) at low latitudes, more precisely, at geomagnetic latitudes of 22°–24°, where $R = 1.45$. At middle and high latitudes ($\Phi > 40°$) the latitude variations in the local annual asymmetry index R are relatively weak ($1.19 < R < 1.24$). The R index during relatively high solar activity ($F = 150$) is greater than that during low solar activity ($F = 75$) at latitudes of $\Phi > 31°$–$33°$. At lower latitudes, the R index decreases with an increase in solar activity. As a result, for $F = 150$, the main R maximum is located at geomagnetic latitudes of 64°–66°, where $R = 1.47$. The data in Fig. 1 allow us to conclude that the local R index is greater than unity at all latitudes and any solar-activity level.

From the data in Fig. 2, one can judge in more detail the character of the solar activity dependences of the R index at geomagnetic latitudes of 23° and 65°, which are obtained from the SDMF2 model. These latitudes correspond to the maximum R at low and high solar activity (Fig. 1). Figure 2 also shows the solar activity dependences of the R components, i.e., *NmF*2 for appropriate geophysical conditions (see Eq. (2)). It can be seen that the R index decreases with increasing solar activity at a geomagnetic latitude of 23°. This decrease is rather minor: from $R = 1.47$ for $F = 70$ to $R = 1.30$ for $F = 230$. At a latitude of $\Phi = 23°$, the *NmF*2 density at noon in January is higher than that in July in the Northern and Southern hemispheres at any solar-activity level.

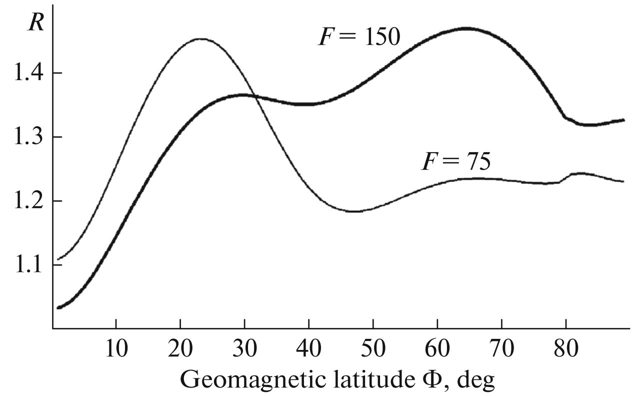

Fig. 1. Variations in the local index of annual asymmetry R at noon with geomagnetic latitude Φ according to the SDMF2 model for low ($F = 75$) and relatively high ($F = 150$) solar activity.

At a geomagnetic latitude of 65°, the R index increases with an increase in solar activity. This increase is significant: from $R = 1.2$ for $F = 70$ to $R = 1.57$ for $F = 230$ (Fig. 2). At this latitude, the noon *NmF*2 density in January is higher than that in July in the Northern and Southern hemispheres at $F > 75$, i.e., almost at any solar-activity level. The only exception is a very low solar-activity level. At a latitude of $\Phi = 65°$, the dependence of *NmF*2 on solar activity is maximal in January in the Northern Hemisphere, when *NmF*2 increases by approximately 5.3 times upon moving from $F = 70$ to $F = 230$. For the rest of the cases (July in the Northern Hemisphere, January and July in the Southern Hemisphere), such increases are maximal in July in the Southern Hemisphere, when they reach a factor of 3.8. Therefore, at a latitude of $\Phi = 65°$ at noon in the Northern and Southern hemispheres, the dependence of *NmF*2 on solar activity in local winter is greater than that in local summer, and this difference in the Northern Hemisphere is much stronger than that in the Southern Hemisphere. This is what leads to an increase in the R index at a given latitude with solar activity.

The all-latitude average value of the R index at noon for a fixed level of solar activity F gives the global index of annual asymmetry R_{G} at noon for this solar-activity level. Figure 3 shows the solar-activity dependences of the R_{G} index obtained with the SDMF2 model and the IRI model with the CCIR and URSI coefficients. It can be seen that the R_{G} index increases with solar activity according to the SDMF2 model. This increase is very weak: $R_{\mathrm{G}} = 1.26$ at $F = 70$ and $R_{\mathrm{G}} = 1.37$ at $F = 230$. According to the IRI model with CCIR and URSI coefficients, the R_{G} index decreases with increasing solar activity. The use of the CCIR

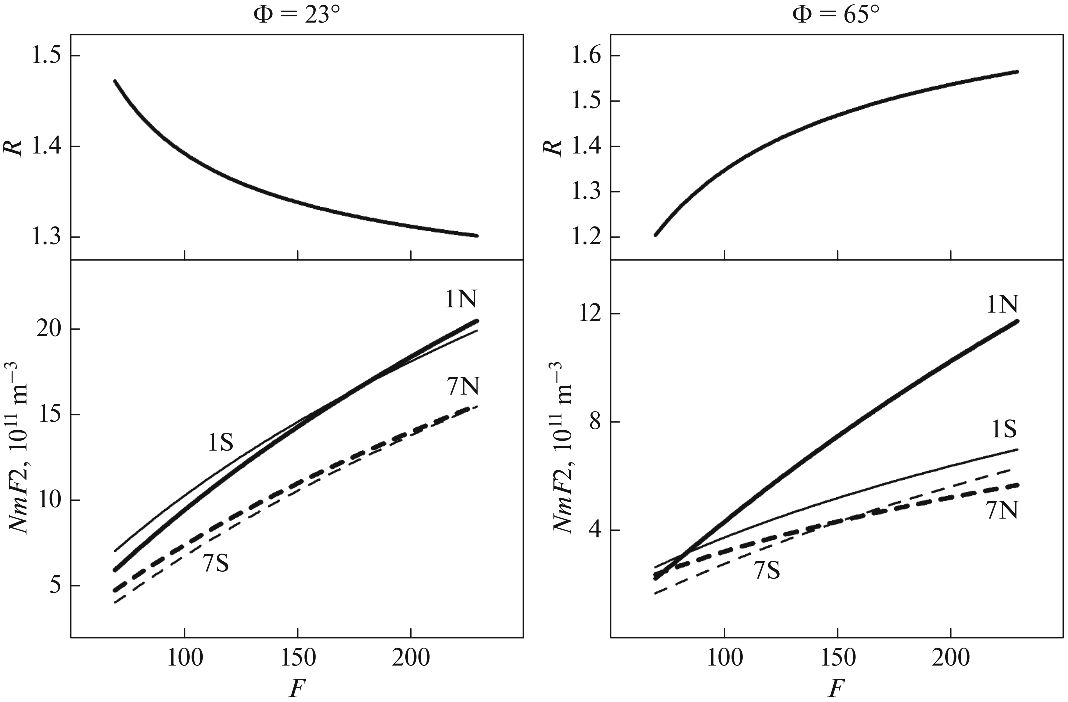

Fig. 2. Dependences of the local index of annual asymmetry R at noon and the components of this index—$NmF2$ densities (1—January, 7—July, N—Northern Hemisphere, S—Southern Hemisphere) on the solar activity index F at geomagnetic latitudes $\Phi = 23°$ and $\Phi = 65°$ according to the SDMF2 model.

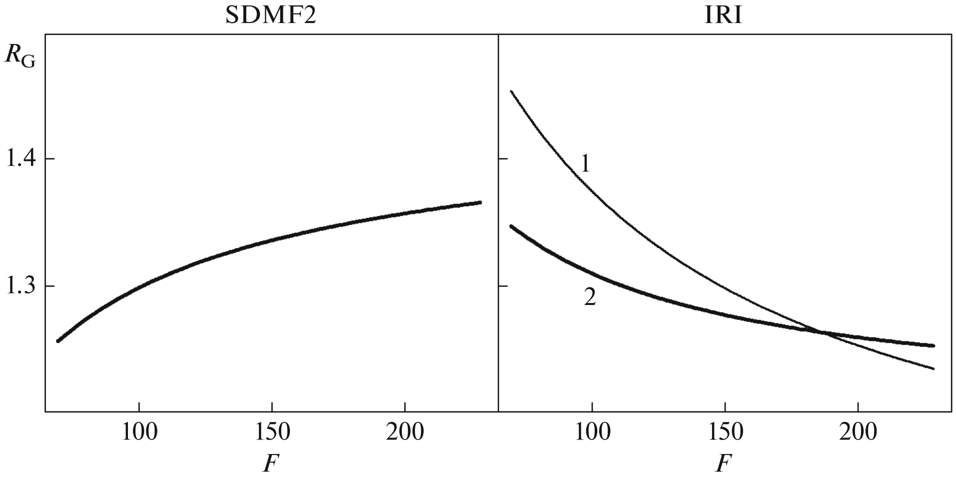

Fig. 3. Dependences of the global index of annual asymmetry R_G at noon on the solar-activity index F according to the SDMF2 model and the IRI model with the CCIR (1) and URSI (2) coefficients.

coefficients leads to a stronger dependence of R_G on solar activity ($R_G = 1.45$ at $F = 70$ and $R_G = 1.23$ at $F = 230$) than the URSI coefficients ($R_G = 1.35$ at $F = 70$ and $R_G = 1.25$ at $F = 230$). Despite the qualitative difference between the R_G indices in the SDMF2 model and the IRI model with URSI coefficients, their average values range from 1.25 to 1.37. Therefore, the average values of the R_G indices for these models do not contradict each other.

3. DISCUSSION

The existence of a maximum of the annual $NmF2$ anomaly at low latitudes (approximately in the region of the crests of the equatorial anomaly) at noon during low solar activity was previously noted based on the radio occultation data of the FORMOSAT-3/COSMIC satellites for specific measurement periods, e.g., the data centered on June 21 and December 21, 2006, within 90 days (Zeng et al., 2008) or the 2009 data (Sai Gowtam and Tulasi Ram, 2017a). The data in Fig. 1 show that, according to the SDMF2 model, this maximum at $\Phi = 22°–24°$ is a regularity of the annual-anomaly index *R* at noon at low solar activity. It was concluded, apparently for the first time, that the longitudinal average *NmF*2 density in January is higher than that in July at any level of solar activity at latitudes of $\Phi = 22°–24°$ in the Northern and Southern hemispheres.

The SDMF2 model gives a decrease in the *R* index with an increase in the solar-activity index *F* at low latitudes ($\Phi < 31°–33°$) and an increase in this index with increasing *F* at middle and high latitudes. The ionospheric stations are concentrated mainly at midlatitudes and, on average, they give an increase in the *R* index with an increase in *F* (Rishbeth and Müller-Wodarg, 2006; Brown et al., 2018), which is consistent with the conclusions from the SDMF2 model. In turn, the inclusion of a larger number of low-latitude stations in the analysis can lead to the opposite dependence of the average *R* index on solar activity. This is a possible reason for the decrease in the average *R* index with an increase in *F* according to the data of mid- and low-latitude ionospheric stations (Yonezawa, 1971).

The possibility of the existence of a maximum *R* at noon at latitudes of $\Phi = 64°–66°$ is noted, apparently, for the first time. This maximum exists at any level of solar activity; it is weakly expressed at low solar activity and becomes the main maximum at increased and high solar activity (Fig. 1). Therefore, the strongest increase in *R* with an increase in the solar-activity index *F* occurs at latitudes of $\Phi = 64°–66°$. This increase is mainly due to the relatively strong increase in *NmF*2 with an increase in *F* in January in the Northern Hemisphere as compared with other components of the *R* index (Fig. 2). According to the estimates, the relatively strong increase in *NmF*2 with increasing *F* in January in the Northern Hemisphere is a property of the ionosphere at middle and high latitudes, i.e., the entire region of the ionosphere, where an increase in *R* is observed with an increase in *F*. Based on an analysis of data from only one pair of the midlatitude stations Boulder and Hobart, it was found that the increase in the *R* (or *AI*) index with increasing solar activity for the *NmF*2 median is more significant than that for *NmF*2 at low geomagnetic activity (Deminov and Deminova, 2021), because the *NmF*2 median at middle latitudes during low solar activity usually corresponds to low ($ap(\tau) < 9$) geomagnetic activity, and the *NmF*2 median during high solar activity more often corresponds to moderate ($9 < ap(\tau) < 20$) geomagnetic activity, where $ap(\tau)$ is the weighted average *ap* index of geomagnetic activity with a characteristic time of $T = 14$ h or $\tau = \exp(-3/T) = 0.8$ (Deminov and Deminova, 2021). Moderate geomagnetic activity is usually associated with substorms as the most frequent cause of geomagnetic disturbances. One possible cause of the higher *R* index at midlatitudes during moderate geomagnetic activity as compared to that during low activity is the winter/summer asymmetry in the frequency of substorm occurrence (Tanskanen et al., 2011) and the annual asymmetry in the thermospheric density (Lei et al., 2013). The first factor is the higher frequency of substorms, which are associated with the generation of large-scale internal gravity waves (IGWs) in the auroral region, during the local winter. The second factor provides increased IGW amplitudes at midlatitudes in January as the most common cause of increased *NmF*2 values at midlatitudes at noon (Deminov and Deminova, 2021). This allows a qualitative understanding of some features of the dependence of *R* on solar activity at middle and, apparently, high latitudes. Nevertheless, the question of the possible causes of the maximum *R* at latitude $\Phi = 64°–66°$ remains open.

According to the SDMF2 model, the global annual asymmetry index R_G increases with an increase in the solar-activity index *F* (Fig. 3). The dependence of R_G on *F* is very weak, which is largely due to the opposite dependence of the local *R* index on *F* at low and higher latitudes. This means that it is advisable to study the mechanisms of the annual asymmetry of *NmF*2 based on an analysis of the latitudinal distribution of the local *R* index, rather than the global R_G index. The model of the *NmF*2 median with the CCIR coefficients (as part of the IRI model) is entirely based on the data from ionospheric stations, which occupy a small part of the Southern Hemisphere, even at midlatitudes (Jones and Gallet, 1962, 1965). Therefore, calculations of the R_G index from the IRI model with the CCIR coefficients lead to erroneous conclusions: the R_G index decreases with increasing *F*, and such a decrease is rather strong (Fig. 3). The model of the *NmF*2 median with the URSI coefficients was also constructed from ground-based data, but it additionally took into account the results of ionospheric modeling, including over the oceans (Rush et al., 1984, 1989). As a result, the R_G index according to the IRI model with the URSI coefficients does not differ much from this index according to the SDMF2 model, but a qualitative difference remains: the R_G index according to the IRI model with the URSI coefficients decreases with an increase in solar activity (Fig. 3). The SDMF2 model is largely based on *foF*2 satellite data, which provided almost complete coverage of all longitudes and latitudes for the selected geophysical conditions (Shubin, 2017). This is the main reason for the higher accuracy of the R_G index according to the SDMF2 model as compared to this index according to the IRI model with both CCIR and URSI coefficients.

4. CONCLUSIONS

The properties of the annual asymmetry in the electron density of the *F*2-layer maximum *NmF*2 at noon were analyzed based on the global empirical model of the *F*2-layer critical frequency median (SDMF2). As a characteristic of this asymmetry, we used the *R* index, i.e., the January/July ratio of the total (at a given and geomagnetically conjugate points) *NmF*2 density at noon averaged over all longitudes. The following conclusions were obtained.

(1) It was found that the *R* index decreases with increasing solar activity at low geomagnetic latitudes ($\Phi < 31°–33°$). At higher latitudes, the *R* index increases with an increase in solar activity.

(2) During low solar activity, the main *R* maximum is located at latitude $\Phi = 22°–24°$. At this latitude in the Northern and Southern hemispheres, the longitudinal average *NmF*2 density in January is higher than that in July for any solar-activity level.

(3) During high solar activity, this maximum *R* is located at $\Phi = 64°–66°$, where the strongest dependence of *R* on solar activity is observed. This is mainly due to the relatively strong increase in *NmF*2 with solar activity in January in the Northern Hemisphere.

(4) The global (average over all latitudes and longitudes) *R* index at noon increases with increasing solar activity in the range from 1.26 to 1.37. Additional analysis showed that the global *R* index decreases with increasing solar activity in the IRI model (with the URSI coefficients and even more so with the CCIR coefficients). This seems to be due to the limited amount of experimental data on the obtainment of the CCIR and URSI coefficients, especially over the oceans.

ACKNOWLEDGMENTS

The authors are grateful to the creators of the IRI website (irimodel.org) for the FORTRAN code to calculate the medians of the *F*2-layer critical frequency *foF*2 with the IRI model both with the CCIR and URSI coefficients.

FUNDING

The study was funded by the Russian Foundation for Basic Research, project no. 20-05-00050 (for low and middle latitudes), and the Russian Science Foundation, project no. 20-72-10023 (for high latitudes).

REFERENCES

Bilitza, D., IRI the international standard for the ionosphere, *Adv. Radio Sci.*, 2018, vol. 16, pp. 1–11.

Brown, S., Bilitza, D., and Yiğit, E., Improvements to predictions of the ionospheric annual anomaly by the international reference ionosphere model, *Ann. Geophys. Discuss.*, 2018. https://doi.org/10.5194/angeo-2018-97

Deminov, M.G. and Deminova, G.F., Dependence of the local index of annual asymmetry for *NmF*2 on solar activity, *Geomagn. Aeron. (Engl. Transl.)*, 2021, vol. 61, no. 2, pp. 227–233.

Gulyaeva, T.L., Arikan, F., Hernandez-Pajares, M., and Veselovsky, I.S., North–south components of the annual asymmetry in the ionosphere, *Radio Sci.*, 2014, vol. 49, pp. 485–496.

Jones, W.B. and Gallet, R.M., The representation of diurnal and geographic variations of ionospheric data by numerical methods (Pt. 1), *Telecomm. J.*, 1962, vol. 29, pp. 129–149.

Jones, W.B. and Gallet, R.M., The representation of diurnal and geographic variations of ionospheric data by numerical methods (Pt. 2), *Telecomm. J.*, 1965, vol. 32, pp. 18–28.

Koochak, Z. and Fraser-Smith, A.C., An update on the centered and eccentric geomagnetic dipoles and their poles for the years 1980–2015, *Earth Space Sci.*, 2017, vol. 4, no. 10, pp. 626–636.

Lei, J., Dou, X., Burns, A., Wang, W., Luan, X., Zeng, Z., and Xu, J., Annual asymmetry in thermospheric density: Observations and simulations, *J. Geophys. Res.: Space*, 2013, vol. 118, pp. 2503–2510.

Mendillo, M., Huang, C.L., Pi, X., Rishbeth, H., and Meier, R., The global ionospheric asymmetry in total electron content, *J. Atmos. Sol.-Terr. Phys.*, 2005, no. 15, pp. 1377–1387.

Mikhailov, A.V. and Perrone, L., The annual asymmetry in the F2 layer during deep solar minimum (2008–2009): December anomaly, *J. Geophys. Res.: Space*, 2015, vol. 120, no. 2, pp. 1341–1354.

Rishbeth, H. and Müller-Wodarg, I.C.F., Why is there more ionosphere in January than in July? The annual asymmetry in the F2-layer, *Ann. Geophys.*, 2006, vol. 24, no. 12, pp. 3293–3311.

Rush, C.M., PoKempner, M., Anderson, D.N., Perry, J., Stewart, F.G., and Reasoner, R., Maps of foF2 derived from observations and theoretical data, *Radio Sci.*, 1984, vol. 19, pp. 1083–1097.

Rush, C., Fox, M., Bilitza, D., Davies, K., McNamara, L., Stewart, F., and PoKempner, M., Ionospheric mapping—an update of foF2 coefficients, *Telecomm. J.*, 1989, vol. 56, pp. 179–182.

Sai Gowtam, V. and Tulasi Ram, S., Ionospheric annual anomaly—new insights to the physical mechanisms, *J. Geophys. Res.: Space*, 2017a, vol. 122, pp. 8816–8830.

Sai Gowtam, V. and Tulasi Ram, S., Ionospheric winter anomaly and annual anomaly observed from Formosat-3/COSMIC radio occultation observations during the ascending phase of solar cycle 24, *Adv. Space Res.*, 2017b, vol. 60, pp. 1585–1593.

Shubin, V.N., Global empirical model of critical frequency of the ionospheric *F*2-layer for quiet geomagnetic conditions, *Geomagn. Aeron. (Engl. Transl.)*, vol. 57, no. 4, pp. 414–425.

Tanskanen, E.I., Pulkkinen, T.I., Viljanen, A., et al., From space weather toward space climate time scales: substorm analysis from 1993 to 2008, *J. Geophys. Res.*, 2011, vol. 116, A00I34. https://doi.org/10.1029/2010JA015788

Yonezawa, T., The solar-activity and latitudinal characteristics of the seasonal, non-seasonal and semi-annual variations in the peak electron densities of the F2-layer at noon and at midnight in middle and low latitudes, *J. Atmos. Terr. Phys.*, 1971, vol. 33, pp. 887–907.

Zeng, Z., Burns, A., Wang, W., Lei, J., Solomon, S., Syndergaard, S., Qian, L., and Kuo, Y.-H., Ionospheric annual asymmetry observed by the COSMIC radio occultation measurements and simulated by the TIEGCM, *J. Geophys. Res.*, 2008, vol. 113, A07305. https://doi.org/10.1029/2007JA012897

Zhao, B., Wan, W., Liu, L., Mao, T., Ren, Z., Wang, M., and Christensen, A.B., Features of annual and semiannual variations derived from the global ionospheric maps of total electron content, *Ann. Geophys.*, 2007, vol. 25, no. 12, pp. 2513–2527.

Translated by M. Chubarova