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Hale Magnetic Cycle on the Sun: Manifestations in Geophysical Characteristics and Possible Influence on the Earth's Climate

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Abstract

Oscillations with periods of ~22 years close to the Hale magnetic cycle on the Sun are observed in a large number of climatic characteristics, and amplitudes of these oscillations often exceed those of 11-yr ones. In this work, we study the manifestations of the solar Hale cycle in different geophysical characteristics, which can contribute to the formation of bidecadal oscillations in the Earth's climate. It was found that temporal variations of cosmic ray fluxes in the stratosphere, as well as geoeffective parameters of solar wind and geomagnetic activity characteristics differ significantly in even and odd solar cycles. The results obtained suggest that the solar Hale cycle can contribute to bidecadal variations in fluxes of energetic charged particles (cosmic rays and auroral electrons) affecting the ionization rate in the atmosphere of high latitudes. In turn, changes in the ionization rate affect the chemical composition and temperature regime of the high-latitudinal atmosphere, which can lead to changes in atmospheric circulation and climate characteristics.

Keywords: Hale cycle; cosmic rays; solar wind; Earth's climate.

1. Introduction

A roughly 22-yr Hale cycle on the Sun, which consists of two consecutive 11-yr cycles, is known to manifest in the magnetic field polarity (e.g., [Hathaway, 2015]). When a new 11-yr cycle begins, the polarity distribution in sunspot groups reverses. Near the sunspot maximum, a reversal of the general magnetic field of the Sun takes place. According to the Gnevyshev-Ohl rule, there is a rather close connection between sunspot number totals per cycle for pairs of "even-succeeding odd" cycles, with the correlation coefficient exceeding 0.9, whereas for pairs of "odd-succeeding even" cycles, the correlation is noticeably weaker (~0.5) (e.g. [Nagovitsyn et al, 2009]). So, the Hale cycle is believed to start from an even 11-yr cycle.

At the same time, oscillations with a period of ~22 years close to the Hale cycle are observed in a large number of climatic parameters: occurrences of droughts in the USA [Cook et al., 1997], occurrences of hurricanes over the oceans [Mendoza and Pazos, 2009], regional temperatures in different seasons ([Pudovkin and Lubchich, 1990], Ogurtsov et al., 2020]). It is noted that a bidecadal variation in climatic characteristics is very often stronger than a decadal one [Raspopov et al., 2004]. So, a question arises whether the solar Hale cycle can influence the Earth's climate and what solar agents may be responsible for this influence. In this work, we consider manifestations of the Hale cycle in geophysical characteristics which could be a link between processes on the Sun and in the Earth's atmosphere.

2. Bidecadal variations of galactic cosmic ray influx in the atmosphere

Currently galactic cosmic rays (GCRs) are considered as an important link between solar activity and the lower atmosphere state due to their capability to penetrate deeply into the atmosphere and pronounced variability on a wide range of time scales. The bidecadal variation in GCR fluxes is manifested as an alternation of dome-shaped and peaked maxima at sunspot minima depending on the polarity of the general magnetic field on the Sun. GCR maxima are dome-shaped under positive polarity $A > 0$ (when magnetic field lines come out from the north pole and enter the south one) and peaked under negative polarity *A < 0*. This results in a clear ~22-yr oscillation in GCR fluxes, which can be seen in their spectra (Figure 1a) constructed on the base of the data of balloon measurements in the stratosphere of middle and high latitudes for 1957-2021 [Stozhkov et al., 2009]. Figures 1b and 1c present mean changes of cosmic ray fluxes in 3 even (20^{th} to 24^{th}, red line) and 3 odd (19^{th} to 23^{rd}, blue line) cycles obtained by the superposed epoch analysis (SPEA), using the same balloon measurement data. The year of sunspot maximum is taken as a zero year. One can see a noticeable difference between cosmic ray fluxes at the descending phase of even and odd cycles. The input of GCRs in the atmosphere in even cycles noticeably exceeds that in odd cycles, with the difference reaching its maximum (~0.3-0.5 $cm^{-2}\cdot s^{-1}$) in the 3^{rd}-4^{th} years after the solar maximum. This allows suggesting that a roughly 22-yr variation in GCR fluxes can be one of possible factors of climate variations on the bidecadal time scale.

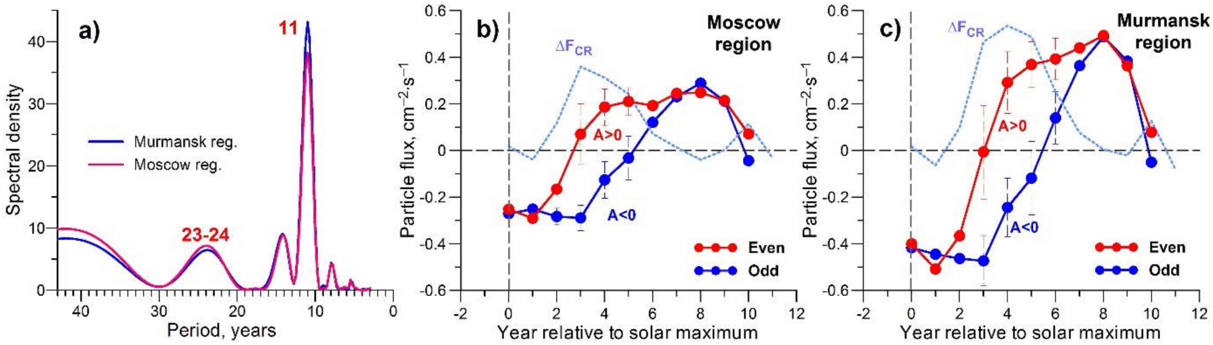

Figure 1. *a) Sampling estimates of the normalized spectral density of mean yearly fluxes of cosmic rays in the stratosphere of high latitudes (Murmansk region) and middle latitudes (Moscow region); b) mean (SPEA) changes of cosmic ray fluxes (detrended) in 3 even and 3 odd cycles (Moscow region); c) the same for Murmansk region. Dotted lines show the difference between mean yearly cosmic ray fluxes in even and odd cycles. Vertical bars show two standard errors of the mean.*

3. Bidecadal variations in geomagnetic activity and solar wind characteristics

Figure 2 (a, b) presents mean (SPEA) changes of yearly occurrences of magnetic storms with sudden (SC) and gradual (GC) commencement in 6 even (12^{th} to 22^{th}) and 6 odd (13^{th} to 23^{rd}) solar cycles, the data being taken from the stations IZMIRAN (http://www.izmiran.ru/magnetism/magobs/MagneticStormCatalog.html) and Slutsk/Pavlovsk [Kanonidi, 2012]. These kinds of storms are associated with different solar sources. Magnetic storms with sudden commencement are usually produced by coronal mass ejections and their occurrences peak at sunspot maxima. Magnetic storms with gradual commencement are usually associated with high-speed streams of solar wind from coronal holes, and their occurrences increase at the descending phase of a solar cycle. One can see that SC storms reveal a similar temporal behavior in even and odd cycles, with the maximal occurrence being observed in the year of sunspot maximum. However, in odd cycles their occurrences are somewhat higher, especially at the descending phase. As to GC magnetic storms, temporal variations in even and odd cycles differ noticeably. In odd cycles, GC storm occurrences grow rapidly and reach their maxima in the $+3^{rd}$ year after the solar maximum. In even cycles, they grow slowly and peak in the $+5^{th}$ year. The difference between SC and GC storm occurrences is most statistically significant at the descending phase of a cycle. The difference between even and odd cycles is also clearly seen in yearly values of geomagnetic *aa*-index (Figure 2c). Thus, geomagnetic activity, which reveals variations depending on the Hale cycle, may be considered as a possible factor of the formation of bidecadal variations in climatic characteristics, along with GCR variations.

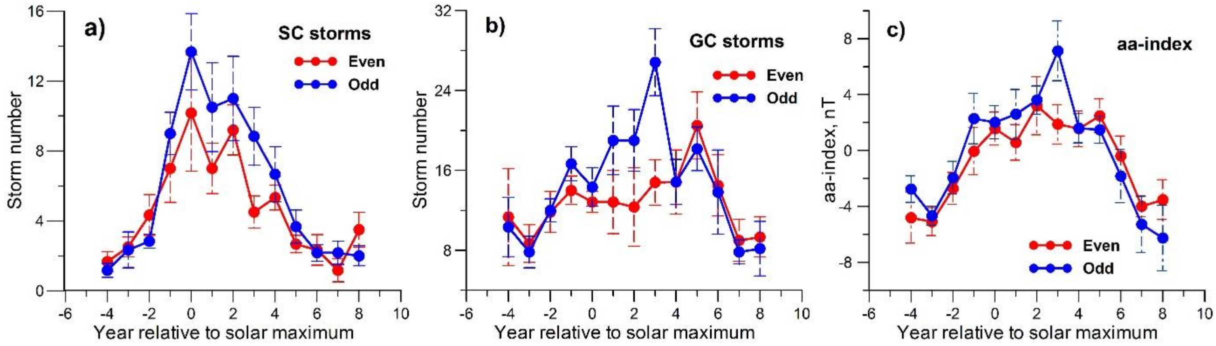

Figure 2. *a) Mean (SPEA) numbers of magnetic storms with sudden commencement (total yearly number of storms from moderate to very strong) in even (red line) and odd (blue line) solar cycles; b) the same for magnetic storms with gradual commencement; c) mean (SPEA) changes of yearly aa-indices (detrended) in even and odd cycles. Vertical bars show two standard errors of the mean.*

As geomagnetic activity is caused by the interaction of solar wind with the Earth's magnetosphere, let us consider variations in solar wind characteristics. The most important geoeffective parameter is the *Bz* component of interplanetary magnetic field (IMF) carried by solar wind, since the development of magnetic storms is closely related to the negative (southward) *Bz*. Along with the *Bz* component, the azimuthal IMF *By* component and solar wind speed are also of importance for geomagnetic disturbances. Geoefficiency of solar wind influence on the Earth's magnetosphere is determined by the "coupling function", which includes all the three indicated parameters [Troshichev, 2022].

Temporal variations of yearly values of the *Bz* component (in the GSM coordinate system) are presented in Figure 3a, the OMNI data (https://omniweb.gsfc.nasa.gov) being used. One can see a negative trend since the early 1960s, as well as a periodicity of ~20 years, which is revealed by a 5-yr smoothing (red line). The results of a spectral analysis (Figure 3b) show that the ~20-yr periodicity close to the Hale cycle is strongly dominating in the spectrum of the *Bz* component (the confidence level calculated relative to the "red noise" [Torrence and Compo, 1998] exceeds 0.98).

Figure 3c presents the results of the SPEA for yearly values of the *Bz* component (detrended), the year of sunspot maximum being taken as a zero year. The red line shows mean variations of the *Bz* component on the time interval from −10 to +12 years relative to the zero years, which are the maxima of even cycles, the blue line shows the same relative to the maxima of odd ones. One can see that temporal variations of yearly *Bz* values are opposite in even and odd cycles. The change of the *Bz* sign occurs near the sunspot maximum. Maximal absolute *Bz* values are observed in the +5th-7th years after the zero year, i.e., at sunspot minimum. At minima of even cycles (with positive polarity of the Sun's general magnetic field, $A > 0$), the *Bz* is, on average, negative (southward), whereas at minima of odd cycles ($A < 0$) it is positive (northward). Thus, the average direction of the *Bz* component at solar minima corresponds to the direction of the general magnetic field of the Sun. Indeed, the analysis of hourly values of the *Bz* component showed that at the minimum of an even cycle (1996) the occurrence of negative *Bz* values (from −1 to −7 nT) is higher by 13% compared with the minimum of an odd cycle (2008), whereas the occurrence of positive values (0–3 nT), on the contrary, is lower. The results obtained suggest that at minima of even cycles, when the southward *Bz* is more frequent, the geoefficiency of solar wind may be higher compared with odd cycles. Indeed, Figure 2b shows the maximal GC storm occurrence at minima of even cycles, which slightly exceeds the GC storm occurrence in odd ones.

A roughly 20-yr periodicity close to the Hale cycle is also well pronounced in temporal variations of the IMF *By* component (Figure 4a). According to the results of a spectral analysis in Figure 4b, this periodicity dominates in the spectrum of the *By* component along with the periodicity of 7.8 years, however, it is less significant than that in the *Bz* component. Mean (SPEA) changes in yearly *By* values (Figure 4c) are opposite in even and odd cycles similarly to *Bz* values, but the most significant differences are observed at the ascending phase and the maximum of a cycle: in odd cycles, the *By* component is, on average, positive (directed from dawn to dusk), whereas in even cycles, it is negative. At the descending phase, the differences between *By* values in even and odd cycles weaken and disappear completely at the sunspot minimum. Thus, temporal variations of geoeffective IMF components *Bz* and *By* reveal a roughly 20-yr periodicity closely related to the Hale cycle, which is manifested in the opposite character of yearly changes in even and odd cycles.

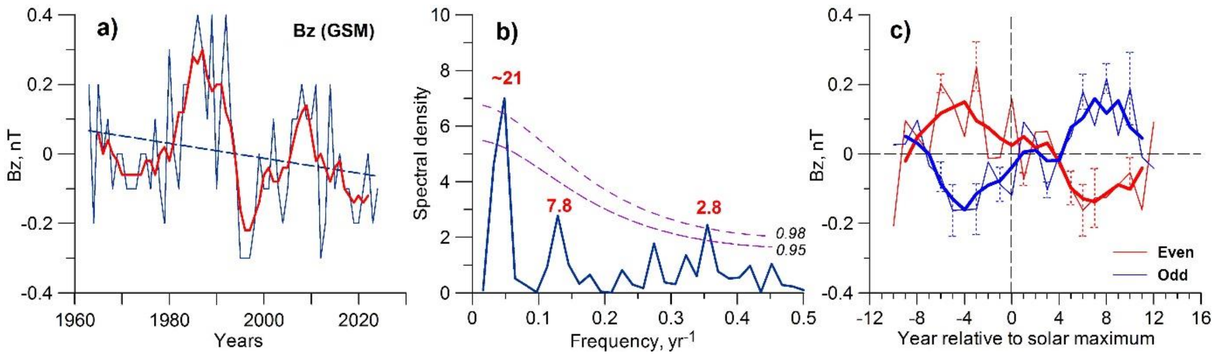

Figure 3. *a) Temporal variations of yearly values of the Bz component (GSM). Thick red line shows 5-yr running averages; b) Fourier spectrum of yearly Bz values (after the removal of the 2nd order polynomial trend). Dashed lines show the confidence levels calculated relative to the "red noise" with AR(1) = 0.3; c) mean (SPEA) changes of yearly Bz values (detrended). Red line – the zero years are maxima of even cycles; blue line – the zero years are maxima of odd cycles. Thick lines show 3-yr running averages. Vertical bars show two standard errors of the mean.*

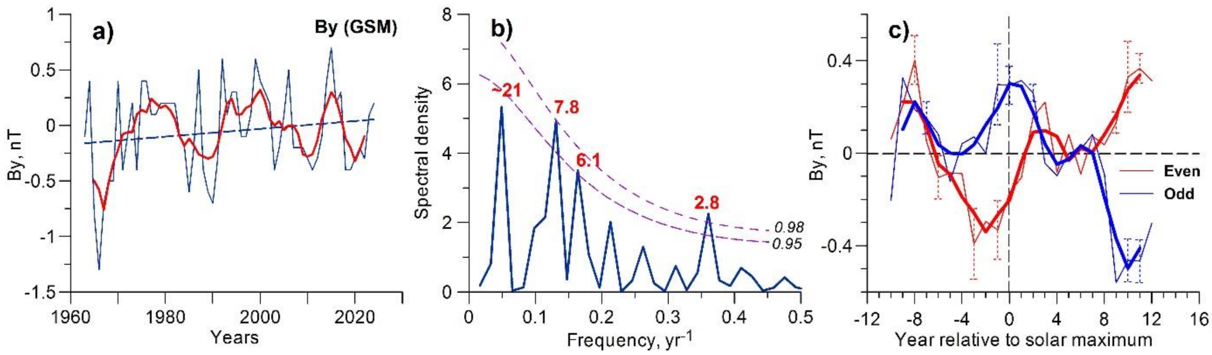

Figure 4. *The same as in Figure 3, but for the By component (GSM) and AR(1) = 0.36.*

The results of the study of variations in solar wind (SW) speed are presented in Figure 5. One can see that yearly values of SW speed do not reveal periodicities close to the Hale cycle. Both temporal variations (Figure 5a) and the Fourier spectrum of SW speed (Figure 5b) demonstrate a strongly dominating periodicity of ~10 years associated with the Schwabe cycle. The results of the superposed epoch analysis (Figure 5c) show that solar wind speed reaches maximal values at the descending phase of a solar cycle, which is due to the enhancement of coronal hole activity.

Although yearly values of SW speed did not demonstrate bidecadal variations, a noticeable difference was detected in the distribution of hourly values of SW speed at the descending phase (the 3rd year after sunspot maximum) of even and odd solar cycles. In even cycles, the occurrence of low values of SW speed (300-400 km/s) was found to be markedly higher compared with odd cycles. On the contrary, in odd cycles the occurrence of SW speed above 500 km/s is higher compared with even cycles. As SW speed is a geoeffective factor, along with the IMF *Bz* and *By* components, the enhancement of SW speed detected in hourly values at the descending phase of odd cycles seems to explain more intensive geomagnetic activity in the +3rd year after the sunspot maximum (Figure 2).

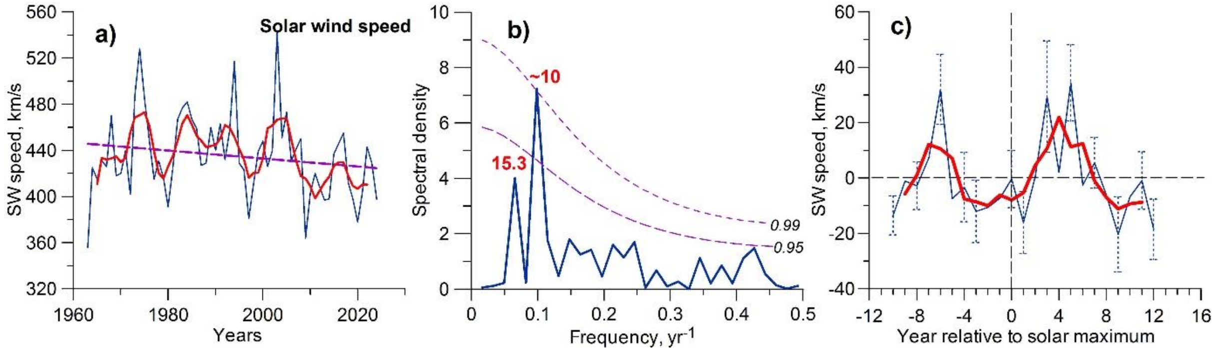

Figure 5. *a) Temporal variations of yearly values of SW speed. Thick red line shows 5-yr running averages; b) Fourier spectrum of yearly values of SW speed (after the removal of the 2nd order polynomial trend). Dashed lines show the confidence levels calculated relative to the "red noise" with AR(1) = 0.33; c) mean (SPEA) changes of yearly values of SW speed in a solar cycle. Thick red line shows 3-yr running averages. Vertical bars show two standard errors of the mean.*

4. Discussion and conclusion

As it was said above, oscillations with a period of ~22 years close to the magnetic Hale cycle are observed in a large number of climatic parameters. An important feature is that a bidecadal variation in climatic parameters is often significantly stronger than a decadal one [Raspopov et al., 2004; Pudovkin and Lubchich, 1989; Ogurtsov et al., 2020]. A pronounced ~22-yr variation was found to be a characteristic feature of storm track latitudes in different regions of the North Atlantic [Veretenenko and Dmitriev, 2024]. In even cycles, there is a noticeable shift of cyclone trajectories to the north (relative to a secular variation) from the +2nd to the 6th year after the sunspot maximum, i.e., at the descending phase and the minimum of a cycle. In odd cycles, cyclone trajectories slightly shift to the south. The effect is most pronounced in the Icelandic Low (Figure 6), which is a specific region of the North Atlantic. North Atlantic cyclones, which usually arise near the eastern coast of North America, arrive in this region, having reached the stage of their maximal development, and their occurrence is maximal. East of the Icelandic Low, cyclones usually start destroying (filling), their occurrence decreases and a roughly 22-yr variation in their trajectories weaken rapidly.

Thus, we can note that the most significant changes in latitudes of cyclone trajectories are observed at the descending phase and the minimum of a solar cycle. As was shown above, at this stage we also observe the most pronounced differences in galactic cosmic ray fluxes and geomagnetic activity in even and odd cycles. This allows suggesting that these factors may contribute to the formation of bidecadal variations in cyclone trajectories, which, in turn, result in bidecadal variations of different characteristics of regional climate at middle and high latitudes (temperature, pressure, precipitation etc.). Indeed, extratropical cyclones in the North Atlantic usually travel from the eastern coast of North America to the Barents Sea, so their paths lie in the region of low geomagnetic cutoff rigidity, which is accessible for cosmic ray particles in a wide energy range. On the other hand, paths of North Atlantic cyclones coincide rather well with the position of the auroral zone, which allows possible influence of auroral electron precipitations during geomagnetic disturbances.

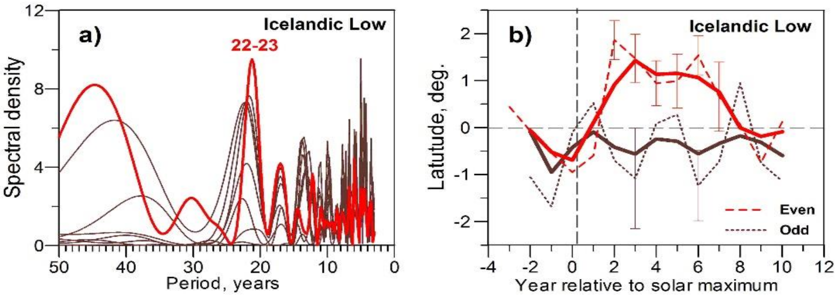

Figure 6. *a) Sampling estimates of the normalized spectral density of average storm track latitudes in the cold months (October-March) in the Icelandic Low for the initial time series (thick red line) and its high frequency components with "cut-off" parameter $T_{cut\text{-}off}$ =7, 11, 17, 23, 29, 37 and 43 years (thin brown lines); b) mean (SPEA) variations of storm track latitudes in 7 even (red dashed line) and 6 odd (brown dotted line) solar cycles. Thick lines show 3-yr running averages. The vertical bars show two standard errors of the mean. According to [Veretenenko and Dmitriev, 2024].*

A possible physical mechanism may involve variations in ionization rate in the high-latitudinal atmosphere associated with variations in galactic cosmic rays and auroral electrons. Increases of ionization rate contribute to changes in the chemical composition (ozone depletion), which, in turn, influence the temperature regime of the middle atmosphere and the intensity of the stratospheric polar vortex affecting cyclone trajectories [Veretenenko and Dmitriev, 2024]. Thus, the results of this study allow suggesting a possible contribution of the solar Hale cycle, which affects fluxes of energetic charged particles (cosmic rays and auroral electrons), to the formation of bidecadal variations in climatic characteristics.

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