Conference materials
UDC 551.590.2
DOI: https://doi.org/10.18721/JPM.161.269

Long-term effects of solar activity on cyclone tracks in the North Atlantic

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Abstract. Long-term changes of extratropical cyclone trajectories in the North Atlantic in cold months (October—March) were analyzed, with the data of Mean Sea Level Pressure archives from Climatic Research Unit, UK (1873—2000) and NCEP/DOE AMIP-II Reanalysis (1979—2021) being used. It was revealed that variations of latitudes of storm tracks in the longitudinal range from 60°W to 10°W are characterized by pronounced periodicities of ~80—90 and ~22 years. This indicates their possible relation to the corresponding periodicities in solar/geomagnetic activity and galactic cosmic ray variations, the secular Gleissberg cycle and the magnetic Hale cycle, respectively. At the maximum of the secular cycle, trajectories of North Atlantic cyclones were found to shift a few degrees south, whereas at the minimum and the descending phase they shift to the north. As North Atlantic cyclones influence significantly weather and climate conditions over Europe, oscillations of their tracks associated with solar activity and related phenomena seem to be of great prognostic importance.

Keywords: solar activity, cosmic rays, extratropical cyclones

Citation: Veretenenko S.V., Dmitriev P.B., Dergachev V.A., Long-term effects of solar activity on cyclone tracks in the North Atlantic, St. Petersburg State Polytechnical University Journal. Physics and Mathematics. 16 (1.2) (2023) 454—460. DOI: https://doi.org/10.18721/JPM.161.269

Материалы конференции
УДК 551.590.2
DOI: https://doi.org/10.18721/JPM.161.269

Долговременные эффекты солнечной активности в вариациях траекторий циклонов в Северной Атлантике

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Аннотация. Проанализированы долговременные изменения траекторий циклонов в Северной Атлантике в холодные месяцы (октябрь—март) на основе карт среднемесячного приземного давления. Обнаружено, что вариации широты основных траекторий циклонов в области долгот от 60°W до 10°W характеризуются периодичностями ~80—90 и ~22 лет, что указывает на их возможную связь с вариациями солнечной/геомагнитной активности и интенсивности потока галактических космических лучей.

Ключевые слова: солнечная активность, космические лучи, внетропические циклоны

Ссылка при цитировании: Веретененко С.В., Дмитриев П.Б., Дергачев В.А. Долговременные эффекты солнечной активности в вариациях траекторий циклонов в Северной Атлантике // Научно-технические ведомости СПбГПУ. Физико-математические науки. 2023. Т. 16. № 1.2. С. 454—460. DOI: https://doi.org/10.18721/JPM.161.269

Introduction

It is well known that cyclonic activity (formation, evolution and movement of extratropical cyclones and anticyclones) is an important factor influencing weather and climate at middle latitudes. Extratropical cyclones from the North Atlantic are responsible for many hazardous weather events over Europe. So, studying influence of solar activity and related disturbances of near-Earth space on cyclone development and trajectories is of significant importance.

Effects of the Sun's activity on extratropical cyclone movement in the North Atlantic were studied in a number of works. Brown and John [1] showed that at sunspot maximum the average latitude of storm tracks in winter months was 2.5° further south than at sunspot minimum. Tinsley [2] revealed that variations of storm track latitudes in the solar cycle may reach ~6° under the west phase of quasibiennial oscillations of the atmosphere. Thus, the aim of this work is to study variations of extratropical cyclone trajectories in the North Atlantic on multidecadal and secular time scales and to compare them with variations of solar activity and related phenomena.

Temporal variations of storm track latitudes

In this study we used gridded data on mean monthly sea level pressure in the Northern Hemisphere from MSLP (Mean Sea Level Pressure) archives of Climatic Research Unit, UK (1873–2000) [3] and NCEP/DOE AMIP-II Reanalysis (1979–2021) [4]. It is known that North Atlantic cyclones usually arise near the eastern coasts of North America (e.g., [5]). Then they move, as a rule, in the north-eastern direction towards Greenland and Iceland and then towards the Barents Sea. The cyclone movement results in the formation of a region of decreased pressure (baric trough) on monthly maps. This region is extended from the eastern coasts of North America to the Arctic coasts of Eurasia. Fig. 1 demonstrates the distribution of mean monthly SLP in the North Atlantic for cold months when extratropical cyclone activity is most intensive. One can see the examples of positions of baric troughs formed by cyclone motion. The axis of the baric trough (the line of minimal pressure values) shows the main direction of extratropical cyclone movement (storm tracks). It is seen that latitudes of most frequent cyclone passages over a given longitude may vary noticeably.

To study variations of North Atlantic storm tracks, we determined latitudes of pressure minima for the longitudinal range from 60°W to 10°W on monthly maps of SLP. The found values were averaged over cold months (October-March), which is a period of intensive extratropical cyclogenesis. Temporal variations of the mean latitudes of storm tracks in the cold period are presented in Fig. 2 for different longitudes in the North Atlantic.

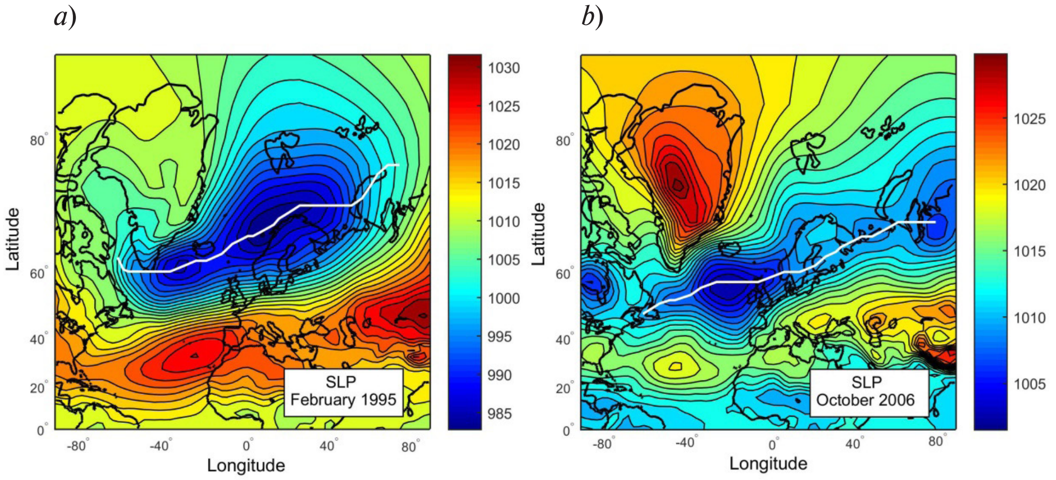

Fig. 1. Maps of mean monthly sea level pressure (in hPa) for February 1995 (*a*) and October 2006 (*b*). White lines show the main direction of cyclone movement (storm track)

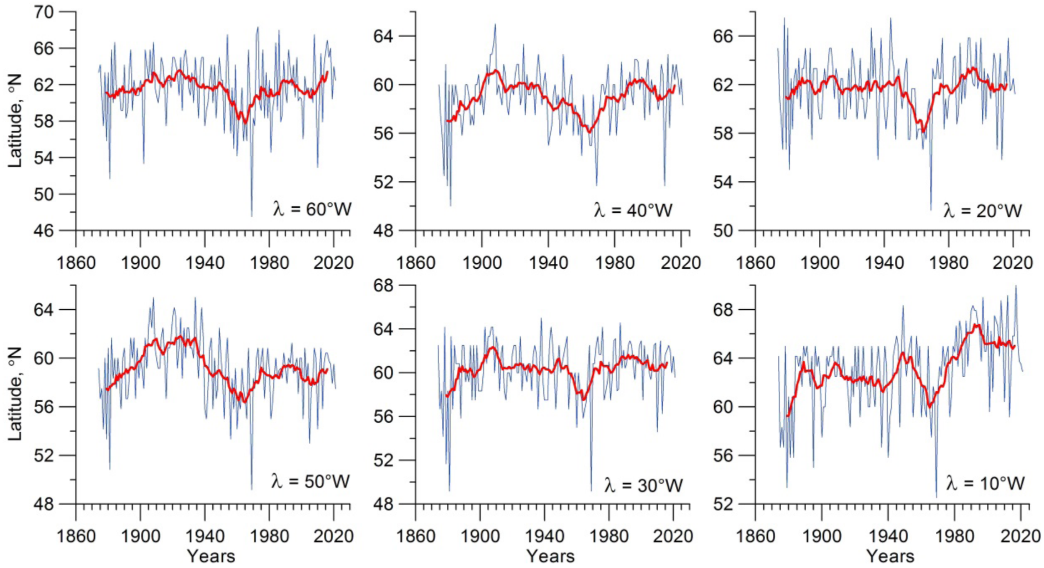

Fig. 2. Temporal variations of the mean latitudes of storm tracks in cold months (October-March) at different longitudes in the North Atlantic. Red lines show 11-yr running averages

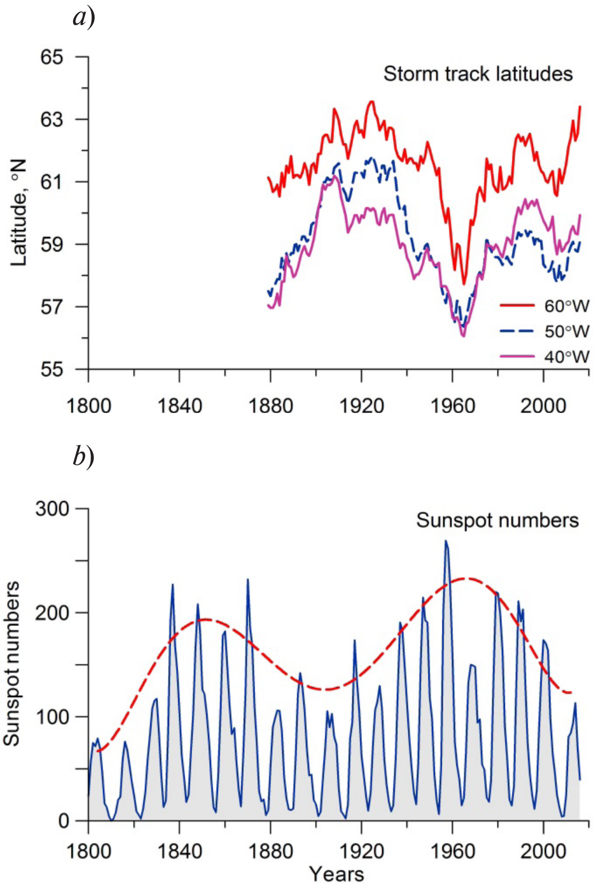

Fig. 3. Long-term changes of storm track latitudes in the western part of the North Atlantic (40–60°W) in the cold half of year (11-yr running averages) (*a*); annual mean sunspot numbers SSN. The dashed line shows the 6th order polynomial approximation of SSN values at maxima of the 11-yr cycle (*b*)

As we can see from Fig. 2, storm track latitudes reveal a pronounced variability both on interannual and longer time scales, including multidecadal and secular ones. Long-term variations of storm track latitudes are shown in Fig. 3, *a* for the western part of the North Atlantic, where extratropical cyclones usually form and reach their maximum development. These data are compared with long-term variations of sunspot numbers SSN [6] presented in Fig. 3,*b*. One can see a clear secular variation in the studied cyclone tracks. Maximal values of storm track latitudes were observed in ~1900–1930, which was a period of the secular decrease of solar activity (a minimum of the secular Gleissberg cycle). On the contrary, minimal values took place in ~1950–1960, i.e. at a maximum of the secular cycle. Since ~1960 the secular solar cycle has been at its descending branch and the studied storm track latitudes have been increasing again. Thus, we can suggest that storm tracks in the North Atlantic are influenced by long-term changes of solar activity. Trajectories of North Atlantic cyclones shift a few degrees south at the maximum of the Gleissberg cycle, whereas at the minimum and the descending phase of the cycle, they shift to the north. The peak-to-peak amplitude of secular variations in storm track latitudes is ~5°.

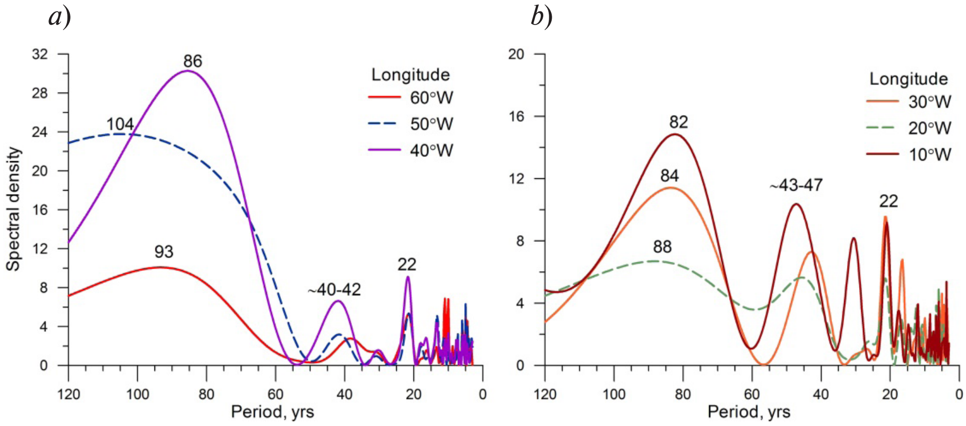

Fig. 4. Sampling estimates of the normalized spectral density of storm track latitudes (initial series) for the western (*a*) and eastern (*b*) parts of the North Atlantic

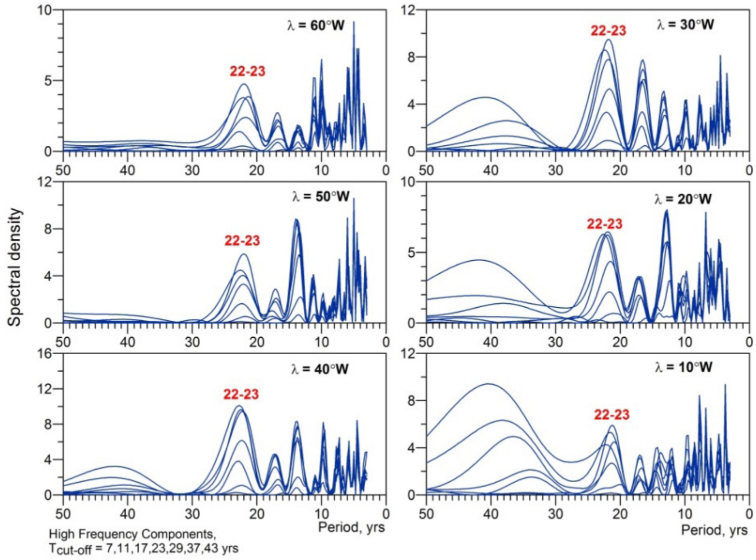

Fig. 5. Sampling estimates of the normalized spectral density of storm track latitudes (high-frequency components with different cut-off parameters $T_{\text{cut-off}}$=7, 11, 17, 23, 29, 37 and 43 years) for the western (left) and eastern (right) parts of the North Atlantic

Spectral characteristics of storm track latitudes

Let us consider spectral characteristics of the studied storm track latitudes. Spectral analysis was performed using the method of a sampling estimate of the normalized spectral density [7]. To confirm a reliability of the detected periodicities, an additional analysis of high-frequency components (HFC) of the studied time series was carried out, with HFC being calculated using the Blackman-Tukey high-frequency filter with different cut-off frequency parameters ($T_{\text{cut-off}}$) [8].

The results of spectral analysis are presented in Fig. 4 and 5 for the initial time series and high-frequency components, respectively. The data in Fig. 4 demonstrate pronounced secular variations of storm track latitudes both in the western part of the North Atlantic (40–60°W) and its eastern part (10–30°W). One can see that, along with secular variations, cyclone trajectories undergo bidecadal (~22 years) and multidecadal (~40–47 years) oscillations which may also be related to solar variability. The results obtained for HFC of storm track latitudes (Fig. 5) show that there are stable maxima of spectral density at periods ~22–23 years at all the longitudes under study. In the eastern part of the North Atlantic, mulidecadal variations with periods ~40–45 years seem to strengthen.

Discussion

As it was shown above, long-term changes of storm track latitudes in the North Atlantic reveal oscillations on bidecaldal, multidecadal and secular time scales, which may be linked to solar activity and related phenomena. On a secular time scale, cyclone paths were found to shift further south at the maximum of the Gleissberg cycle compared to the minimum/descending phase of this cycle, with the peak-to-peak amplitude of secular variations in storm tracks reaching ~5°. This effect seems to be similar to those detected in the 11-yr solar cycle [1–2]: the average latitude of winter storm tracks was further south at sunspot maxima than at sunspot minima. Thus, secular variations of solar activity may be responsible for the detected ~80-90-yr periodicities in storm tracks. Let us note that secular variations in storm tracks are the most pronounced in the western part of the North Atlantic (40–60°W), where processes of cyclogenesis (formation and deepening of cyclones) predominate. In the eastern part of the North Atlantic (10-30°W), where filling (destruction) of cyclones gets more frequent, secular variations in storm tracks seem to weaken, whereas multidecadal ones strengthen.

Another characteristic feature of storm track variations seems to be ~22-yr oscillations close to the magnetic (Hale) cycle on the Sun. These oscillations were detected at all the longitudes under study. However, they are the most pronounced at the longitudes 30–40°W, which is a region of the highest temperature contrasts in the Arctic frontal zone forming near the Greenland coasts [9]. In the cold half of year temperature gradients in the layer 1000-500 hPa (~0–5.5 km) in this region were found to undergo strong ~22-yr oscillations [9].

The 22-yr Hale cycle is manifested in magnetic polarity of both sunspots and polar fields on the Sun. It consists of two successive 11-yr cycles with opposite magnetic field polarity. Reversals of solar magnetic fields results in a roughly 22-yr variation in intensity of galactic cosmic rays (GCRs) arriving at Earth. Depending on the overall magnetic field of the Sun, at minima of solar cycles GCR maxima may be flat-topped or peaked [10]. The 22-yr cycle was also revealed in geomagnetic activity [11]. In Fig. 6 one can see the results of spectral analysis of geomagnetic

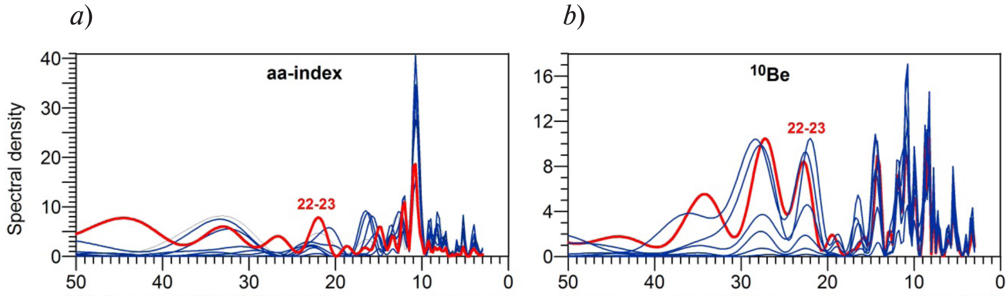

Fig. 6. Sampling estimate of the normalized spectral density of geomagnetic *aa*-index (*a*) and cosmogenic isotope ^{10}Be concentration in Greenland ice cores (*b*) for the initial series (red lines) and high-frequency components with different cut-off parameters (blue lines)

aa-index (detrended values) and concentration of cosmogenic isotope ^{10}Be produced in the atmosphere by cosmic rays. The data on *aa*-index and ^{10}Be were taken from [12] and [13], respectively. The data in Fig. 6 demonstrate stable maxima of spectral density at periods ~22–23 years which are related to the solar Hale cycle. Thus, we can suggest that GCR fluxes, as well as geomagnetic activity and related electron precipitations may be involved in the formation of a roughly 22-yr variation in storm tracks.

Spectral characteristics of storm track latitudes (Fig. 4) also demonstrate a noticeable variation of ~40–45 years, which seems to strengthen in the eastern part of the North Atlantic where cyclogenesis processes weaken. Similar variations are observed in solar characteristics, including the North-South asymmetry of sunspot activity (e.g., [14]) and variations of solar cycle length [15]. This allows suggesting that the indicated variation in cyclone trajectories may also be related to solar activity.

The obtained results suggest that possible agents of solar activity influence on cyclone motion may be geomagnetic activity and galactic cosmic ray variations. Extratropical cyclone trajectories are closely related to the mean position of the polar jet stream (a narrow band of strong winds in the upper troposphere) which is influenced by the stratospheric polar vortex (cyclonic circulation forming in the stratosphere in cold months). Under a strong vortex, the polar jet stream tends to strengthen and shift to the north, while under a weak vortex, it slows down and meanders. So, the detected shift of cyclone trajectories to the north with a secular decrease of solar activity may be due to the polar vortex intensification which, in turn, may be associated with an increase of stratospheric ionization produced by cosmic rays. Another factor influencing the state of the polar vortex, and then cyclone trajectories, seems to be geomagnetic activity and related electron precipitations which result in changes of chemical composition and temperature of the polar middle atmosphere. However, the mechanism of solar activity effects on extratropical cyclone movement needs further studies.

Conclusions

The study revealed noticeable variability of extratropical cyclone trajectories in the North Atlantic on the bidecadal, multidecadal and secular time scales, which may be related to solar activity. Cyclone paths were found to shift south at the maximum of the secular Gleissberg cycle and north at the minimum and the declining phase, with the peak-to-peak amplitude of secular variations of storm tracks reaching ~5°. A distinguished feature of North Atlantic cyclone trajectories is a pronounced ~22-yr variation close to the magnetic Hale cycle on the Sun, which is also observed in geomagnetic activity and galactic cosmic ray intensity. A possible mechanism of solar activity influence on extratropical cyclone movement may involve changes in intensity of the stratospheric polar vortex via ionization changes caused by auroral electrons and galactic cosmic rays.

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Received 28.10.2022. Approved after reviewing 08.11.2022. Accepted 09.11.2022.