Long-Term Variability of North Atlantic Storm Tracks: Possible Influence of Solar Activity and Cosmic Ray Variations

Svetlana Veretenenko, Pavel Dmitriev, and Valentin Dergachev

Abstract In this work we study long-term variability of the main directions of extratropical cyclone movement (storm tracks) in the North Atlantic basing on the data of MSLP (Mean Sea Level Pressure) archives from Climatic Research Unit, UK (1873–2000) and NCEP/DOE AMIP-II Reanalysis (1979–2021). It was revealed that, in the period of intensive cyclogenesis (October–March), the storm track latitudes in the longitudinal range from 60 to 10 ºW are characterized by noticeable variations with the periods of ~80–90, ~40–45 and ~22–23 years, which indicates their possible association with solar activity and related phenomena. Cyclone trajectories were found to be shifted to the north at the minimum of the secular Gleissberg cycle and to the south at its maximum, with the peak-to-peak amplitude reaching ~5º. On the bidecadal time scale, cyclone trajectories lie ~1−2º further north in even solar cycles. The detected changes of cyclone trajectories provide evidence for long-term variations in intensity of the stratospheric polar vortex, with possible factors of the vortex intensification being ionization changes associated with galactic cosmic ray variations and geomagnetic activity.

Keywords Solar activity · Cosmic rays · Extratropical cyclones

1 Introduction

Cyclonic activity (formation, evolution and movement of extratropical cyclones and anticyclones) is an important factor affecting weather and climate at middle latitudes. Extratropical cyclones coming from the North Atlantic are responsible for many hazardous weather events over Europe. So, investigation of possible influence of solar activity and related phenomena in the near-Earth space on the development and trajectories of extratropical cyclones is of great importance. Brown and John [1] revealed that the average latitude of storm tracks in the winter months was 2.5º further south at sunspot maximum compared with sunspot minimum. Tinsley [2]

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A. Kosterov et al. (eds.), *Problems of Geocosmos—2022*, Springer Proceedings in Earth and Environmental Sciences, https://doi.org/10.1007/978-3-031-40728-4_30

showed that this effect is most pronounced under the west phase of quasibiennial oscillations of the atmosphere, the difference of storm track latitudes in the solar cycle reaching ~6º. Thus, this work focuses on the study of possible effects of solar activity and related phenomena on extratropical cyclone trajectories in the North Atlantic on bidecadal, multidecadal and secular time scales.

2 Experimental Data and Their Analysis

2.1 The Analyzed Data

It is known that North Atlantic cyclones usually arise near the eastern coasts of North America and move, as a rule, in the north-eastern direction towards Greenland and Iceland and then towards the Barents Sea (e.g., [3]). The movement of cyclones results in the formation of a broad baric trough (a decreased pressure region) on monthly pressure charts, which usually stretches from the eastern coasts of North America to the Arctic coasts of Eurasia. The characteristic distribution of mean monthly values of sea level pressure (SLP) in the North Atlantic is shown in Fig. 1 for cold months when extratropical cyclone activity is most intensive. One can see the examples of baric troughs formed by extratropical cyclone motion. The axis of a baric trough (the line of pressure minima) shows the path which is generally followed by cyclones (storm track). It is seen that latitudes at which cyclones cross a given longitude most frequently may vary noticeably depending on a time period.

To study long-term variations of North Atlantic cyclone trajectories, we used the gridded mean monthly data of sea level pressure in the Northern Hemisphere taken from MSLP (Mean Sea Level Pressure) archives of Climatic Research Unit, UK (1873–2000) [4] and NCEP/DOE AMIP-II Reanalysis (1979–2021) [5]. Basing on these data, we constructed monthly charts of SLP and determined pressure minima

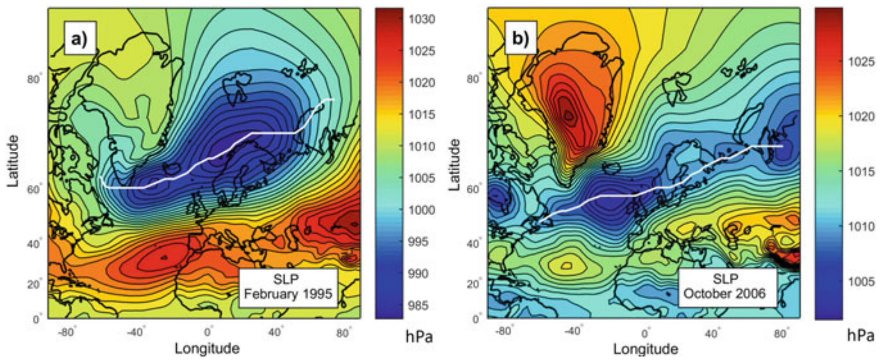

Fig. 1 Distribution of monthly sea level pressure (in hPa) in the North Atlantic for February 1995 **a** and October 2006 **b**. White lines indicate the main trajectories of cyclone movement (storm tracks)

and their latitudes at the longitudes from 60 to 10 °W. Then the latitudes were averaged over cold months (October–March), which is the period of the strongest cyclonic activity at extratropical latitudes. Rather rare cases when cyclone trajectories were directed to the south-east were excluded from the analysis. Temporal variations of the average latitudes of storm tracks in the cold period are shown in Fig. 2 for different longitudes λ in the North Atlantic.

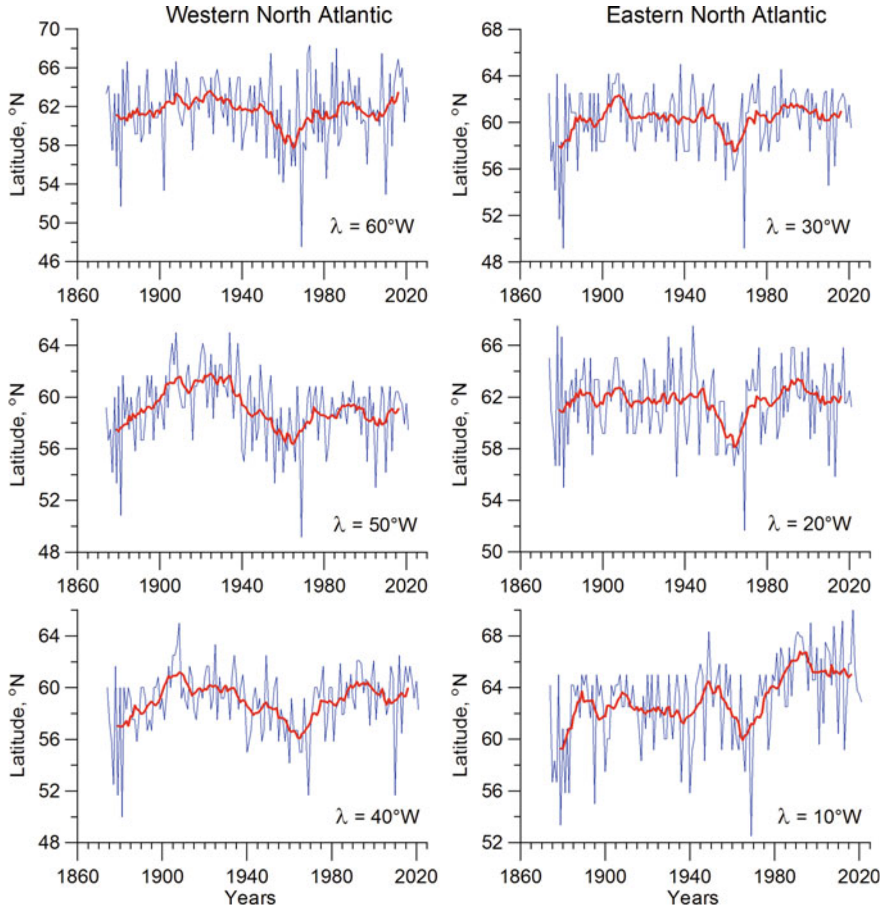

Fig. 2 Temporal variations of the average storm track latitudes in cold months (October–March) at different longitudes in the western (left) and eastern (right) part of the North Atlantic. Thick red lines show 11-yr running averages

2.2 Temporal Variations of Storm Track Latitudes on a Secular Time Scale

As Fig. 2 shows, cyclone trajectories are characterized by a noticeable variability on time scales from interannual to secular. Secular variations in storm track latitudes seem to be more pronounced in the western part of the North Atlantic ($\lambda = 40-60$ ºW) which is a region where cyclogenetic processes (cyclone formation and intense deepening) are predominating. In the eastern part of the North Atlantic, where cyclone destruction (filling) becomes more frequent, secular variations in storm track latitudes weaken, but multidecadal ones seem to intensify. This is confirmed by the results of spectral analysis presented in Fig. 3a and b (left panel), the spectral analysis being performed using the method of a sampling estimate of the normalized spectral density [6]. As we can see in Fig. 3, secular variations in cyclone trajectories strongly predominate in the western North Atlantic. Along with secular variations, storm track latitudes undergo bidecadal (~22 years) and multidecadal (~40–45 years) oscillations, which strengthen in the eastern part of the North Atlantic.

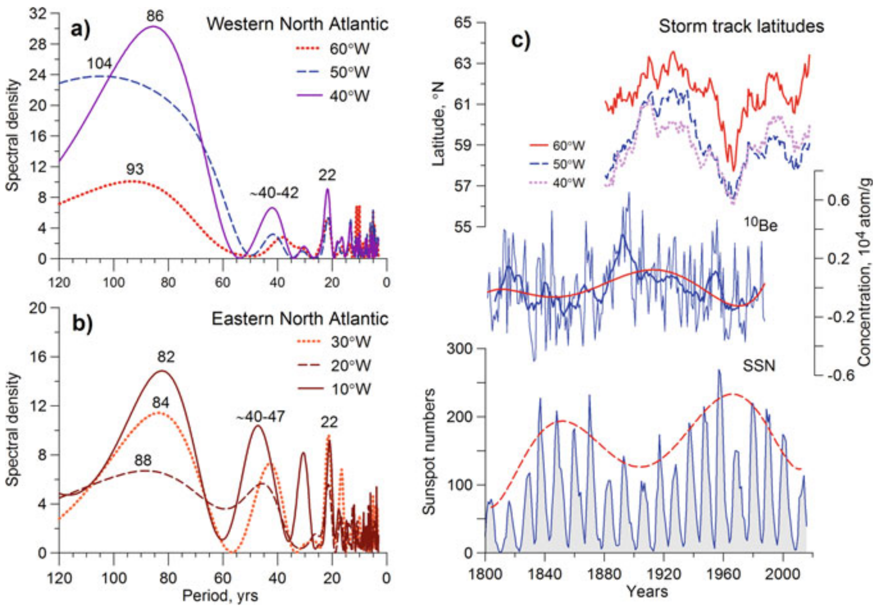

Fig. 3 Left: sampling estimates of the normalized spectral density of storm track latitudes for the western **a** and eastern **b** North Atlantic. Right: long-term variations of storm track latitudes (11-yr running averages) in the western North Atlantic (top panel), concentration of the cosmogenic isotope ^{10}Be in polar ice (after the linear trend removal) (middle panel) and sunspot numbers SSN (bottom panel). Thick blue and red lines show 11-yr running averages and the 5th order polynomial approximation of the ^{10}Be concentration, respectively. The dashed line shows the 6th order polynomial approximation of SSN values at maxima of the 11-yr cycles

To assess the amplitude of the secular variations in cyclone trajectories, the least-square fitting of storm track latitudes to a sine function was performed. In particular, for the longitude 40 ºW, this allowed getting the sine wave with the period 86.5 years and the amplitude 1.43º, with the 95% confidence bounds being 0.93º and 1.94º. Similar estimates of the amplitudes of secular variations ~1–1.5º were obtained for the longitudes 50 and 60 ºW. This implies that the difference between storm track latitudes at the minimum and maximum of the Gleissberg cycle amounts to about 3º. At the time, the temporal behavior of the 11-yr running averages in Fig. 3c show that the peak-to-peak amplitude of storm track latitude variations in the western North Atlantic may be larger and reach ~5º. The standard deviations for running averages were found to amount ~2º for the longitudes 40 and 50 ºW and ~3º for the longitude 60 ºW. Thus, the peak to peak amplitude for secular changes in latitudes of cyclone trajectories exceeds two standard deviations in the region near the south-eastern coasts of Greenland (40–50 ºW) and is somewhat lower than two standard deviations in the region near the eastern coasts of North America (60 ºW). The obtained estimates suggest a reality of secular variations detected in trajectories of North Atlantic cyclones.

In Fig. 3c 11-yr running averages of storm track latitudes in the western North Atlantic are compared with long-term variations in sunspot numbers SSN [7] and concentration of the cosmogenic isotope ^{10}Be in Greenland ice cores [8]. ^{10}Be is produced in the atmosphere by cosmic rays, so its concentration in polar ice may be used as a characteristic of cosmic ray intensity in the past. One can see that maximal values of storm track latitudes were observed in ~1900–1930, which was a minimum of the secular Gleissberg cycle of solar activity accompanied by an enhancement of galactic cosmic ray fluxes. Minimal values of storm track latitudes took place in ~1950–1960, i.e., at a maximum of the secular solar cycle when cosmic ray fluxes were lowered. Since ~1960, the secular cycle of solar activity has been at its descending phase and latitudes of North Atlantic storm tracks have been increasing again.

Thus, the above data allow suggesting that secular variations of storm track latitudes in the North Atlantic may be linked with corresponding variations in solar activity and galactic cosmic ray intensity. Cyclone trajectories were found to shift to the north at a minimum of the Gleissberg cycle and at its descending branch and to the south at its maximum. The peak-to-peak amplitude of the secular variations of storm track latitudes is ~3−5º. The detected changes of cyclone trajectories in the secular solar cycle seem to be similar to those detected in the 11-yr cycle [1, 2]: the average latitude of winter storm tracks was found to be further south at sunspot maxima than at sunspot minima.

2.3 Bidecadal and Multidecadal Variations of Storm Track Latitudes

As the data in Figs. 2 and 3 show, cyclone tracks undergo changes not only on a secular time scale, but also on bidecadal and multidecadal ones. To confirm a reliability of the found periodicities, an additional analysis of high-frequency components (HFC) of the studied time series of storm track latitudes was carried out. The analyzed HFC were calculated with the use of the Blackman-Tukey high-frequency filter with different cut-off frequencies (periods) $T_{cut\text{-}off}$ [9]. This method allows removing low-frequency components from the initial time series and checking up a stability of the detected periodicities.

The results of the spectral analysis are presented in Fig. 4. We can see stable maxima of HFC spectral density at periods of ~22–23 years at all the studied longitudes, which provides evidence for a reliability of bidecadal oscillations in the main trajectories of North Atlantic cyclones. We can also note that in the eastern North Atlantic, along with secular and bidecadal variations, cyclone tracks reveal multidecadal ones with periods of ~40–45 years, which seem to strengthen as cyclone trajectories lie further north-east.

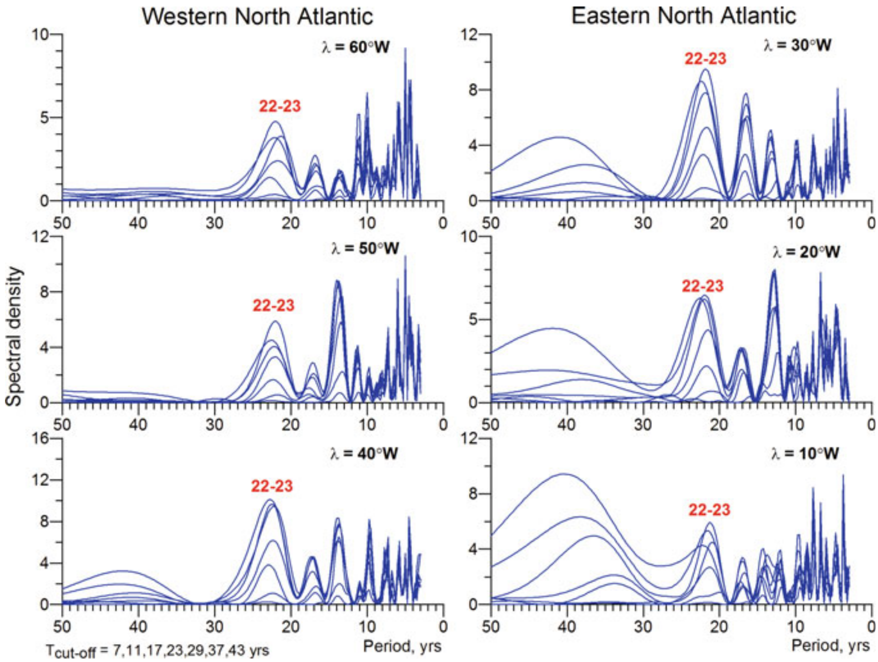

Fig. 4 Sampling estimates of the normalized spectral density of storm track latitudes (high-frequency components with different cut-off parameters $T_{cut\text{-}off} = 7, 11, 17, 23, 29, 37$ and 43 years) for the western (left) and eastern (right) parts of the North Atlantic

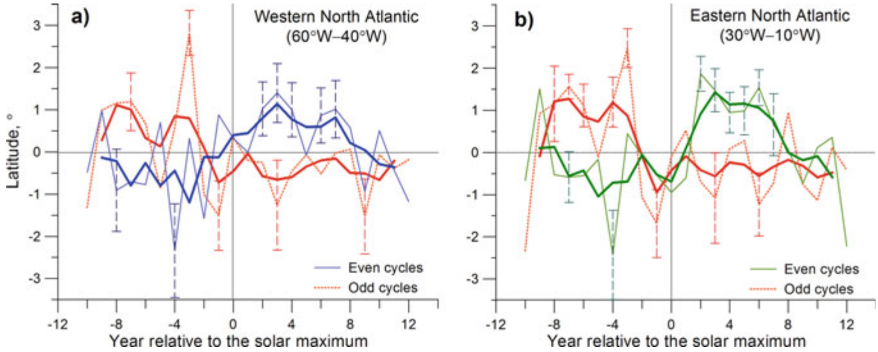

Fig. 5 Mean (SPEA) changes of storm track latitudes (after the subtraction of the 5th order polynomial) in the western **a** and eastern **b** North Atlantic in the course of even (12 to 24th) and odd (13th to 23rd) solar cycles. The year of the solar maximum is taken as a zero year. Thick lines show 3-yr running averages. Vertical dashed bars show two standard errors of the mean

Let us consider how the detected bidecadal oscillations of cyclone tracks are realized. In order to answer this question, a superposed epoch analysis (SPEA) of storm track latitude variations (obtained by subtracting a secular variation defined as the 5th order polynomial approximation) was carried out for even-numbered and odd-numbered solar cycles. Figure 5 demonstrates the results of superposed epoch analysis, the year of sunspot maxima being taken as a zero year. The presented variations were averaged over the western (40−60 ºW) and eastern (10−30 ºW) North Atlantic.

The data in Fig. 5 show that in both studied regions of the North Atlantic cyclone trajectories are noticeably (by ~1−2º) shifted northward in even cycles, whereas in odd ones they are slightly shifted to the south. The shift to the north in even cycles was found to be the most significant in the eastern North Atlantic. In this region the deviations of storm track latitudes from the secular variations exceed noticeably two standard error of the mean (years + 2, + 3 and + 6). The statistical significance of the shifts amounts to 0.95 (years + 2 and + 6) and 0.90 (year + 3) according to the modified Student’s t-test, which takes into account the serial correlation in the time series. In the western part of North Atlantic the northward shift of cyclone tracks seems to be less significant than in the eastern part. One can also see that the difference between storm track latitudes in even and odd solar cycles is maximal (up to ~2−3º) at the declining phase and a minimum of the solar cycle (from + 2 to + 6 years after the sunspot maximum).

3 Discussion of the Results

The results of this study provide evidence of variations in latitudes of North Atlantic cyclone trajectories on bidecadal, multidecadal and secular time scales which may be associated with solar activity and related phenomena. Let us consider possible reasons for these variations.

Trajectories of extratropical cyclones are known to be influenced by the position of the polar jet stream, which is a narrow band of strong winds in the middle and upper troposphere. In turn, the polar jet position depends on the strength of the stratospheric polar vortex (large-scale cyclonic circulation forming in the polar stratosphere in cold months). When the polar vortex is strong, the polar jet tends to strengthen and shift northward, whereas under a weak vortex the polar jet slows down, shifts southward and meanders. So, the detected shifts of cyclone tracks in the North Atlantic indicate long-term variations in the strength of the stratospheric polar vortex. The polar vortex seems to strengthen at a minimum of the secular Gleissberg cycle and to weaken at its maximum, resulting in the shift of storm tracks to the north and to south, respectively. On a bidecadal time scale, the vortex seems to be stronger, with cyclone tracks being shifted northward, in even solar cycles compared with odd ones.

The obtained results allow suggesting an important part of solar activity and related phenomena in long-term variations of intensity of the stratospheric polar vortex and corresponding changes of cyclone trajectories in the North Atlantic. Indeed, the detected periodicities in storm track latitudes of ~80–90, ~40–45 and ~22 years are similar to those observed in a number of solar characteristics. The secular Gleissberg cycle is manifested in the modulation of the amplitude of 11-yr solar cycles, which is clearly seen in Fig. 3c (bottom panel). Another important feature of solar activity is ~22-yr (Hale) cycle observed in magnetic polarity of both sunspots and polar fields on the Sun. This cycle consists of two successive 11-yr cycles with the opposite magnetic field polarity. Multidecadal variations with periods of ~45 years are observed in the North–South asymmetry of sunspot activity (e.g., [10]), as well as in variations of solar cycle length [11].

One of possible agents, which can contribute to the vortex intensification, is galactic cosmic rays, whose fluxes are strongly modulated by solar activity. GCR intensity undergoes variations on different time scales, including secular and bidecadal ones. According to the reconstruction [12], secular variations of cosmic ray fluxes with energies above 0.1 GeV may reach $\pm$ 15–20% relative to the trend values. On a bidecadal time scale, GCR fluxes are characterized by the alternation of flat and peaked maxima depending on the polarity of the Sun's overall magnetic field. When the polarity is positive, the onset of the peak cosmic ray flux occurs earlier compared with that under the negative polarity, so the peak is more dome-shaped [13]. The polarity reversal takes place near the sunspot maximum; the polarity becomes positive in even solar cycles and negative in odd ones. Figure 6a shows yearly values (detrended) of cosmic ray fluxes F_{CR} in the mid-latitudinal stratosphere [14] averaged over three even cycles (20 to 24th) and three odd (19th to 23rd) cycles. One can see a significant difference between GCR fluxes in even and odd cycles at the

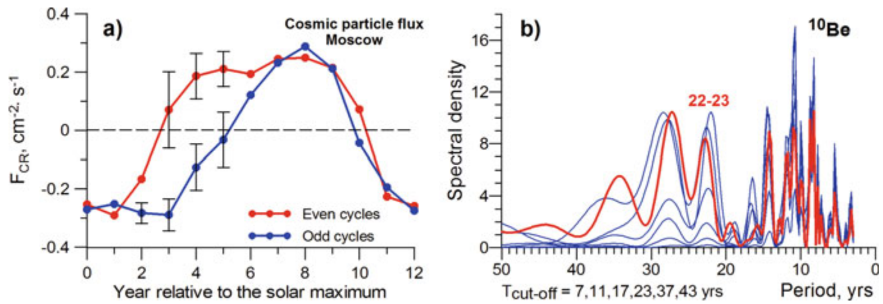

Fig. 6 **a** Mean (SPEA) variations of cosmic particle flux F_{CR} in the mid-latitudinal stratosphere (Moscow region, geomagnetic cutoff rigidity $R_c = 2.4$ GV) for even and odd solar cycles. The year of the solar maximum is taken as a zero year. Vertical bars show two standard errors of the mean. **b** Sampling estimate of the normalized spectral density of concentration of the cosmogenic isotope ^{10}Be in Greenland ice cores for the initial series (red line) and high-frequency components with different cut-off parameters (blue lines)

declining phase (from + 2 to + 5 years) of the cycle. So, a noticeable northward shift of cyclone tracks in even cycles (Fig. 5) is observed under the dome-shaped GCR maximum, when an influx of cosmic rays in the atmosphere is increased compared with odd cycles. This allows suggesting an important part of GCRs in the formation of the ~22-year periodicity in cyclone track latitudes. One can also note that both secular and bidecadal variations of GCR fluxes are manifested in the concentration of the cosmogenic isotope ^{10}Be in polar ice. This can be seen in Fig. 3c (middle panel), as well as in Fig. 6b which shows stable maxima of spectral density of the ^{10}Be concentration at the periods of ~22–23 years both for the initial series and their high-frequency components.

A possible mechanism of the polar vortex intensification may involve changes in ionization rate produced by cosmic rays in the middle atmosphere of high latitudes, which, in turn, contributes to changes of its chemical composition and temperature regime. Increases of ionization rate are known to enhance the production of odd nitrogen ($NO_x = N + NO + NO_2$) and odd hydrogen ($HO_x = H + OH + HO_2$) families (e.g., [15, 16]) participating in catalytic cycles of ozone destruction. So, an enhanced production of these minor compounds in the polar atmosphere leads to a decrease in the content of ozone, which is a radiatively active gas capable to influence radiative fluxes both in shortwave and longwave ranges. In the absence of sunlight, ozone acts as a greenhouse gas absorbing outgoing longwave radiation of the Earth and the atmosphere. So, in cold months ozone depletion associated with ionization increases will contribute to a cooling of the polar middle atmosphere. In turn, the cooling may enhance temperature gradients between polar and middle latitudes and, then, the strength of the polar vortex. Intensification of the vortex associated with ionization increases in the course of solar proton events of January 2005 [17] provides evidence for a possible influence of cosmic ray variations on the polar vortex state.

Another important mechanism of solar activity effects on extratropical cyclone development includes GCR influence on electric characteristics of the atmosphere and cloud microphysics. Ionization changes associated with GCR variations can affect not only the chemical composition of the polar middle atmosphere, but also the atmosphere conductivity, which, in turn, influences the density of vertical electric currents J_z flowing from the ionosphere to the surface. An enhancement of electric currents associated with GCR flux increases, as well as with ionospheric potential changes in polar caps contributes to the accumulation of space charge on cloud edges and intensification of microphysical processes that may result in increased cloud cover [18, 19]. Decreases of cloud cover detected in association with sharp decreases of GCR fluxes on a daily time scale (Forbush decreases) [20–22] seem to provide evidence for GCR influence on cloud formation.

In turn, clouds influence significantly both shortwave and longwave radiation fluxes in the atmosphere. During cold half of the year, when the income of shortwave solar radiation to high latitudes is decreased, clouds affect mainly outgoing longwave radiation (OLR) of the Earth and the atmosphere, producing a warming effect on the underlying atmospheric layer. One should note that outgoing radiation fluxes differ noticeably depending on the type of the Earth's surface. According to the climatological data [23], in cold months OLR fluxes amount to ~140–150 $W{\cdot}m^{-2}$ over the icy surface of Greenland and ~180–200 $W{\cdot}m^{-2}$ over the warmer ocean surface near the south-eastern coasts of Greenland, where North Atlantic cyclones usually travel (Fig. 1). So, effects of cloud changes associated with GCR changes may be stronger over the ocean, which, in turn, may influence temperature contrasts in this region and, then, the polar jet characteristics. The data in [24] showed that temperature contrasts in the Arctic frontal zone (the south-eastern coasts of Greenland) do really reveal ~22-yr variations, with the contrasts being higher in even cycles and lower in odd ones. It should also be stressed that the mechanism involving GCR effects on electric current density, cloud formation and the radiative-thermal balance of the high-latitudinal atmosphere seems to be more effective in autumn months, when the polar vortex is just starting to form and not yet well-developed.

Another agent of solar activity, which may contribute to the intensification of the polar vortex and the corresponding shift of cyclone trajectories northward, seems to be geomagnetic activity. As the data in Fig. 5 show, the most significant changes of storm track latitudes are observed at the declining phase of the solar cycle, i.e., when geomagnetic activity is intensified due to the increase in activity of coronal holes producing high-speed streams of solar wind. The 22-yr cycle in geomagnetic activity was found in [25]. The results of spectral analysis of geomagnetic *aa*-index (taken from [26]) in Fig. 7 do really show both bidecadal and multidecadal oscillations.

The mechanism of geomagnetic activity influence on the vortex state seems to involve changes in the chemical composition and temperature of the high-latitudinal atmosphere due to auroral electron precipitations accompanying geomagnetic disturbances. A possibility of this mechanism was proved by modeling studies [27]. Model studies [28] showed that a combined impact of different kinds of charged particles entering the polar atmosphere, including galactic and solar cosmic rays and auroral electrons, can affect the strength of the polar vortex.

Thus, long-term oscillations of storm track latitudes revealed in this study may be explained by variations in intensity of the stratospheric polar vortex on time scales

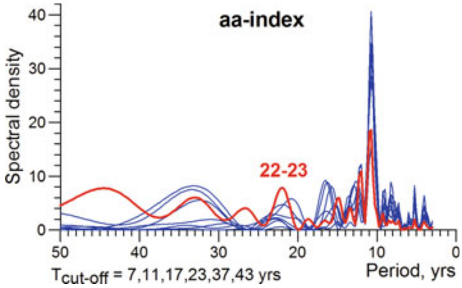

Fig. 7 Sampling estimate of the normalized spectral density of geomagnetic *aa*-index for the initial series (red line) and high-frequency components with different cut-off parameters (blue lines)

from bidecadal to secular. A possible reason of the vortex intensification seems to be ionization changes associated with galactic cosmic rays and auroral electrons and, in turn, influencing the chemical composition and temperature regime of the polar middle atmosphere. Another mechanism of the detected storm track variations may involve GCR effects on electric current density and related changes in cloud formation influencing the radiative-thermal balance of the high-latitudinal atmosphere. So, to clarify the nature of the detected long-term variability in trajectories of extratropical cyclones, further comprehensive studies are needed. In particular, long-term variations of total solar irradiance associated with solar activity, as well as processes in the ocean–atmosphere system should also be taken into account.

4 Conclusions

The results of this study showed:

1. Latitudes of the main trajectories of extratropical cyclones in the North Atlantic reveal oscillations on bidecadal, multidecadal and secular time scales, with periods being of ~22, ~40–45 and ~80–90 years, respectively, which may be associated with solar activity.
2. On a secular time scale, cyclone trajectories were found to be shifted further north at the minimum of the Gleissberg cycle and further south at the maximum, with the peak-to-peak amplitude of storm track latitude variations being ~3−5º. Since ~1960s, at the descending branch of the secular cycle, storm tracks have been shifting northward again.
3. On a bidecadal time scale, cyclone trajectories are noticeably shifted further north in even-numbered solar cycles, the greatest amplitude (~1.5−2º) being observed at the declining phase and the minimum of the cycles. The effect is the most pronounced in the eastern part of the North Atlantic.
4. The detected changes in storm track latitudes provide evidence for long-term variations in intensity of the stratospheric polar vortex, with possible factors of the vortex intensification being galactic cosmic rays and geomagnetic activity. The physical mechanism of the vortex intensification seems to involve changes in the

chemical composition and temperature regime of the polar middle atmosphere due to ionization changes produced by energetic particles. Another possible mechanism involves GCR influence on electric current density affecting cloud formation and the radiation-thermal balance in the high-latitudinal atmosphere.

Acknowledgements MSLP data were provided by Climatic Research Unit, UK, at https://crudata.uea.ac.uk/ and NOAA/OAR/ESLR PSL, Boulder, Colorado, USA, at https://psl.noaa.gov/. Cosmic ray fluxes in the stratosphere were provided by Lebedev Physical Institute, at https://sites.lebedev.ru/ru/sites/DNS_FIAN.html. We thank the referees for carefully reading the paper and helpful remarks.

References

1. Brown, G.M., John, J.I.: Solar cycle influences on tropospheric circulation. Journal of Atmospheric and Terrestrial Physics 41, 43–52 (1979).
2. Tinsley, B.A.: The solar cycle and the QBO influences on the latitude of storm tracks in the North Atlantic. Geophysical Research Letters 15(5), 409–412 (1988).
3. Vorobjev, V.I.: Synoptic meteorology. Hydrometeoizdat, Leningrad (1991).
4. Climatic Research Unit, https://crudata.uea.ac.uk/cru/data/pressure, last accessed 2004/08/08.
5. NOAA PSL, https://psl.noaa.gov/data/gridded/data.ncep.reanalysis2.surface.html, last accessed 2022/01/26.
6. Jenkins, G., Watts, D.: Spectral analysis and its application. Holden-Day, San Fransisko (1968).
7. WDC-SILSO, Royal Observatory of Belgium, http://www.sidc.be/silso/datafiles, last accessed 2018/05/16.
8. Beer, J., Blinov, A., Bonani, G. et al. Use of ^{10}Be in polar ice to trace the 11-year cycle of solar activity. Nature 347, 164–166 (1990).
9. Alavi, A.S., Jenkins, G.M.: An example of digital filtering. Applied Statistics 14, 70–74 (1965).
10. Obridko, V.N., Nagovitsyn, Yu.A.: Solar activity, cyclicity and prediction methods. BBM, St. Petersburg (2017).
11. Jelbring, H.: Analysis of sunspot cycle phase variations–based on D. Justin-Schove's proxy data. Journal of Coastal Research. Special Issue 17, 363−369 (1995).
12. Stohkov, Y.I., Okhlopkov, V.P, Svirzhevsky, N.S.: Cosmic ray fluxes in present and past times. Solar Physics 224, 323–333 (2004).
13. Thomas, S.R., Owens, M.J., Lockwood, M.: The 22-year Hale cycle in cosmic ray flux – evidence for direct heliospheric modulation. Solar Physics 289, 407–421 (2014).
14. Stozhkov, Y.I.; Svirzhevsky, N.S.; Bazilevskaya, G.A.; Kvashnin, A.N.; Makhmutov, V.S.; Svirzhevskaya, A.K.: Long-term (50 years) measurements of cosmic ray fluxes in the atmosphere. Adv. Space Res. 44, 1124–1137 (2009).
15. Rusch, D.W., Gerard, J.-C., Solomon, S., Crutzen, P.J., Reid, G.C.: The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere I. Odd nitrogen. Planetary Space Science 29, 767–774 (1981).
16. Solomon, S., Rusch, D.W., Gerard, J.-C., Reid, G.C., Crutzen, P.J.: The effect of particle precipitation events on the neutral and ion chemistry of the middle atmosphere: II. Odd hydrogen. Planetary Space Science 29, 885–893 (1981).
17. Veretenenko, S.: Effects of Solar Proton Events of January 2005 on the middle atmosphere dynamics in the Northern hemisphere. Advances in Space Research 68, 1814–1824 (2021).
18. Tinsley, B.A.: The global atmospheric electric circuit and its effects on cloud microphysics. Rep. Progr. Phys. 71, 066801 (2008).
19. Tinsley, B.A.: Uncertainties in evaluating global electric circuit interactions with atmospheric clouds and aerosols, and consequences for radiation and dynamics. J. Geophys. Res. 127, e2021JD035954 (2022).

20. Pudovkin, M.I.; Veretenenko, S.V.: Cloudiness decreases associated with Forbush-decreases of galactic cosmic rays. J. Atmos. Terr. Phys. 57, 1349–1355 (1995).
21. Svensmark, .J., Enghoff, M. B., Shaviv, N. J., Svensmark, H.: The response of clouds and aerosols to cosmic ray decreases. J. Geophys. Res. 121, 8152–8181 (2016).
22. Matsumoto, H., Svensmark, H., Enghoff, M.B.: Effects of Forbush decreases on clouds determined from PATMOS-x. J. Atmos. Sol.–Terr. Phys. 230, 105845 (2022).
23. NOAA PSL, https://www.psl.noaa.gov/data/gridded/data.olrcdr.interp.html, last accessed 2023/01/25.
24. Veretenenko, S.V, Dergachev, V.A., Dmitriyev, P.B.: Solar rhythms in the characteristics of the Arctic frontal zone in the North Atlantic. Adv. Space Res. 45, 391–397(2010).
25. Cliver, E.V., Boriakoff, V., Bounar, K.H.: The 22-year cycle of geomagnetic and solar wind activity. Journal of Geophysical Research 101(A12), 27091–27109 (1996).
26. World Data Center for Solar-Terrestrial Physics, Moscow, Russia, http://www.wdcb.ru/stp/geomag/geomagn_aa_Aa_ind.html, last accessed 2022/02/16.
27. Baumgaertner, A.J.G., Seppälä, A., Jöckel, P., Clilverd, M.A.: Geomagnetic activity related NOx enhancements and polar surface air temperature variability in a chemistry climate model: Modulation of the NAM index. Atmospheric Chemistry and Physics 11, 4521–4531 (2011).
28. Rozanov, E., Calisto, M., Egorova, T., Peter, T., Schmutz, W.: Influence of the precipitating energetic particles on atmospheric chemistry and climate. Surveys in Geophysics 33, 483–501 (2012).