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Comparative Analysis of Solar Activity Influences on Trajectories of Extratropical Cyclones in Different Regions of the North Atlantic

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Abstract

Influences of solar activity on the latitudinal position of the main trajectories (storm tracks) of extratropical cyclones were compared in different regions of the North Atlantic: 1) the western North Atlantic (60–40°W), which is a region of intensive cyclone formation and deepening; 2) the Icelandic Low region (30–10°W), where cyclones usually reach their maximum development and their occurrence is maximal; 3) the eastern North Atlantic (0–20°E), where processes of cyclone filling become dominating. It was found that secular oscillations (with periods ~80–90 years) of storm track latitudes, which may be associated with the solar Gleissberg cycle, strongly dominate in the western North Atlantic. These oscillations weaken in the Icelandic Low region and disappear to the east of Greenwich (0–20°E), where multidecadal oscillations (with periods ~60 years) were detected. On the bidecadal time scale, oscillations of storm track latitudes, with periods close to the Sun's magnetic Hale cycle, were found in all the studied regions of the North Atlantic. Storm tracks noticeably shift to the north in even solar cycles (according to the Zurich numbering) and slightly to the south in odd ones. The 22-year oscillations are most pronounced in the Icelandic Low region and weaken sharply east of Greenwich. The obtained results show that the region of the Icelandic Low seems to be most sensitive to solar activity influences.

Keywords: *solar activity; cyclone trajectories; Icelandic Low.*

Introduction

Extratropical cyclonic activity is known to be an important factor influencing weather and climate at middle latitudes. Deep cyclones coming from the North Atlantic cause many extreme weather events and natural disasters in Europe (hurricane winds, heavy rainfall, floods etc.) So, studying solar activity influences on the development and movement of extratropical cyclones is of significant practical importance, as it helps us to improve the quality of weather and climate forecasts.

In a number of studies, it was shown that cyclonic activity is influenced by solar activity related phenomena, such as solar flares [Schuurmans and Oort, 1969], solar and galactic cosmic ray variations [Veretenenko and Thejll, 2004; Artamonova and Veretenenko, 2011], sector boundaries of interplanetary magnetic field [Wilcox et al., 1974] etc. In the works [Brown and John, 1979; Tinsley, 1988], variations of cyclone trajectories in the 11-year solar cycle were studied. It was found that storm track latitudes in the eastern North Atlantic are lower at maxima of the solar cycle than at minima. A similar storm track variation was detected on a secular time scale in the North Atlantic west of the Greenwich meridian [Veretenenko et al., 2023]. The aim of this work is to study in more detail and compare the manifestations of solar activity influence on cyclone trajectories in three regions of the North Atlantic, including the area lying east of Greenwich.

Experimental data and their analysis

Formation of North Atlantic cyclones usually takes place near the eastern coast of North America, where in the cold half of the year high temperature contrasts and a favorable structure of the thermobaric field are observed. The subsequent movement of cyclones goes, as a rule, northeast through Iceland to the Barents Sea, which results in the formation of an extended low-pressure area (baric trough) on monthly maps of sea level pressure. The axis of the trough (the central line connecting pressure minima) indicates the direction of the predominant movement of cyclones (storm track). So, we determined latitudes of pressure minima at longitudes from 60ºW to 20ºE for the cold months (October-March), which is a period of intense extratropical cyclogenesis. The gridded monthly data from the MSLP (Mean Sea Level Pressure) archives of the Climatic Research Unit (https://crudata.uea.ac.uk/) for 1873–1978 and NCEP/DOE AMIP-II Reanalysis (https://psl.noaa.gov/) for 1979–2021 were used as the experimental base. The obtained latitudes of storm tracks were averaged over three regions: 1) the western North Atlantic (60–40°W), which is a region of intensive cyclone formation and deepening; 2) the Icelandic Low region (30–10°W), where cyclones usually reach their maximum development and their occurrence is maximal; 3) the eastern North Atlantic (0–20°E), where processes of cyclone filling become dominating.

Figure 1 presents the temporal variations of average latitudes of storm tracks in the cold half of the year in different regions of the North Atlantic, as well as their spectral characteristics obtained using the method of a sampling estimate of the normalized spectral density [Jenkins and Watts, 1968].

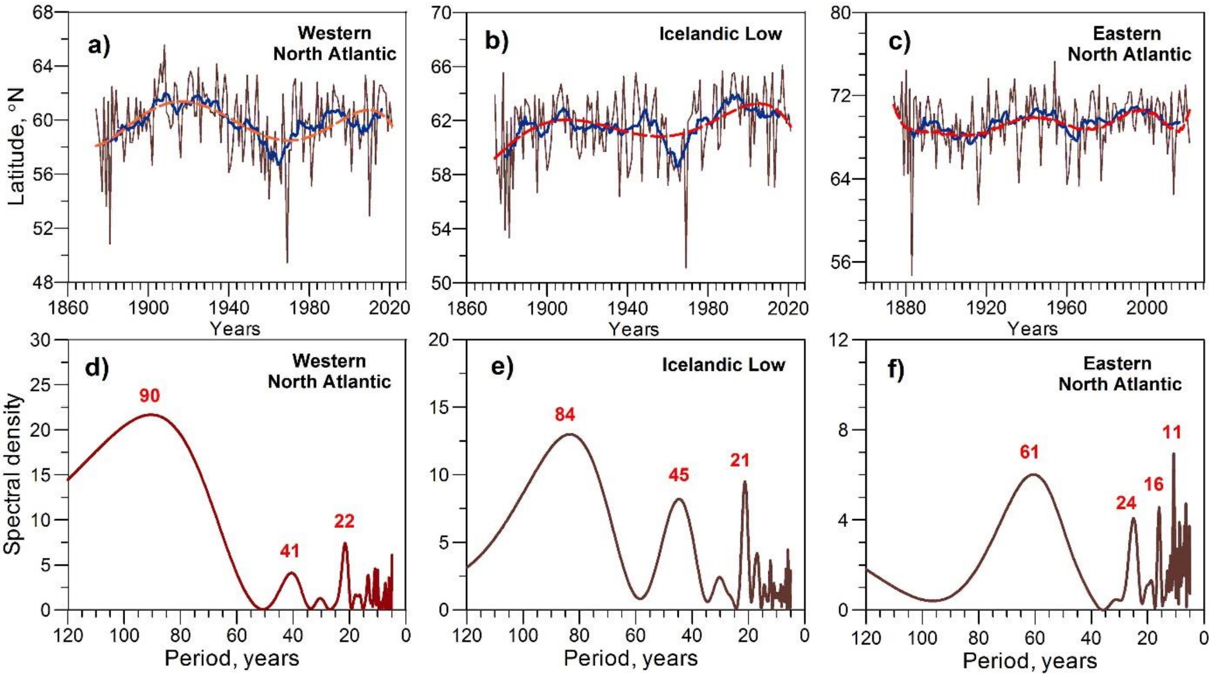

Figure 1. *Top: Temporal variations of average storm track latitudes in the cold months (October-March) in different regions of the North Atlantic. Thick blue lines and dashed red lines show 11-year running averages and the 5th order polynomial approximation, respectively. Bottom: Sampling estimates of the normalized spectral density of storm track latitudes in different regions of the North Atlantic.*

One can see that latitudes of storm tracks in the North Atlantic reveal secular (~80–90 years), multidecadal (~40–45 and ~60 years) and bidecadal (~21–24 years) oscillations which may be associated with solar activity. To assess the amplitudes of the detected oscillations, we carried out an approximation of the studied storm track latitudes by the polyharmonic model [Serebrennikov and Pervozvansky, 1965], which included the main quasi-periods. The initial signal $X(t)$ (storm track latitudes in a given region at time t) was assumed to consist of polyharmonic and noise components:

$$X(t) = A_0 + \sum_{k=1}^{\nu} R_k \cos\left(\frac{2\pi t}{T_k} - \varphi_k\right) + n(t),$$

where A_0 is a constant, R_k is the amplitude, ν and Tk (k =1, 2, 3, …) are the number and the value of quasi-periods, respectively, n(t) is a stationary random process ("white noise"). The polyharmonic model for each region included the periods indicated in Figure 1 (bottom panels). The results of the estimates are presented in Figure 2.

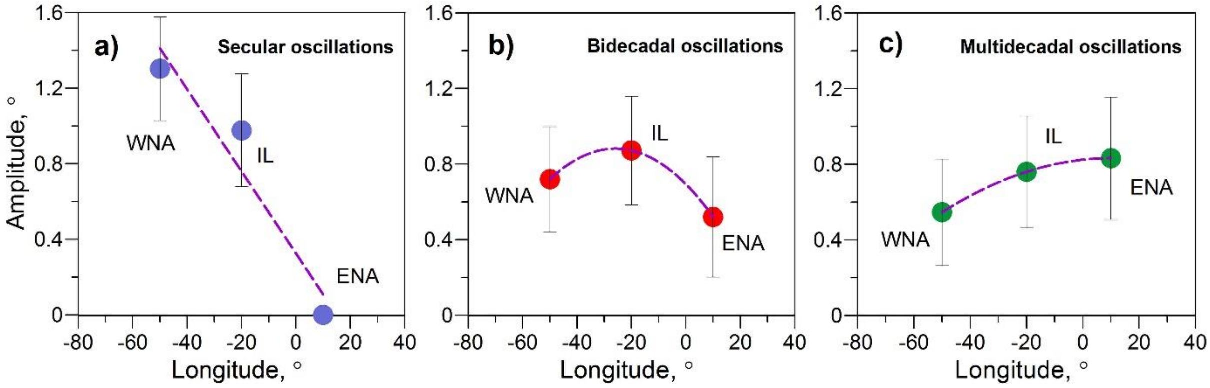

Figure 2. *Amplitudes of secular (a), bidecadal (b) and multidecadal (c) oscillations of storm track latitudes in the western North Atlantic (WNA), the Icelandic Low (IL) and the North Atlantic east of Greenwich (ENA). Thick dashed lines show the linear (a) and the 2nd order polynomial (b, c) approximation. The vertical bars show 2 standard deviations.*

The data in Figure 2 show that secular oscillations in storm track latitudes strongly dominate in the western North Atlantic, where cyclogenetic processes are most intensive. The amplitude of the secular oscillations is ~1.3° in this region and then it decreases to ~1° in the Icelandic Low, where bidecadal and multidecadal oscillations intensify. Secular oscillations disappear completely east of Greenwich. Bidecadal oscillations are a characteristic feature of storm tracks throughout the North Atlantic (Figure 1, bottom panels). They reach the highest amplitude (~0.9°) in the Icelandic Low, where the cyclone occurrence is maximal, and weaken noticeably, with the amplitude decreasing to ~0.5°, in the area east of Greenwich, where cyclone filling (destruction) predominates. One can note that east of Greenwich, oscillations in storm track latitudes differ significantly from those observed west of Greenwich. In this area, secular oscillations disappear and multidecadal oscillations with periods of ~60 years become dominating. Bidecadal oscillations weaken compared with those west of Greenwich and oscillations with shorter periods of ~11 and 16 years become stronger than bidecadal ones. Thus, we can note the attenuation of long-term variations in latitudes of cyclone trajectories and the intensification of short-term ones when cyclones move from the west to the east. The amplitudes of oscillations in storm track latitudes estimated on the base of the polyharmonic model are summarized in Table 1.

Table 1. *Amplitudes of oscillations in storm track latitudes in different regions of the North Atlantic*

Region	Time scale			
	Secular	Multidecadal	Bidecadal	Decadal
Western North Atlantic	1.3°	0.55° (41 yrs)	0.72°	–
Icelandic Low	0.98°	0.76° (45 yrs)	0.88°	–
Eastern North Atlantic	–	0.83° (61 yrs)	0.52	0.66° (11 yrs) 0.63 (16 yrs)

Let us consider in more detail bidecadal oscillations in latitudes of the main cyclone trajectories, which are observed throughout the North Atlantic. Figure 3 (top panels) presents the results of an additional spectral analysis of high-frequency components (HFCs) of the studied time series, which allows us to eliminate low-frequency components and to check up the stability of the detected quasi-periods on the periodogram. The HFCs were calculated using the Blackman-Tukey high-frequency filter with different "cut-off" frequencies (periods) $T_{cut\text{-}off}$. The data in Figure 3 demonstrates stable maxima of spectral density at periods of ~22-25 years, which confirms the reliability of bidecadal oscillations in storm track latitudes in all the studied regions.

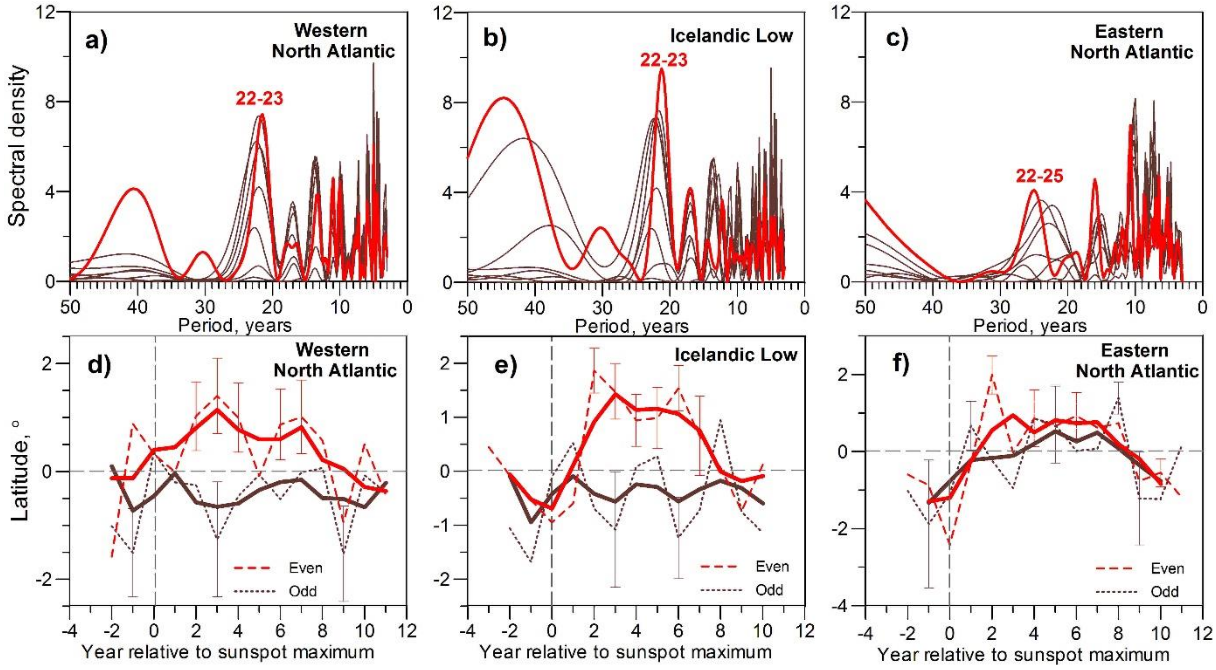

Figure 3. *Top: Sampling estimates of the normalized spectral density of average storm track latitudes in the cold months (October-March) in different regions of the North Atlantic for the initial time series (thick red lines) and their high frequency components with "cut-off" parameter $T_{cut\text{-}off}$ =7, 11, 17, 23, 29, 37 and 43 years (thin brown lines). Bottom: Mean (SPEA) variations of storm track latitudes in 7 even (red dashed lines) and 6 odd (brown dotted lines) solar cycles. Thick lines show 3-year running averages. The vertical bars show two standard errors of the mean.*

The detected bidecadal variations in latitudes of storm tracks are close to the Hale magnetic cycle observed in the polarity of magnetic fields on the Sun. The Hale cycle consists of two consecutive 11-year cycles. At the beginning of each 11-year cycle, the polarity distribution in sunspot groups reverses, whereas near the sunspot maximum, the reversal of the overall magnetic field of the Sun occurs. The Hale cycle is believed to start from an even (according to the Zurich numbering) cycle (e.g., [Nagovitsyn et al., 2009]). Figure 3 (bottom panels) shows the results of the superposed epoch analysis (SPEA) of variations in storm track latitudes (obtained by subtracting a secular variation) for even (12th to 24th) and odd (13th to 23rd) cycles. The year of the sunspot maximum (the overall magnetic field reversal) is taken as a zero year. One can see that, during the declining phase and the minimum of even solar cycles, a noticeable shift of cyclone trajectories to the north (relative to a secular variation) takes place, whereas during the declining phase and the minimum of odd cycles, only an insignificant southward shift is observed. The difference between storm track variations in even and odd cycles is maximal in the Icelandic Low region, where bidecadal oscillations are most pronounced compared with other regions of the North Atlantic (Figure 3b). In the Icelandic Low region, the northward shift reaches ~1–2º from the second to the sixth years after the solar maximum, with the confidence level amounting 0.96–0.98 according to the estimates using the Monte-Carlo method. East of Greenwich, the difference between storm track variations in even and odd solar cycles decreases markedly, so bidecadal oscillations in cyclone trajectories become less pronounced (Figure 3c).

Thus, the above results show that bidecadal oscillations in cyclone trajectories are due to a noticeable northward shift in even solar cycles and a weak southward shift in odd ones. These oscillations are strongest in the Icelandic Low region, which is a particular region of the North Atlantic. It is characterized by the highest occurrence of cyclones, which arrive in this region having reached the stage of their maximum development. However, high temperature contrasts between the icy surface of Greenland and the warmer ocean contribute to cyclone re-deepening (regeneration). In this region, the intensification of cyclone re-deepening was detected in association with energetic Solar Proton Events [Veretenenko and Thejll, 2004]. All this allows suggesting that the Icelandic Low is the most sensitive region to solar activity influences.

As cyclone movement is influenced by the intensity of the stratospheric polar vortex, one can suggest that solar activity influences on cyclone trajectories are realized via variations of the vortex intensity. Cyclone trajectories shift poleward under a strong vortex and equatorward under a weak one [Kidston et al., 2015]. Thus, the detected oscillations in storm track latitudes suggest the corresponding oscillations in the vortex strength. Figure 4 shows the dependence of storm track latitudes in the Icelandic Low region on maximal values of zonal wind velocity in the stratosphere over the North Atlantic. One can see that an increase of zonal wind velocity contributes to the northward shift of cyclone trajectories, the highest correlation being observed between storm track latitudes and wind velocity at the stratospheric levels 70 and 50 hPa (~18–20 km), which is a region of maximal ionization by galactic cosmic rays (GCRs) [Bazilevskaya et al., 2000].

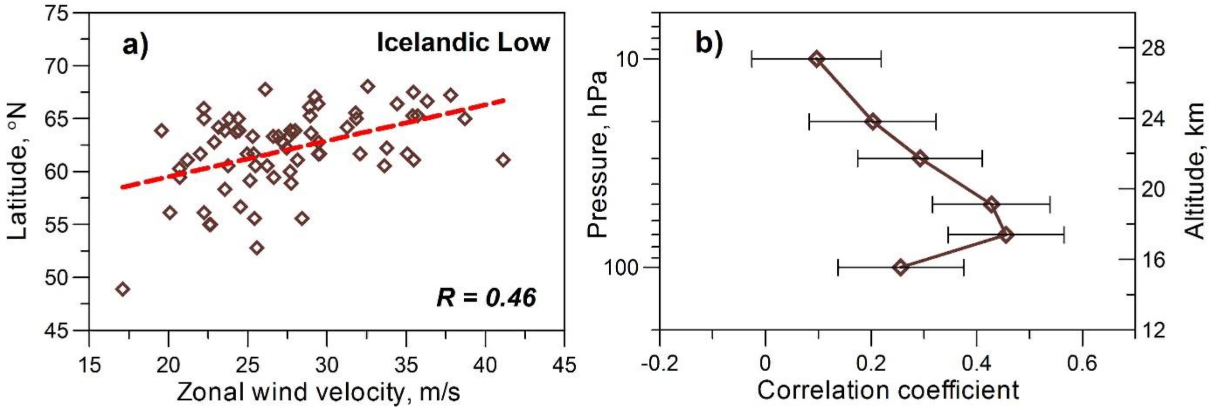

Figure 4. *a) Average storm track latitudes in the Icelandic Low in the winter months (December-January) versus maximal values of zonal wind velocity at the level 70 hPa over the North Atlantic; b) correlation coefficients between storm track latitudes in the Icelandic Low in winter and maximal zonal wind velocity over the North Atlantic at different stratospheric levels. The horizontal bars show two standard errors of the correlation coefficient.*

Thus, the shift of cyclone trajectories to the north provides evidence for intensification of the stratospheric polar vortex, whereas the southward shift indicates the vortex weakening. A possible reason for the northward shift is the influence of increases in ionization rate due to GCRs on the vortex intensity. The data in [Veretenenko et al., 2023] showed that the northward shift of storm tracks both on the secular and bidecadal time scales takes place under an enhanced intensity of galactic cosmic rays. On a secular time scale, storm tracks were shifted northward when GCR intensity (characterized by the concentration of the cosmogenic isotope ^{10}Be in polar ice) reached maximal values at the minimum of the Gleissberg cycle. On a bidecadal time scale, the northward shift is observed during the declining phase of even cycles when GCR fluxes are enhanced compared with those in odd ones. This allows suggesting that the northward shift of cyclone trajectories is caused by the polar vortex intensification due to GCR flux increases.

A mechanism of the polar vortex intensification under ionization increases may involve changes in the temperature regime of the polar middle atmosphere resulting from changes in its chemical composition (ozone depletion due to enhanced production of odd hydrogen HO_x ($H+OH+HO_2$) and odd nitrogen NO_x ($N+NO+NO_2$) families, which catalytically destroy ozone. Under polar night conditions, ozone acts as a greenhouse gas, absorbing the outgoing long-wave radiation of the Earth and the atmosphere. So, ozone destruction may contribute to a cooling of the polar middle atmosphere, which, in turn, may result in the increase of temperature contrasts between middle and high latitudes and the polar vortex intensification.

Conclusions

Latitudinal position of the main directions of cyclone movement (storm tracks) reveals variations, which may be associated with solar activity, in all the studied regions of the North Atlantic. Secular oscillations in storm track latitudes close to the solar Gleissberg cycle are most pronounced in the areas west of Greenwich where cyclones usually arise and develop most intensively. In the area east of Greenwich, where processes of cyclone destruction are more frequent, secular oscillations disappear and multidecadal ones become dominating. Bidecadal oscillations in storm track latitudes close to the magnetic Hale cycle are due to a noticeable northward shift of cyclone trajectories during the declining phase of even solar cycles. These oscillations are observed throughout the North Atlantic, but they are most expressed in the Icelandic Low area. East of Greenwich, bidecadal oscillations weaken sharply, but those with shorter periods intensify. The obtained results suggest that the Icelandic Low area, which is characterized by the highest occurrence of cyclones in the North Atlantic, is most sensitive to solar activity influences.

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