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Solar Activity Influences on Extratropical Cyclone Trajectories in the North Atlantic

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Abstract
In this work we continue studying long-term variability of the main trajectories of extratropical cyclones (storm tracks) in the North Atlantic, basing on the data of MSLP (Mean Sea Level Pressure) archives from the Climatic Research Unit, UK (1873-2000) and NCEP/DOE AMIP-II Reanalysis (1979-2021). It was revealed that the average latitudes of storm tracks in the cold months (October-March) at longitudes from 60ºW to 10ºW undergo oscillations with the periods of ~80-100, ~40-45 and ~22 years, which indicates their possible connection with solar activity. Cyclone trajectories were found to be shifted southward at the maximum of the Gleissberg cycle and northward at its minimum, with the peak-to-peak amplitude of the secular variations reaching ~5º in the western North Atlantic. Since 1960s, at the descending branch of the secular cycle, cyclone trajectories have been shifted northward again. On the bidecadal time scale, a northward shift of storm tracks was revealed in even solar cycles, the effect being the most pronounced (~1-2º) in the eastern part of the North Atlantic. The detected oscillations of cyclone trajectories indicate long-term changes in the position of the polar jet stream, which is influenced by the intensity of the stratospheric polar vortex. A possible mechanism of solar influences on the polar vortex state involves ionization changes due to energetic charged particles (galactic cosmic rays and auroral electrons), which affect the chemical composition and temperature regime of the polar atmosphere.

Keywords: cyclone trajectories; solar activity; galactic cosmic rays.

Introduction

Extratropical cyclonic activity (formation, development and movement of cyclones and anticyclones) is an important part of the general circulation of the atmosphere providing the mass and heat exchange between high and low latitudes. Mobile extratropical cyclones, usually forming and developing over oceans, influence significantly weather and climate at middle latitudes in both hemispheres. In the Northern hemisphere, cyclones coming from the North Atlantic are responsible for many hazardous events over Europe. Recently, heavy rainfall caused by cyclone Bernd (July 2021) resulted in a severe flood in Central Europe with more than 2 hundred victims. Thus, a study of possible influence of solar activity and related phenomena on cyclonic activity at extratropical latitudes is of great importance to improve the quality of weather and climate forecasts.

According to the data [Brown and John, 1979], cyclone trajectories in the eastern North Atlantic revealed a solar cycle dependence, with their mean latitude of storm tracks in winter being 2.5º further south at solar maximum than at solar minimum. Tinsley [Tinsley, 1988] showed that this effect is the most pronounced, reaching ~6º, under the west phase of quasi-biennial oscillations of the atmosphere. On a longer time scale, model studies of circulation in the North Atlantic region during the Maunder minimum of solar activity were carried out in [Luterbacher et al., 2001]. The results of this study showed the southward shift of cyclone tracks under reduced solar activity, which seems to be in disagreement with the results by Brown and John [1979] and Tinsley [1988], who revealed a northward shift of North Atlantic cyclones with decreasing sunspot activity on a decadal time scale. So, further studies are needed to clarify possible influence of solar activity on extratropical cyclone movement on longer time scales.

For this reason, the aim of this work is to consider long-term variations in trajectories of extratropical cyclones in the North Atlantic and their possible association with solar activity.

Experimental data and their analysis

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 Iceland and, then, towards the Barents Sea. The cyclone movement and evolution results in the formation of an extended region of lowered pressure (a baric trough) on monthly maps of sea level pressure (SLP). The examples of a baric trough in cold months, when extratropical cyclogenesis is most intensive, are presented in Figure 1. The white line indicates the axis of a baric trough (the central line connecting minimal pressure values at different longitudes), which corresponds to a region of predominant passages of cyclones (storm track). One can see that the position of storm tracks may noticeably vary depending on a time period.

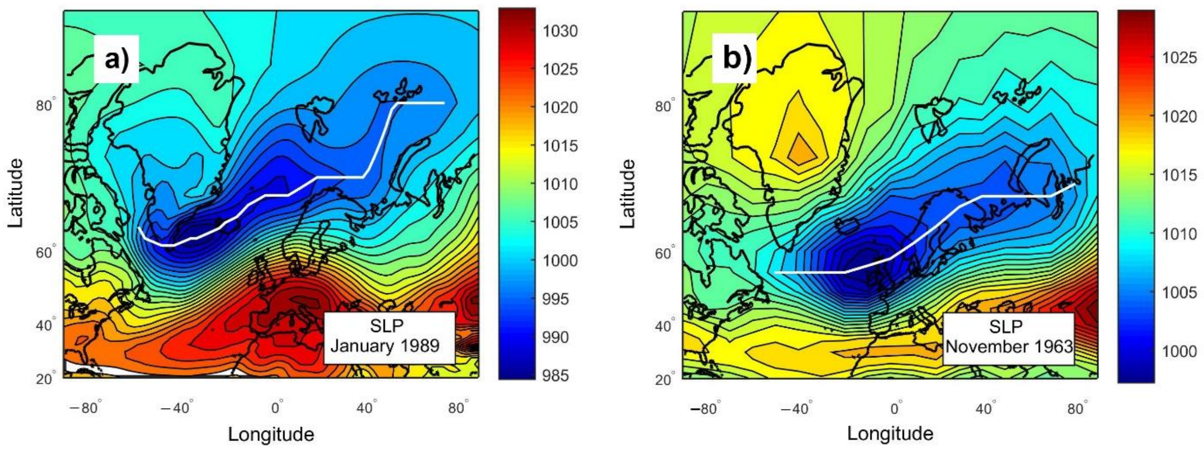

Figure 1. *Distribution of mean monthly values of SLP (in hPa) in the North Atlantic area for January 1989 (a) and November 1963 (b). The baric trough axes indicating the main directions of cyclone movement (storm tracks) are shown by white lines.*

As experimental base for this study, we used gridded monthly data from 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. To determine the position of a storm track, pressure minima and their latitudes were found for the longitudes from 60ºW to 10ºW. Then the latitudes of pressure minima were averaged over cold months (October-March), which is the period of intensive cyclogenesis at middle latitudes.

Temporal variations of the obtained storm track latitudes are presented in Figure 2. One can see noticeable variability of North Atlantic storm tracks both on interannual and longer time scales, including multidecadal and secular. Secular variations (periods ~80-100 years) seem to be more pronounced in the western North Atlantic (longitudes 60-40ºW), where cyclones usually form and deepen most intensively. This is confirmed by the results of spectral analysis (Figure 3, left panel) performed using the method of a sampling estimate of the normalized spectral density [Jenkins and Watts, 1968]. In the eastern North Atlantic, where processes of cyclone filling become more frequent, secular variations in storm track latitudes weaken, but bidecadal (~22 years) and multidecadal (~40-45 years) ones intensify.

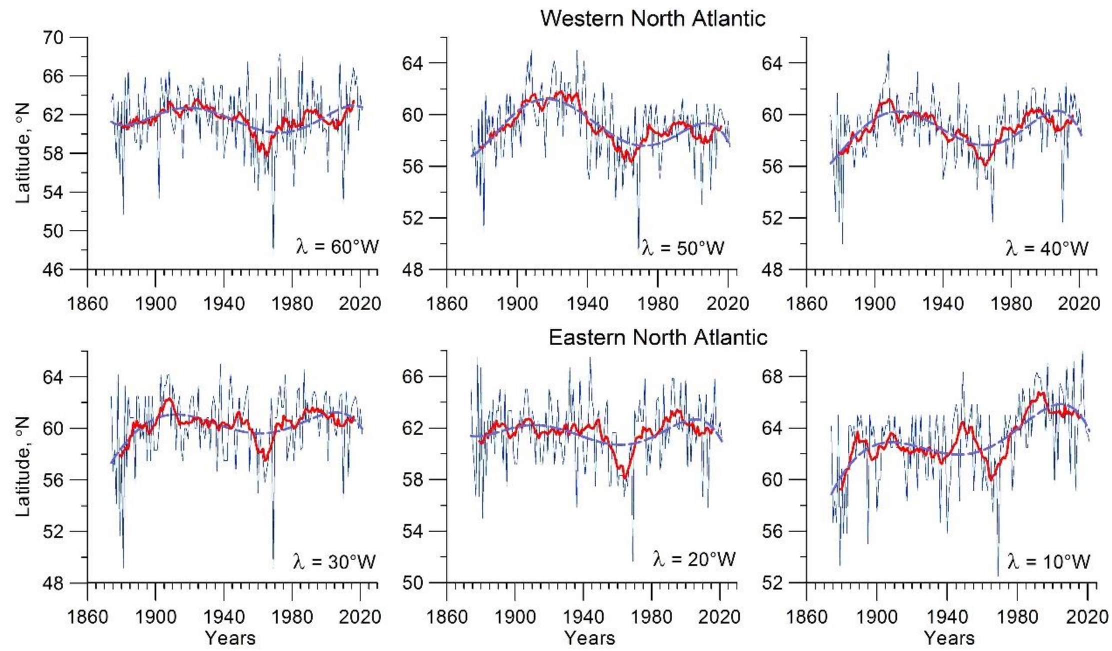

Figure 2. *Temporal variations of average storm track latitudes in cold months (October-March) at different longitudes of the North Atlantic. Thick red lines and dashed blue lines show 11-year running averages and 5th order polynomial approximation, respectively,*

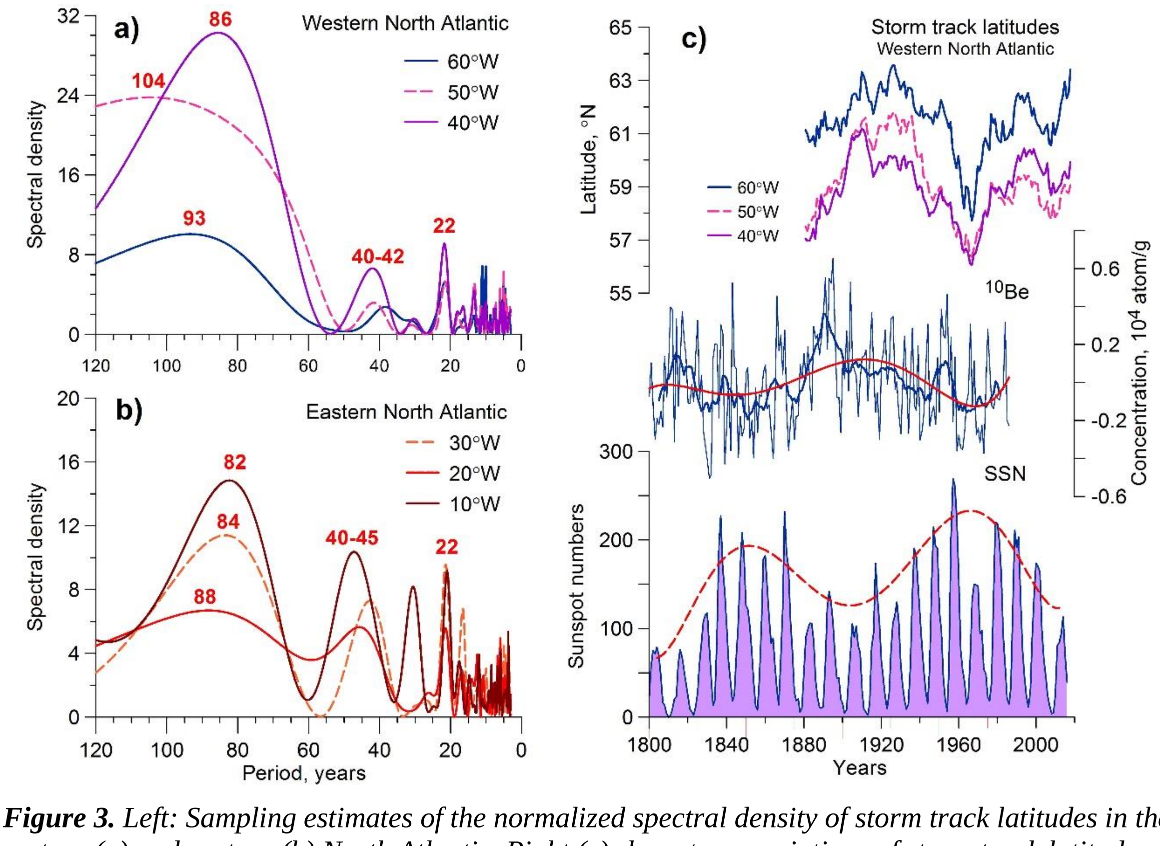

Figure 3. *Left: Sampling estimates of the normalized spectral density of storm track latitudes in the western (a) and eastern (b) North Atlantic. Right (c): long-term variations of storm track latitudes in the western North Atlantic (11-year running averages), the ^{10}Be concentration in polar ice (after the linear trend removal) and yearly sunspot numbers SSN (http://www.sidc.be/silso/datafiles). Thick blue and red lines show 11-year running averages and the 5th order polynomial approximation of the ^{10}Be concentration, respectively. The dashed red line shows the 5th order polynomial approximation of SSN at maxima of the 11-year cycle.*

Figure 3c presents a comparison of long-term variations in storm track latitudes (11-year running averages) in the western North Atlantic with sunspot numbers SSN and concentration of the cosmogenic isotope ^{10}Be in polar ice [Beer et al., 1990]. ^{10}Be concentration is used to characterize the intensity of galactic cosmic rays (GCRs), which are currently believed to be one of most plausible agents transferring solar signals to the lower atmosphere. One can see that during the period of the minimum of the secular Gleissberg cycle (~1900-1930), when GCR intensity was enhanced, storm tracks in the western North Atlantic were noticeably shifted to the north. At the maximum of the secular cycle (~1940-1960), which was accompanied by a decrease in GCR intensity, storm tracks were shifted southward. The peak-to-peak amplitude of the secular variations in cyclone trajectories amounts to ~5°. Since the ~1960s, at the descending phase of the secular solar cycle, storm track latitudes in the western North Atlantic have been increasing again. Thus, the above results suggest a possible influence of solar activity on extratropical cyclone trajectories in the North Atlantic.
To confirm a reliability of bidecadal periodicities in cyclone trajectories, an additional analysis of the high-frequency components (HFCs) of the studied time series was carried out. The HFCs were calculated using the Blackman–Tukey high-frequency filter with different "cut-off" frequencies (periods) $T_{cut\text{-}off}$. The results of spectral analysis of the HFCs are presented in Figure 4. One can see stable maxima of spectral density at the periods ~22-23 years at all the studied longitudes of the North Atlantic, which indicates the reliability of bidecadal oscillations in storm track latitudes.

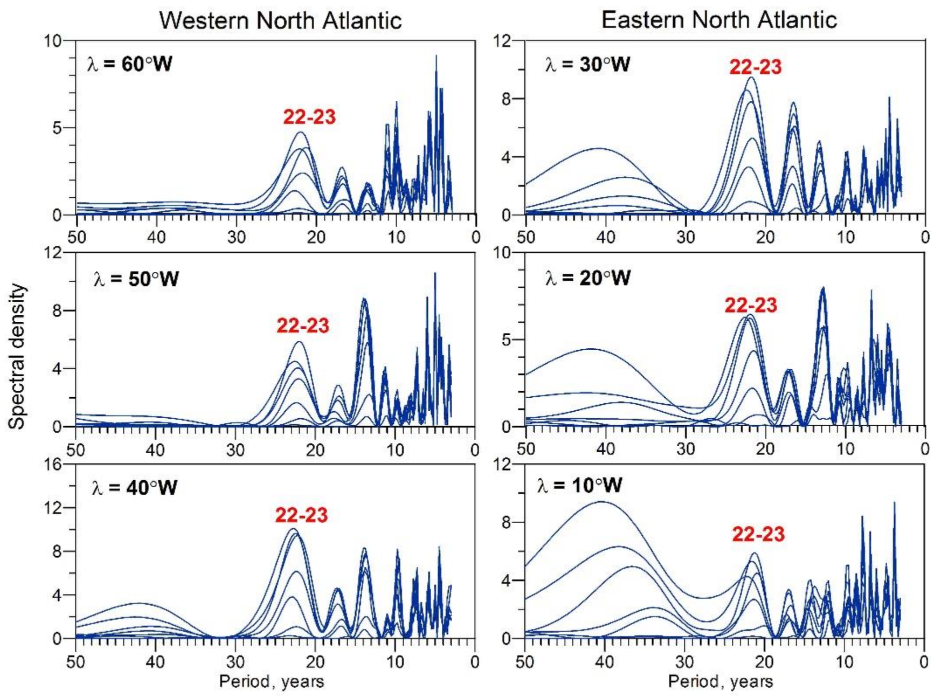

Figure 4. *Sampling estimates of the normalized spectral density of storm track latitudes (HFCs with different cut-off parameters* $T_{cut\text{-}off}$ *= 7, 11, 17, 23, 29, 37 and 43 years) at different longitudes.*

To clarify the nature of the detected bidecadal oscillations, a superposed epoch analysis (SPEA) of variations in storm track latitudes for even (12th to 24th) and odd (13th to 23rd) solar cycles was performed. The variations were obtained by subtracting a secular variation (presented as the 5th order polynomial) and averaged over the western (40-60°W) and eastern (10-30°W) North Atlantic. The results of SPEA are shown in Figure 5, the year of the solar maximum being taken as a zero year.

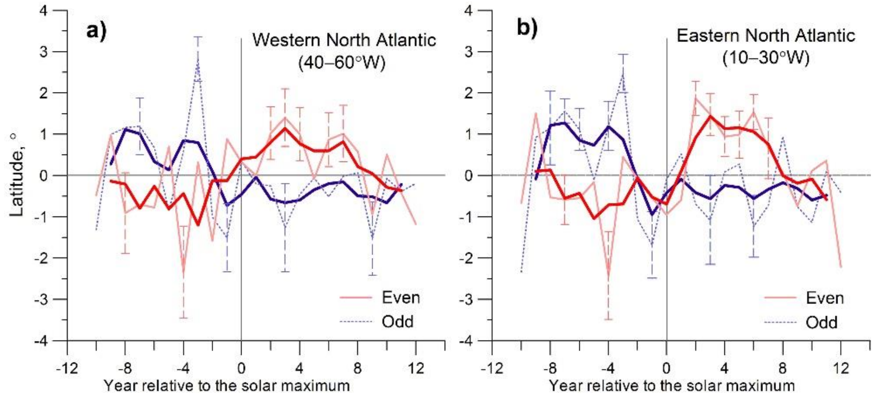

Figure 5. *Mean (SPEA) changes of storm track latitudes (after the subtraction of a secular variation) in the western (a) and eastern (b) North Atlantic for 7 even (12th to 24th) and 6 odd (13th to 23rd) solar cycles. The year of solar maximum is taken as a zero year. Thick lines show 3-year running averages. Vertical dotted lines show 2 standard errors of the mean.*

The results of the SPEA showed that variations of cyclone trajectories differ noticeably in even and odd solar cycles. In even cycles they are shifted to the north relative to a secular variation, the effect being the most pronounced (up to ~1-2°, with the confidence level above 0.95) in the eastern North Atlantic, whereas in odd cycles they are slightly shifted to the south. The largest northward shift in even cycles is observed from the 2nd to 6th year, i.e., at the descending phase and the minimum of the solar cycle.

The obtained results suggest a link between latitudinal oscillations of cyclone trajectories and solar cycles, first of all, the secular Gleissberg cycle and the ~22-year magnetic (Hale) cycle. Multidecadal (~40-45 years) variations, similar to those in storm track latitudes (Figures 3 and 4), are observed in north-south asymmetry of sunspot activity [Obridko and Nagovitsyn, 2017]. Let us consider possible mechanisms of solar influences on cyclone trajectories. The movement of extratropical cyclones is known to be closely related to the position of the polar jet stream, which is influenced by the intensity of the stratospheric polar vortex. Under a strong vortex, the polar jet strengthens and shifts poleward, resulting in a poleward shift of cyclone trajectories, whereas under a weak vortex, it slows down and shifts towards the equator. Thus, the variations of storm track latitudes on secular, multidecadal and bidecadal time scales provide evidence for corresponding oscillations in the position of the polar jet stream and the intensity of the polar vortex. The polar vortex seems to strengthen at the minimum of the Gleissberg cycle and in even solar cycles, resulting in the northward shift of cyclone trajectories, and to weaken at the secular maximum and odd cycles.

As the stratospheric polar vortex is formed in the area accessible for different kinds of energetic charged particles [Veretenenko, 2022], a possible factor of the vortex intensification may be galactic cosmic rays, whose fluxes are strongly influenced by solar activity. Secular variations of GCRs are clearly seen in the ^{10}Be concentration (Figure 3c) and may reach ±15-20%, according to the reconstruction [Stozhkov et al., 2004]. The 22-year cycle is manifested in GCR intensity as an alternation of dome-shaped and peaked maxima depending on the polarity of the Sun's overall magnetic field. Figure 6a shows the results of the SPEA of yearly cosmic ray fluxes measured in the mid-latitude stratosphere [Stozhkov et al., 2009] in even and odd solar cycles. One can see that in even cycles (when the polarity becomes positive near the sunspot maximum) GCR influx in the atmosphere noticeably exceeds that in odd cycles (when the polarity becomes negative). This difference is most pronounced at the descending phase of solar cycles, i.e., when the northward shift of cyclone tracks is the largest (Figure 5). Another agent influencing the vortex state may be geomagnetic activity, which also reveals ~22-year oscillations (Figure 6b), and related auroral electron precipitations.

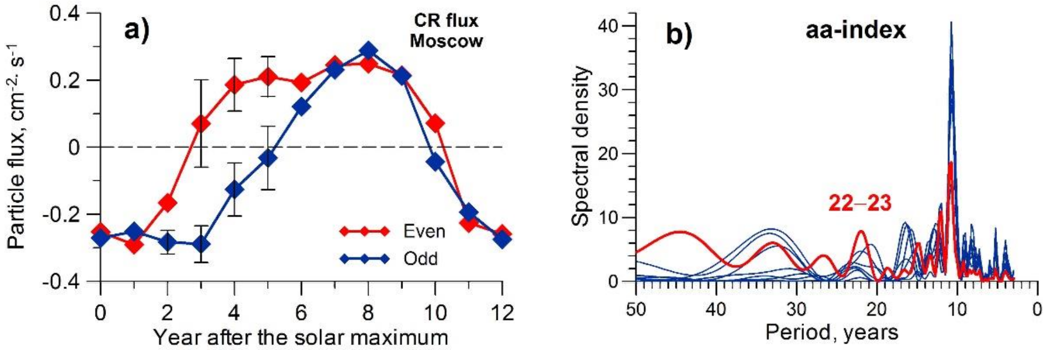

Figure 6. *a) Mean (SPEA) variations of cosmic ray fluxes (detrended) in the stratosphere in even and odd solar cycles. The year of solar maximum is taken as a zero year. b) Sampling estimates of the normalized spectral density of geomagnetic aa-index for the initial series (red line) and HFCs with different cut-off parameters $T_{cut\text{-}off}$ = 7, 11, 17, 23, 29, 37 and 43 years (blue lines).*

An intensification of the vortex may be caused by ionization increases in the polar atmosphere due to variations of energetic charged particles. Ionization increases contribute to enhanced production of nitrogen and hydrogen oxides destroying ozone, which under polar night conditions acts as a greenhouse gas absorbing outgoing longwave radiation of the Earth and the atmosphere. So, ozone depletion may result in a cooling of the polar middle atmosphere contributing to an increase of temperature gradients between middle and polar latitudes and, then, the vortex intensification. Another way of the vortex strengthening may involve radiative forcing of cloudiness changes associated with enhancement of vertical electric currents due to ionization increases [Tinsley, 2008].

Conclusions

Latitudes of the predominant cyclone trajectories (storm tracks) in the North Atlantic undergo oscillations with periods of ~80-100, ~40-45 and 22 years, which may be associated with solar activity. Cyclone trajectories were found to be shifted noticeably to the north at the minimum of the secular Gleissberg cycle, as well as at the descending phase and the minimum of even-numbered solar cycles. A possible mechanism of the detected effects seems to involve the intensification of the polar vortex due to ionization increases associated with galactic cosmic rays and auroral electron precipitations.

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