Characteristics of the subtropical jet stream over the North Atlantic from reanalysis data

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Abstract. Variability of characteristics (latitudinal location and wind speed) of the subtropical jet stream in the Northern Hemisphere for the winter (December-February) and summer (June-August) seasons in 1958-2017 is investigated with NCEP/NCAR, JRA-55, NCEP/DOE, and ERA-Interim reanalysis data. It is shown that the jet is shifting to the equator (0.58°N per decade) and is increasing (0.51 m/s per decade) in the Atlantic sector (0°-60°W) during the winter season. In 2000-2017 a large contribution to these trends is made. The jet is shifting poleward (0.23°N per decade) and is increasing (0.35 m/s per decade) in the summer season. An analysis of variability of the characteristics of the subtropical jet stream is performed for 1958-1979 (cooling of the global surface temperature), 1979-2000 (warming of the global surface temperature), and 2000-2017 (stabilization of the global surface temperature). Correlations between the variability of the jet characteristics and the variability of the meridional upper-tropospheric temperature gradient, the position and intensity of the Azores High, the concentration of sea ice in the North Atlantic Ocean, the total ozone content, the index of the North Atlantic Oscillation, and the atmosphere vortex circulation in the Atlantic sector are found.

1. Introduction
The jet stream, as defined by the World Meteorological Organization, is a narrow stream of strong wind with a quasi-horizontal axis located in the upper troposphere or stratosphere and characterized by large vertical and horizontal wind shifts and one or more speed maxima.

Classification of jet streams in the troposphere was carried out in early studies [1]. One of these jets is a subtropical jet stream (SJS), and the other one is a middle-latitude jet stream defined in the modern literature as the eddy-driven jet [2]. An important conclusion of [1] is that jet streams are formed within the altitude frontal zone and the wind speeds in them depend on the temperature contrast in the underlying air layers.

The subtropical jets are centered [2] at the poleward boundaries of the Hadley cell in both hemispheres near 30°N for winter with speeds more than 30 m/s at the 200 hPa level. The interest in SJSs is related, first, to the fact that they are pronounced characteristics of the global atmosphere circulation which depends on climate change and, second, the continental regions located under the SJSs are arid regions when the jet location displacements lead to changes in the hydrothermal regime that influences economic activity [3].

The subtropical jet is driven primarily by the Hadley circulation, a strong meridional circulation driven by heating in the tropics and cooling in the extratropics. The formation of the Hadley
circulation and the subtropical jet has been examined using zonal mean idealized models driven by atmospheric heating. Also, more recent studies [16] suggest a strong influence of eddies on the subtropical jet and the Hadley circulation.

A comparison of the effects of various forcings on the meridional circulation shows that the largest contribution to the tropical circulation is from diabatic heating. Diabatic heating at around 5°S and cooling at around 20°N are the primary drivers of the circulation. In those cases where the calculations include induced nonlinear advection effects there is considerable enhancement of the tropical circulation by eddies and a clear vertical extension of the tropical cell as a result of diabatic heating. This indicates that the meridional circulation produced by nonlinear advection resulted primarily from eddies and diabatic heating.

The model projections [4-8] of the SJS characteristics (latitudinal location, wind speed, altitude) in an anthropogenic changing climate in the 21st century showed that under global warming jet streams should shift to the poles if only the radiative forcing of greenhouse gases is taken into account [4, 5]. This increases the height of the tropical tropopause and increases the upper-tropospheric temperature gradient. It is shown in [5] that under global warming the Hadley circulation cell weakens and expands, displacing the jet stream to the pole, however, for El Niño events, the Hadley cell is strengthened, compressed, and the SJS shifts to the equator.

In [6], based on a set of models from CMIP3, it is shown that in the 21st century a significant intensification of the circulation is expected at the levels of 200-100 hPa. In [7], a model study of the effect of anthropogenic aerosols on changes in the northern winter extratropical circulation was performed. A shift to the equator of the SJS is established in response to aerosol cooling in the middle latitudes, which is more pronounced over the North Pacific than over the North Atlantic. In [8], using an ensemble of CMIP5 models, it was shown that an increased amount of carbon dioxide significantly shifts the zonal tropospheric circulation to the pole in the Southern Hemisphere (SH), however, in the Northern Hemisphere (NH) such a shift has not been detected.

In many works, the characteristics of SJSs were investigated for the historical period on the basis of observational data and reanalyses [9-15]. The authors of [9] investigated the jet stream characteristics based on the average mass fluxes calculated from reanalysis data of ERA-40 and NCEP-NCAR for 1979-2001. They found that in this period the jet streams increase their altitude position and shift to the poles in both hemispheres. In the NH, both streams weaken, the SH SJS weakens, and the SH eddy-driven jet intensifies.

The space-time variability of the NH SJS speed is studied [10] based on NCEP-NCAR reanalysis data for 1948-2005. It is shown that there is no change in the latitude of the jet during this period, but its speed increases during the cold period of the year. The author of [11] used satellite data on changes in the total ozone content to establish the positions of the subtropical and polar fronts in whose zones jet streams develop. He found that the shift to the pole of subtropical jets was 3.7° in the Northern Hemisphere and 6.5° in the Southern Hemisphere for 1979-2010.

The variability of the characteristics of jet streams of both hemispheres is investigated [12] based on NCEP-NCAR reanalysis data for 1958-2008. The results showed that the shift to the pole of northern and southern winter SJSs for 1978-2008 occurs at a faster rate and in more zonally extended areas than in the pre-satellite period of 1958-1978. For most seasons of 1978-2008 intensification of the northern and southern SJSs was found.

The authors of [13] determined the variability of the characteristics of the NH and SH SJSs in the winter and summer seasons based on NCEP-NCAR reanalysis data on the wind speed at the level of 200 hPa for 1950-2009. Temperature data at 300 hPa were also used to calculate the meridional temperature gradients in the upper troposphere of the subtropical and middle latitudes. It was established that for the NH winter in its eastern part the latitudinal shift of the SJS is absent, and the intensity of the jet increases. The intensity of the jet does not change for the same season in the western part, but its position shifts by 6° to the pole. During the summer season, no changes in the position and velocity of the SJS in the western region were detected, in the eastern region the position of the jet does not change, but its intensity slightly increases.
An extended study of the characteristics of the NH and SH subtropical and polar jets for 1980-2014 was carried out in [15] using the data of five reanalyses (MERRA, MERRA-2, ERA-Interim, JRA-55, and NCEP CFSR) according to their methodology in [14]. The characteristics (latitude, wind speed, altitude) of the jets were calculated from daily data on monthly, seasonal, and annual scales, as well as in longitude sectors with a length of 20°, which makes it possible to obtain the variability of jet characteristics on various time and space scales.

The authors of [15] showed that the NH SJS shifts to the pole in winter over Asia and in autumn over the western part of the Pacific Ocean, while in winter an equatorial shift takes place over the eastern part of the Pacific Ocean. The variability of wind speed established in the paper, as well as the latitudinal position, depends on the choice of the season and region. In [15], the case of break of a jet stream in the Atlantic sector (0°-60°W) is given.

In the present paper, the variability of the latitudinal location and wind speed of the NH SJS in the Atlantic sector during 1958-2017 is studied, in which the characteristics of the jet are calculated for the winter and summer seasons. As a forcing for the variability of the characteristics of the jet, the meridional top-tropospheric temperature gradient, the position and variability of the characteristics of the Azores High, the ice concentration in the Arctic seas, the ozone content in the Arctic stratosphere, and the relative vorticity as a characteristic of the vortex activity of the atmospheric circulation in the Atlantic sector are considered.

2. Data and methods

The initial data used the temperature and wind speed fields in the troposphere from NCEP/NCAR I (1958-2017, 2.5°x2.5°), JRA-55 (1958-2017, 1.25°x1.25°), NCEP/DOE II (1979-2017, 2.5°x2.5°), and ERA-Interim (1979-2017, 1°x1°) reanalyses. Analysis of the latitude location and wind speed of the jet stream was carried out at the 200 hPa level, since it is the level where maximum velocities of the western winds in the upper troposphere of the subtropics are observed.

If the lower limit of the wind speed is 30 m/s, isolated areas of the reanalysis grid cells with wind velocities equal to or exceeding 30 m/s are distinguished on the maps of the wind fields at the 200 hPa level. These regions in the northern subtropics form a jet stream streak whose width is 10°-20° latitude and the latitude location depends on the season (Figure 1a).

It is problematic to use the entire jet stream streak to calculate the latitude position and the wind speed of the jet. The notion of the jet stream axis is used for this purpose in this paper. For its detection, for each longitude within the jet stream band there is a cell with the maximum velocity of the horizontal wind, and this cell is considered to belong to the axis of the jet stream.

A set of such cells for all longitudes determines the axis of the jet stream (Figure 1b). Since the latitude location and the wind speed are known for each cell, the jet stream characteristics are determined through the averaging procedures for both the individual Atlantic sector and the Northern Hemisphere as a whole.

The series of seasonal values of the latitudinal location of the jet stream axis and wind speed were analyzed both for 1958-2017 and 1958-1979, 1979-2000, and 2000-2017 corresponding to the cooling, warming, and stabilizing global surface temperature.

A comparison of the results of the study of various reanalyses did not give significant deviations between themselves. Therefore, average values of the results of these reanalyses are given in the tables and figures. Since NCEP/DOE and ERA-Interim reanalyses begin in 1979, mean values for NCEP/NCAR and JRA-55 reanalyses are given for 1958-2017 and 1958-1979, and average values for all four reanalyses are given for 1979-2000 and 2000-2017.

The temperature regime in the upper troposphere was determined by calculating the average seasonal temperatures over latitudinal zones 0°-30°N, 30°N-60°N and at vertical levels of 400, 300, 250, and 200 hPa.
In assessing the trends in the characteristics of the subtropical jet stream, as well as the correlations, the statistical significance of the calculated values was determined by a two-sided $t$-test of the null hypothesis with a significance level $\alpha=0.05$.

3. Results

The trends of the latitudinal location of the jet stream axis and wind speed are given in Table 1. This table shows the NH SJS location and speed trends averaged for all meridians and separately for the Atlantic sector. Positive trends in the NH SJS location mean its displacement toward the pole and negative trends, toward the equator in Table 1. Positive and negative wind speed trends mean increased and decreased intensity of the jet.

| Season | Period       | All meridians | Atlantic sector |
|--------|--------------|---------------|-----------------|
|        |              | Location trend, $^\circ$N per decade | Speed trend, m/s per decade | Location trend, $^\circ$N per decade | Speed trend, m/s per decade |
| Winter | 1958-2017    | 0.09          | 0.51            | -0.58           | 0.51            |
|        | 1958-1979    | 0.20          | 0.34            | -0.28           | 0.89            |
|        | 1979-2000    | 0.45          | 0.22            | 0.22            | 0.24            |
|        | 2000-2017    | 0.30          | 0.46            | -1.28           | 0.72            |
|        | 1958-2017    | 0.16          | 0.18            | 0.23            | 0.35            |
| Summer | 1958-1979    | 0.14          | 0.88            | 0.90            | -0.89           |
|        | 1979-2000    | 0.52          | -0.15           | -0.03           | 0.72            |
|        | 2000-2017    | -0.28         | 0.35            | -1.33           | 0.89            |

It follows from Table 1 that positive latitudinal trends occur for all time periods in the winter season for the zone-averaged SJS, especially pronounced after 1979; however, they are insignificant. The NH SJS significantly shifts to the pole for the summer season of 1958-2017, and this trend is most pronounced during the warming period of 1979-2000. There is an insignificant displacement of the jet to the equator for summer during the period of stabilization of the global temperature of 2000-2017.

The displacement of the NH SJS to the equator is typical for most periods and for 1958-2017 and 2000-2017 this movement is significant for winter in the Atlantic sector. There is a significant NH SJS...
displacement to the pole for the summer of 1958-2017, especially pronounced during the global cooling period of 1958-1979, and in 2000-2017 the jet is significantly shifted to the equator.

The wind speed, both in the zone-averaged jet and in the Atlantic sector, shows a tendency to increase for the whole period of 1958-2017 and for most subperiods. An exception is the period of global cooling in 1958-1979, in which the zone-averaged SJS intensifies and the SJS in the Atlantic sector weakens.

The following approach was applied to investigate the dependence of the SJS speed on the temperature in the upper troposphere. We chose the temperature difference integrated from 400 to 200 hPa between the zones of 0°-30°N & 30°N-60°N as a meridional temperature gradient in the region of SJS formation.

The coefficients of linear correlation between the time series of the temperature gradient and the NH SJS speed for summer and winter are shown in Table 2. High positive statistically significant correlations (especially for winter) allow us to state that the increase in the intensity of the NH SJS is caused by an increase in the meridional temperature gradient.

Table 2. Correlations between NH SJS speed and 0°-30°N & 30°N-60°N temperature gradient. Significant values are in bold.

|                      | 1958-2017 | 1958-1979 | 1979-2000 | 2000-2017 |
|----------------------|-----------|-----------|-----------|-----------|
| Winter, all meridians| 0.72      | 0.66      | 0.77      | 0.72      |
| Winter, Atlantic sector| 0.26    | 0.30      | 0.39      | 0.17      |
| Summer, all meridians | 0.38     | 0.30      | 0.53      | 0.51      |
| Summer, Atlantic sector| 0.13   | 0.40      | 0.11      | 0.38      |

From the results given in the present paper it follows that the most pronounced signs of variability of the NH SJS are the displacement toward the pole and its intensification. The main factor of impact on SJS is the temperature gradient between the zones of 0°-30°N & 30°N-60°N. However, this factor does not explain the specific behavior of the SJS in the North Atlantic, which manifests itself in splitting the stream into separate streaks.

One of the reasons for this behavior of the NH SJS in the Atlantic sector is the influence of the Azores High (AH). The deep AH reaches the tropopause, and if the AH center location is close to the SJS location, then the jet stream splitting followed by the merger of both streaks takes place. Figure 2 shows this splitting by a one-day example (January 17, 2012), and in Figure 1 one can observe this effect for a long time.

Observation of the SJS in specific time periods has revealed its following feature in the Atlantic sector: The SJS is blocked and splits into two separation streaks when the AH reaches the height of the tropopause. These two streaks round the AH on the north and south sides, respectively.

Each AH event at the level of 200 hPa continues from 5 to 15 days with mean AH center location of 31.9°N for winter. The SJS splits into two streaks where the main streak rounds the south side of the AH periphery and the polar streak rounds the north side of the AH periphery. A comparison of the mean axis location of the main streak (19.2°N) and the mean location of the southern side of the AH periphery (26.0°N) for winter, as well as the mean axis location of the polar streak (46.9°N) and the mean location of the northern side of the AH periphery (35.9°N) gives an understanding of the presence of a spiral structure shown in Figure 1 over the North Atlantic.
Figure 2. Wind speed (in m/s) and geopotential height (in geopotential meters) for January 17, 2012. Figure (a) shows 1000 hPa level and Figure (b), 200 hPa level.

Table 3. Time series trends of NH SJS location and Azores High location at 200 hPa level. Significant values are in bold.

| Season | Period      | NH SJS location trend in Atlantic sector, °N per decade | Azores High location trend, °N per decade |
|--------|-------------|--------------------------------------------------------|------------------------------------------|
| Winter | 1958-2017   | -0.58                                                  | -0.54                                    |
|        | 1958-1979   | -0.28                                                  | 0.43                                     |
|        | 1979-2000   | 0.22                                                   | -0.82                                    |
|        | 2000-2017   | -1.28                                                  | -1.99                                    |
|        | 1958-2017   | 0.23                                                   | 0.01                                     |
| Summer | 1958-1979   | 0.90                                                   | 0.01                                     |
|        | 1979-2000   | -0.03                                                  | 0.02                                     |
|        | 2000-2017   | -1.33                                                  | 0.00                                     |
The trends of the main streak location and the AH center location at 200 hPa are given in Table 3. From Table 3 it can be assumed that a significant AH center shift to the equator (-0.54°N per decade) leads to corresponding significant SJS location shift (-0.58° N per decade). The effect of the temperature gradient factor on the SJS in the Atlantic sector with a correlation coefficient of 0.26 is much less than its effect on the SJS across all meridians (correlation coefficient: 0.72) for winter (see Table 2), and this effect gives an insignificant correlation for 1958-1979 and 2000-2017.

A peculiarity of the appearance of AH in summer at the level of 200 hPa is that each event is short (1-2 days) and in most cases (about 90%) the main SJS streak passes north (42.3°N) of the northern side of the AH periphery (33.4°N). The summer location of the AH center does not change, whereas the SJS axis shifts to the south (see Table 3) and the main factor of impact on the SJS is the temperature contrast in the underlying air layers. The effect of this factor on the SJS in the Atlantic sector was much greater than on the SJS for all meridians (see Table 2) with correlation coefficients of 0.40 versus 0.30 for 1958-1979. However, the SJS movement to the equator must stop when the main streak reaches the northern side of the AH periphery.

The impact of the other factors on the SJS characteristics was considered for the Atlantic sector. These factors are the ice concentration in the Greenland Sea and the Baffin Sea, the North Atlantic Oscillation Index (NAO), the total ozone content (TOC) over the SJS zone (90°N-30°N, ERA-Interim), the vorticity indices of cyclonic circulation (Vc) and anticyclonic one (Va) for tropospheric levels of 1000, 500, and 300 hPa from ERA-Interim reanalysis. The Vc was determined as the sum of the negative values of the relative vorticity (Vr) over the North Atlantic in the northern region relative to SJS (90°N-40°N), and the Va was calculated from the positive values of Vr in a region close to the AH (40°N-20°N).

From an analysis of Tables 4 and 5 it follows that the variability of the concentration of ice began to have a significant effect on the SJS characteristics from the beginning of the 21st century for winter. Increased melting of the Arctic ice began in this period, which led to changes in the meridional atmospheric circulation. The North Atlantic Oscillation affects the variability of the SJS characteristics mainly for summer, and the most significant correlation (0.60) for the SJS location is manifested at the beginning of the 21st century. Insignificant correlation coefficients between the TOC and SJS characteristics indicate a possible dependence of the variability especially for the summer of 2000-2017. There is a weak SJS dependence with a cyclonic atmospheric circulation in the middle and upper troposphere of the Atlantic sector for the winter of 1958-1979 (Tables 4, 5). However, for the anticyclonic atmospheric circulation (Table 5) a significant correlation with the SJS location (from -0.36 to -0.46) was found. This correlation is observed for the low troposphere for winter.

**Table 4.** Correlation coefficient of NH SJS speed and climatic factors: sea ice concentration (IE), North Atlantic Oscillation Index (NAO), total ozone content (TOC), vorticity index of cyclonic circulation (Vc), vorticity index of anticyclonic circulation (Va). Significant values are in bold.

| Factor       | 1958-2017 Winter | 1958-1979 Winter | 1979-2000 Winter | 2000-2017 Winter |
|--------------|------------------|------------------|------------------|------------------|
| IE           | -0.14            | -0.14            | -0.24            | **-0.45**        |
| NAO          | -0.09            | -0.06            | -0.76            | 0.13             |
| TOC          | -0.14            | -0.14            | -0.24            | **-0.45**        |
| Vc, 1000 hPa | -0.14            | 0.16             | -0.09            | 0.05             |
| Vc, 500 hPa  | -0.20            | 0.00             | -0.40            | -0.23            |
| Vc, 300 hPa  | -0.22            | -0.01            | -0.41            | -0.21            |
| Va, 1000 hPa | **-0.27**        | -0.14            | -0.21            | -0.24            |
| Va, 500 hPa  | **-0.27**        | -0.06            | 0.15             | -0.15            |
| Va, 300 hPa  | -0.10            | -0.06            | 0.25             | -0.10            |
Table 5. Correlation coefficient of NH SJS location and climatic factors: sea ice concentration (IE), North Atlantic Oscillation Index (NAO), total ozone content (TOC), vorticity index of cyclonic circulation (Vc), vorticity index of anticyclonic circulation (Va). Significant values are in bold.

| Factor       | 1958-2017 | 1958-1979 | 1979-2000 | 2000-2017 |
|--------------|-----------|-----------|-----------|-----------|
|              | Winter    | Summer    | Winter    | Summer    |
| IE           | -0.12     | 0.38      | -0.09     | -0.04     | -0.18 | -0.23 | -0.54 | -0.29 |
| NAO          |           |           |           |           |       |       |       |       |
| TOC          |           |           |           |           |       |       |       |       |
| Vc, 1000 hPa | -0.14     | 0.13      | -0.02     | 0.06      | 0.12  | 0.28  | -0.24 | -0.37 |
| Vc, 500 hPa  | -0.12     | 0.07      | -0.28     | -0.02     | 0.10  | 0.03  | -0.13 | -0.07 |
| Vc, 300 hPa  | -0.14     | 0.00      | -0.27     | -0.07     | 0.09  | 0.05  | -0.17 | -0.10 |
| Va, 1000 hPa | -0.42     | 0.04      | -0.36     | -0.18     | -0.46 | -0.08 | -0.46 | 0.24  |
| Va, 500 hPa  | -0.13     | 0.08      | 0.22      | -0.05     | -0.19 | -0.15 | -0.33 | 0.17  |
| Va, 300 hPa  | -0.06     | 0.06      | 0.30      | 0.01      | -0.06 | -0.18 | -0.26 | 0.18  |

4. Conclusions

No changes in the latitudinal location of the zone-averaged NH SJS were detected during the 60-year period (1958-2017) in winter, but the wind speed increased by 3 m/s. The jet moved to the pole by 1° latitude, and the wind speed increased by 1 m/s for the summer of 1958-2017. The jet moved to the equator at 3.5° latitude, and the wind speed increased by 3 m/s in the Atlantic sector in the winter season of 1958-2017. Such a change in the SJS characteristics takes place during stabilization of the global temperature in 2000-2017.

The jet moves to the pole (1.4° latitude) and intensifies (2 m/s) in the Atlantic sector in the summer of 1958-2017. The jet shift to the pole (2° latitude) is accompanied by a decrease in the wind speed (1.8 m/s) during the warming of the global surface temperature of 1979-2000. The jet shifts to the equator (2.3° latitude) with an insignificant increase in the wind speed in the summer of 2000-2017.

The zonal averaged wind speed in the jet during all time intervals in winter and summer is mainly associated with the upper-tropospheric meridional temperature gradient with the highest correlation coefficient in the winter season. This correlation is significant for the Atlantic sector in the winter of 1958-2017 & 1979-2000 and in the summer of 1958-1979 & 2000-2017. Thus, the changes in the meridional temperature gradient in the upper troposphere cannot be considered as determining factors in the Atlantic sector.

The influence of the AH on the SJS characteristics in the Atlantic sector makes it possible to explain the splitting of the jet in the winter season and the existence of its northern and southern branches.

It has been shown that a significant factor associated with the change in the NH SJS characteristics is the change in sea ice area in the North Atlantic in the winter of 2000-2017. Also, the change in the NH SJS location is associated with the AH location and accompanied by a change in the vortex anticyclonic activity at the Earth’s surface in winter.

Acknowledgments

This study was carried out with partial financial support of the Russian Academy of Sciences, scientific project I.51.

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