Long-term Variability of Rossby Wave Breaking in the Subtropical Jet Stream Area

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Abstract—Climatology and variability of anticyclonic (AC-type) and cyclonic (C-type) wave breaking in the region of the subtropical jet stream are investigated using the previously developed method for identifying and clustering Rossby wave breaking events. Potential vorticity at an isentropic surface of 350 K from the ERA-Interim and ERA5 reanalyses are used. The results of applying the methods for the two reanalyses are similar. However, there is a high inconsistency for cyclonic wave breaking events, especially in summer. The maximum for both types of wave breaking is registered in summer. There are two main maximum areas for the AC type: Atlantic and Pacific. A specific feature of the C type is the climatic maximum in East Asia, probably due to the summer development of the East Asian monsoon. The intensity of the AC-type wave breaking for the entire Northern Hemisphere during the year demonstrates a positive trend. Seasonal changes of the AC type were also consistent for the two reanalyses, global changes are less consistent for cyclonic wave breakings, and significant trends are basically absent. The regional analysis revealed that the frequency of AC-type wave breaking in summer decreases over the Eastern Atlantic and increases over Europe. The agreed and possibly related changes in the AC and C types are recorded in the Asia-Pacific. In summer, there is a decrease in the C-type occurrence over East Asia and an increase in the AC-type occurrence over the Eastern Pacific. However, these changes were found only for the ERA-Interim and require further analysis and interpretation.

1. INTRODUCTION

The origin of the great number of large-scale weather-generating phenomena in the troposphere depends on the propagation and breaking of long Rossby waves [3, 5, 15, 18, 20, 40]. The authors [28, 29] gave the definition of the Rossby wave breaking (RWB), which occurs when cold advection in the eddy flow leads to the meridional breaking of potential vorticity (PV) contours, so that the meridional derivative of PV is negative. Depending on the direction of the inclination of the breaking PV contours, the Rossby wave breaking is divided into anticyclonic (AC) and cyclonic (C) types [26, 38]. The Rossby wave breaking occurs when PV fluxes are formed, with the poleward movement of air masses with low PV and the movement of air with high PV toward the equator [38]. For example, the Rossby wave breaking when the flow with low PV

moves to the pole and the west relative to the flow with high PV is classified as the AC-type breaking. The process when the flow with low PV moves to the pole and the east relative to the high-PV flow is classified as the C-type breaking. Two RWB types have different transport and mixing properties [30].

There are many patterns in the RWB processes, which have been explored to different extents. Potential vorticity observations [14, 16] show that the upper subtropical troposphere is the area of the most frequent Rossby wave breaking, similar to the "surf-zone" in the wintertime stratosphere mid-latitudes. As well as in the stratosphere, the tropospheric flow is very inhomogeneous here, with the wave-like type in immediate proximity to the wave breaking area, where the flow is highly nonlinear. The wave breaking has a close connection with the regimes and characteristics of jet streams. The jet stream regime is highly dependent on the relationship between two types of jet streams in the lower atmosphere: subtropical and mid-latitude ones. In addition to different latitudinal positions, these two jet stream types differ in the vertical structure, variability characteristics, and external forcing [21]. The subtropical jet is concentrated close to the subtropical boundary of the Hadley cell, it is relatively stable and largely caused by the transfer of the absolute angular momentum of the mean meridional circulation. The mid-latitude jet is located inside the Ferrel cell and is connected with mid-latitude storm tracks. This jet is formed mainly as a result of the baroclinic wave eddy momentum flux convergence. Both jets are characterized by the vertical wind shear associated with the low-level meridional temperature gradient, but the vertical shear and the temperature gradient are higher for the subtropical jet. Two types of jets can merge into one or can be split into two separate interacting jets, which launches complex processes [31, 35]. The strong jet in the upper troposphere near the subtropical boundary of the Hadley cell is observed in winter in both hemispheres. In the Northern Hemisphere winter, the jet stream has a pronounced longitudinal structure with two jets over the Atlantic Ocean and one jet over Asia and the Pacific Ocean. Nevertheless, in winter, the jet over the Pacific Ocean in the Northern Hemisphere, which is often called subtropical due to its latitudinal position, is partly generated and maintained by eddies. More precisely, it can be considered as a jet with thermal and eddy forcing [9, 22]. For summer, a very special feature is noted, the so called "northward jump" of the subtropical jet [23]. This is closely connected with an increase in the number of wave breaking and blocking events in summer [4, 6, 8, 39]. The approach based on the presentation of PV perturbations as normal modes in the models of atmospheric dynamics shows that the eddy length scale is the key parameter determining the pattern of wave breaking and feedback of eddies with the mean flow. Consequently, long waves break more often anticyclonically and short waves break cyclonically. When baroclinity in the upper tropospheric layers increases, long waves become more unstable and break anticyclonically, shifting the jet toward the pole.

Some studies [19, 34] showed that the humidity growth favors more frequent occurrence of cyclonic wave breaking as compared to anticyclonic one. The author of [32] explained this fact: latent heat emission increases the intensity of cyclones more than that of anticyclones, hence, more C-type events occur. Since the AC and C types shift the jet to the pole and equator [38], respectively, the increase in the number of C-type events will favor the jet displacement to the equator.

The authors of [37] for the first time provided the objective analysis of anticyclonic and cyclonic RWB types for the Northern Hemisphere in winter during 1958–2006. It was shown that the winter climatology of the frequency and size (zonal extent) of both RWB types at an isentropic surface of 350 K in the Northern Hemisphere and the spatial distribution of the RWB are consistent with theoretical concepts of the RWB in the shear flow. For example, according to [17], when Rossby waves propagate from the extratropical troposphere to the stratosphere, the main flow is the zonal averaged shear flow, which includes western winds alternating with eastern ones. Assuming that the main flow moves with a speed that is a function of latitude and the wave has a certain phase velocity, there is a place where the flow speed coincides with the wave phase velocity. This is a line called the critical line for the fixed value of latitude, and its neighborhood is called the critical layer where the RWB occurs.

The climatology and long-term variability of the RWB over the longest period were considered in [7, 15]. The authors of [7] rely on the variability of potential temperature on the dynamic tropopause (PV-θ) over the period of 1979–2011 based on the NCEP DOE Reanalysis 2 data. The authors of [15] investigated the variability based on potential vorticity at the levels between 320–380 K over the period of 1981–2015 using the MERRA-2 data. Seasonal features and average annual parameters were studied in both papers. To understand the potential of RWB identification methods, it is necessary to recall the basic regularities of intersecting isentropic surfaces and constant PV surfaces (Ertel potential vorticity field). The surface of 370 K basically intersects the constant PV surfaces approximating the tropopause of 2–4 PVU (potential vorticity unit) only in the tropics and does not cover the area of the subtropical jet. The surface of 330 K crosses the surfaces of 2–6 PVU only in the mid-latitudes and describes processes associated with the polar-front jet stream. The surface of 350 K crosses the dynamic tropopause in the transition area between the tropics and

mid-latitudes on the subtropical slope. The dynamic tropopause (2 PVU) intersects both surfaces of 330 and 350 K and, therefore, comprehensively captures processes in the subtropical and middle latitudes.

Paper [2] presents the overview of the key processes related to the Rossby wave breaking, as well as the method for their identification and clustering. The potential of applying this method for analyzing the climatology and long-term variability of the RWB number is also discussed there. The considerable development of reanalysis data allows full-fledged research in this area. The objective of the present paper is to investigate the Rossby wave breaking in the region of the subtropical tropopause which has a significant effect on the temperature and precipitation anomalies in Eurasia in summer, as its characterizes the advection of air masses from the tropics. Therefore, the variability of potential vorticity at the level of 350 K was chosen as the analyzed parameter [33]. Despite the advantages in the analysis of blocking formation, the value of PV-   insufficiently indicates specific features of the RWB in the transitional subtropical zone. A reason for such close attention was the situation with an increasing number of flash floods, heat waves, and wildfires [11, 36]. It is known that the irreversible deformation of the vorticity field accompanying the breaking may both provoke heavy precipitation due to the vertical mixing in the troposphere and be a reason for the set-in of the stable blocking anticyclone [20, 40]. In addition, the fact of northward displacement of the Hadley cell edge was revealed [15, 25], and the shift of the subtropical jet stream was noted in some papers [15]. Therefore, the detailed assessment of the RWB variability in the area of the subtropical jet is necessary. Moreover, as shown in [5], the change in the position of jet streams may lead to the change in the RWB type.

The objective of the study is the detailed analysis of climatology and long-term variability of Rossby wave breaking in the subtropical tropopause region. The analyzed period is longer than that used previously, from 1979 to 2018. The focus is not only on average annual and season features, but also on regional climatic manifestations of the RWB and variability for every month, which allows discussing a number of important issues.

2. DATA AND METHODS

The calculation of climatology and long-term variability of Rossby wave breaking was based on the results obtained in [2] and previously presented for the ERA-Interim reanalysis data as longitude-time diagrams (available at http://sibnigmi.ru/RWB/RU/RWB_long-term_1979-2019/). The annual, seasonal (calendar), and monthly values were analyzed. In addition to the ERA-Interim (EI), we provide the results of calculations based on the ERA5 (E5) reanalysis for 1979–2018 [12], which was developed to substitute the ERA-Interim available for the period until August 2019.

In 2021, the European Centre for Medium-range Weather Forecasts (ECMWF) published the preliminary version of the E5 dataset for the period of 1950 to 1978 containing data at isentropic surfaces and equal vorticity surfaces [10]. At this stage, these data are not used for obtaining an estimation of long-term RWB variability, since there is a certain inhomogeneity in the series of primary breakings which was composed of two E5 series (the graph is not presented). However, calculations were performed to analyze the daily variability of the RWB based on the E5 over the whole available period of 1950–2020. They may be useful in the synoptic analysis of blocking and are also available (https://bit.ly/3i8d1GC). However, it should be emphasized that the ERA5 version for 1950–1978 is currently preliminary (https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5).

The analysis of long-term variability of the RWB parameters was based on the following approach. First of all, global changes were estimated for cyclonic and anticyclonic RWB types. Let us briefly recall the main stages of reanalysis data processing from [2]. For the EI and E5 data, at first the procedure was carried out for identifying primary breakings by the PV levels from 0.3 to 9.8 PVU with a step of 0.5 PVU at the PV-   surface of 350 K for 12:00 UTC. Then, they were grouped and filtered, and the centers interpolated to the regular 0.75 grid were found for the groups of events. Thus, the coordinates and characteristics of the number of involved PVU breaking levels and total area of breaking zones were obtained for the subsequent analysis for each time of initial data. Due to the considerable spatial compression of information at the stage of clustering, a relatively small number of values turned out to be at the grid points. This subsequently led to some nuances in calculations based on the regular grid. Let us consider this in more detail.

For analyzing the climatology, the sum of breaking levels was calculated for each grid point and was normalized with respect to the point with the maximum sum (to ensure that the resulting frequency maps are representative for the Northern Hemisphere analysis). This procedure was executed both for the entire observation series and separately for the seasonal and monthly samples. In addition, the aggregation over the sectors equal to 45 of longitude was performed to evaluate the real values of the RWB frequency of
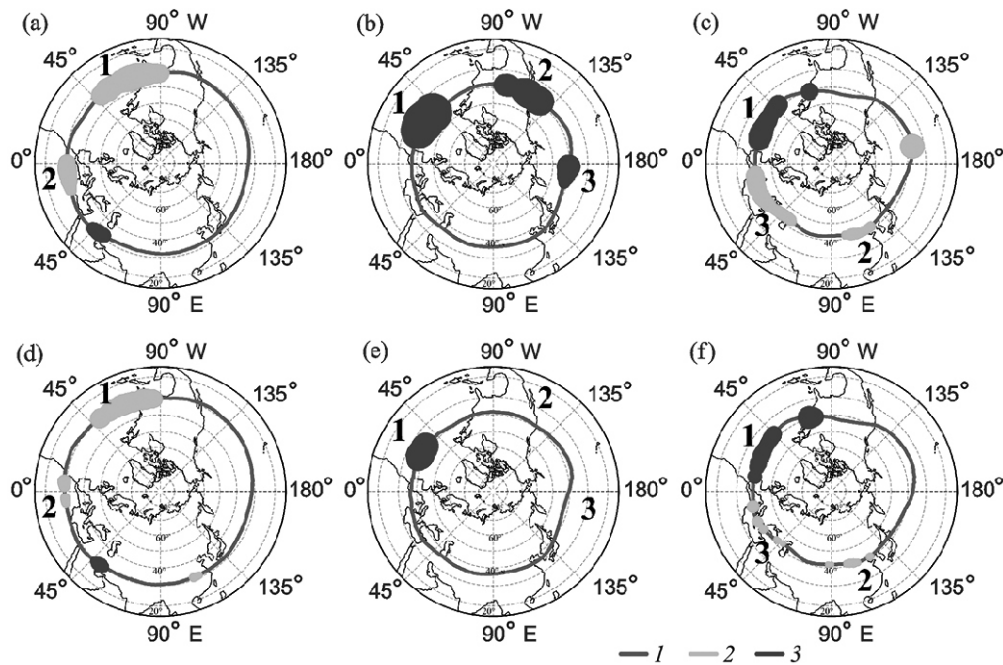
Fig. 1. (*1*) The mean position of the area of 2–6 PVU, (*2*) the significant (*p* = 0.05) expansion, (*3*) the narrowing, the width reflects a degree of the trend slope coefficient in (a, d) April, (b, e) October, and (c, f) summer for (a–c) the ERA-Interim and (d–f) ERA5 reanalyses. The areas of trend changes for calculations have the following borders: in April: (1) 45 – 95 W, (2) 5 W–22 E; in October: (1) 17 –45 W, (2) 93 –132 W, (3) 160 E–177 W; in summer: (1) 2 –61 E, (2) 12 – 53 W, (3) 82 –127 E. The article with colored figures is available at the site http://link.springer.com.

occurrence. Note that it is difficult to calculate the real frequency on the grid due to the data compression to the grid points as a result of clustering.

The variability was assessed for the entire Northern Hemisphere and for individual sectors with the maximum RWB frequency. For this purpose, various spatial aggregations were carried out using the data on the number of breaking levels situated at the grid points. When selecting sectors for the regional estimation of the breaking parameters variability, the authors relied on the potential vortex properties. The Rossby wave evolution depends on the PV gradient. When the meridional PV gradient is low, high-amplitude Rossby waves can break, leading to the mixing of PV in longitude in the limited area of the wave breaking. The RWB is manifested as a large-scale and irreversible breaking of PV contours at isentropic surfaces [27]. It may be assumed from general considerations that the areas of vorticity lines where breakings most often occur, are on average wider than the areas with no breakings. Therefore, the authors analyzed trends in the thickness of the PV contour of the area of 2–6 PVU for the level of 350 K. The trends were computed for monthly mean values of the meridional difference between the coordinates of the field of vorticity of 2 and 6 PVU for each longitude point with a step of 0.75 . This procedure was executed for the both datasets. Figure 1 presents the results for April, the entire summer, and October, and other results can be found in the web version (https://bit.ly/3zD74av). The areas of significant changes were selected proceeding from the following criteria. Firstly, the area should be larger than or equal to 15 of longitude; secondly, the areas with a break of less than or equal to 5 were united into one zone. Even if the modified area was detected only from one dataset (which rarely occurred), the variability of breakings in this area was assessed for the both reanalyses (Figs. 1b and 1e).

3. RESULTS AND DISCUSSION

3.1. Climatology of Breakings

Table 1 presents the total number of breakings for the seasons and the whole year. It is clear that the number of the detected AC-type RWBs almost does not differ for the analyzed reanalyses, and their annual sums almost coincide. The number of C-type breakings according to the ERA5 and ERA-Interim differs more significantly (on average by 1.5 times).

Table 1. The total number of anticyclonic and cyclonic Rossby wave breakings according to the ERA5 and ERA-Interim reanalyses

Season	AC type		C type	
	E5	EI	E5	EI
Winter	3013	3142	413	617
Spring	3798	3896	558	977
Summer	9129	8934	2279	2995
Autumn	6783	6677	1320	1758
Total	22723	22649	4570	6347

Figure 2 presents the RWB frequency of occurrence for the seasons, the full version is available at https://bit.ly/3AGoKUj. Not the absolute frequency at each grid point but the frequency relative to the maximum grid point is presented, which is necessary for illustrating the areas of maximum frequency. The absolute frequency is represented by the numbers for the 45 sectors. Only data for the E5 dataset are given for the AC-type RWBs, as a good consistency with the EI data was generally revealed. For the C type, both results are provided to show the areas and seasons for which the differences are maximal.

In general, the presented distributions agree with the conclusions made in [7, 15], but there are some differences. For the anticyclonic breakings, the areas with maximum frequency are situated over the North Atlantic and North Pacific. Over the Atlantic Ocean, except for the summer, the zone of the maximum is shifted to the eastern regions. Over the Pacific Ocean, the areas of the maximum are more manifested in summer. The local maximum detected [15] in the area of the Sea of Okhotsk in summer is fuzzier in our distributions. For the cyclonic breakings, there is the maximum in the area of northern East Asia in all studies, including out distributions, which is probably caused by the monsoon development in summer. Our distributions, as well as the distributions in [15] point out the maximum of cyclonic RWBs in summer as compared to the other seasons. On the contrary, in paper [7] the maximum RWB was found for the winter, which is probably associated with specific features of the PV- data. The authors explain this by the shift of the baroclinity zone toward the equator. Unfortunately, paper [15] does not present data for the transition seasons, therefore, their comparative analysis is difficult.

According to the EI, the frequency of C-type breakings in all seasons is higher than according to the E5. For winter, the area of maximum differences is situated in the Eastern Pacific off the western coast of North America. In spring, the zone of maximum differences is located over North America. For summer and autumn in most of the Northern Hemisphere, the RWB frequency is lower according to the E5. Especially significant differences (almost two-fold) can be seen in East Asia, in the sector of 90 –135 E. The revelation of reasons for the above differences goes beyond the scope of the present research and will be considered in future studies. The working hypothesis explains this by the general difficulty in determining geometry of C-type breakings during the period of maximum cyclone activity over the continents, especially over Eurasia.

3.2. Variability of Rossby Wave Breaking Parameters

Global changes. Figure 3 shows the annual characteristics of the RWB parameters for the entire Northern Hemisphere which take into account the number of days with the RWB and the number of PV levels involved in the breaking (similar to the longitude-time diagrams (http://sibnigmi.ru/RWB/RU/RWB_long-term_1979-2019/) but with summing over longitudes) according to the considered reanalyses. Data of the two datasets on the AC-type breaking intensity are consistent and demonstrate a significant reliable positive trend. This agrees with the results of [15], but the trend detected in the present study is more pronounced. The authors of [15] also discussed a possible impact of climate warming on the displacement of high- and mid-latitude jets toward the pole, which may affect an increase in the AC-type RWB frequency and a decrease in the C-type RWB frequency.

The parameters of cyclonic breakings are less consistent for the two datasets, and the reliable negative trend component can be seen only for the ERA-Interim.

All seasonal and monthly graphs are available at https://bit.ly/39zD5WD. Let us consider only significant changes (the confidence is >80%, such level is caused by the fact that the analyzed characteristic is a
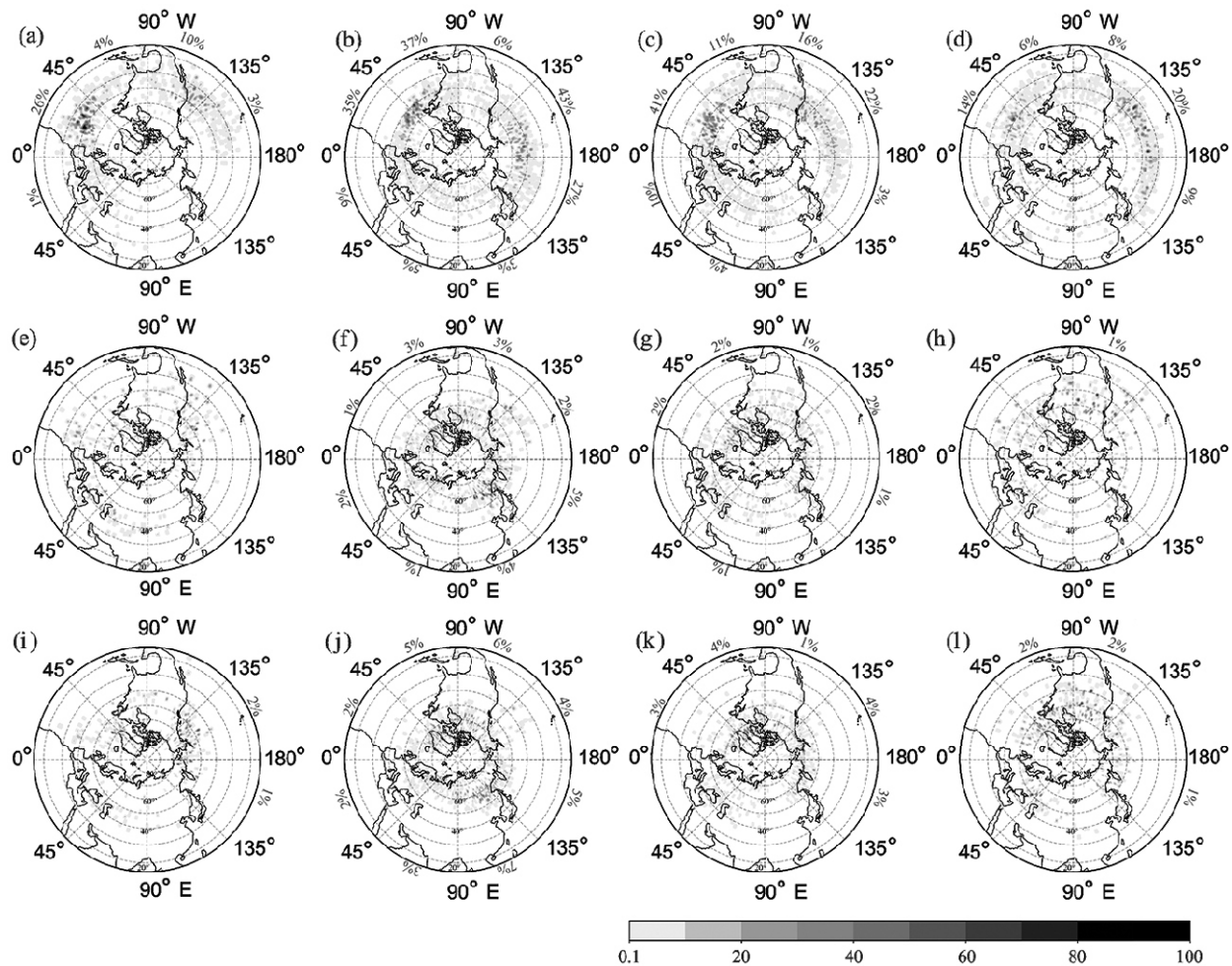
Fig. 2. The distribution of the Rossby wave breaking frequency (seasonal total) relative to the maximum zone in the Northern Hemisphere: (a–d) AC type according to the ERA-Interim, (e–l) C type according to the (e–h) ERA5 and (i–l) ERA-Interim. (a, e, i) Winter; (b, f, j) summer; (c, g, k) autumn; (d, h, l) spring. The intensity of the color of the zone characterizes the total number of united breaking events at each grid point, the number of events was normalized relative to the point with the maximum number of cases per season. The numerals show the values of the absolute frequency for the 45 sectors.

priori characterized by high variability). Seasonal changes in the AC-type RWB parameters are also consistent like annual ones for the two reanalyses, the positive reliable trend (the significance is >90%) was found for all seasons except autumn. For cyclonic breakings, changes are also less consistent: according to the EI, there is a negative trend for all seasons except autumn; according to the E5, a significant negative trend is typical of winter only. For the AC-type RWB, the maximum growth is observed in January–May and July according to the EI and except February and May for the E5. For the C-type RWB, due to higher variability typical of separate months, there are almost no significant trends, significant negative variations are typical of December only. For the cyclonic breaking, there is a high inconsistency between the reanalyses: for example, for July, the negative insignificant trend (79% of values) was observed for the EI data, while the positive and significant trend (86%) was obtained for the E5. As noted above, geometry of the C-type RWB is more complex, and the issue of the resulting differences for the C type should be analyzed separately.

Taking into account a pronounced increase in the frequency of the AC-type RWB, let us show which regions contain extreme cases for this type (for the C type, such search was not performed due to the inconsistency of the reanalyses). The resulting graphs are available at https://bit.ly/3uasfje. According to Fig. 2, the Atlantic and Pacific zones were distinguished when the maxima for the seasons were divided into zonal sectors. It should be noted that the reliability of the trends is slightly lower than for the RWB summed over the entire Northern Hemisphere. This is associated with the occurrence of large variance due to the increase in interannual variability. For winter, the most consistent changes were recorded for the Atlantic sector, the
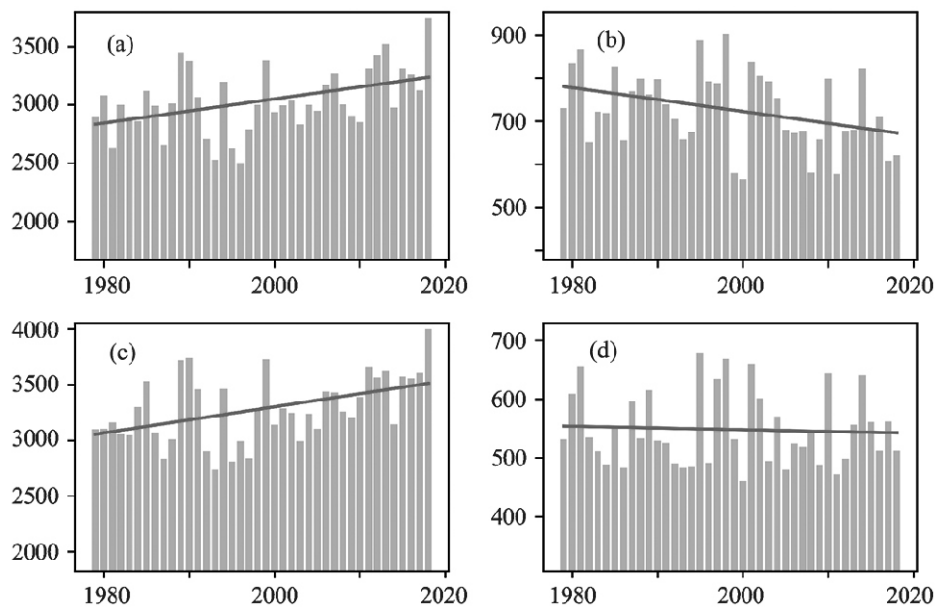
Fig. 3. The variability of the annual number of breaking events taking into account the number of days and involved level of (a, c) AC- and (b, d) C-type breaking for the Northern Hemisphere based on two reanalyses: (a, b) ERA-Interim and (c, d) ERA5. (a) Trend Tr = 10.35, the trend significance $p = 0.005$; (b) Tr = -2.76, $p = 0.022$; (c) Tr = 11.73, $p = 0.003$; (d) Tr = -0.30, $p = 0.732$.

positive trend with the maximum confidence is typical of the E5. In July, on the contrary, the maximum changes are registered in the Pacific zone, the positive trend is consistent for the two datasets, and the maximum reliability is typical of the EI. The frequency of AC-type breakings in the Atlantic zone based on the EI confidently decreases but remains invariable according to the E5. The spring period stands out due to the fact that positive significant changes in the AC-type RWB frequency are typical of the both zones and were found in the both datasets. No significant changes are observed for autumn, which is quite natural. The changes found for the spring season are consistent with those from [7].

Regional changes. Let us proceed to more detailed regional analysis of maximum changes in the area of 2–6 PVU associated with the subtropical jet stream. The most reliable changes were obtained for the AC-type RWB (the full version is available at https://bit.ly/3ETlabR). Over the Western Atlantic, a positive trend in the RWB number was found in April according to the EI. Over Europe, a reliable increase in the RWB frequency occurs in May according to the EI. A pronounced but statistically insignificant (due to variance) decrease in the AC-type RWB frequency is observed over the Eastern Atlantic in June. An increase in the frequency in July was recorded over the Central Pacific, also only according to the EI. Despite the decreasing thickness of the zone of maximum vorticity over the Eastern Atlantic, there is an increase in the RWB number here in July for the both reanalyses. An increase in the RWB number was detected over Europe in August according to the both datasets. Despite a general growth of the RWB number in winter, their confident decrease was found over North America in December. In September and October, the RWB number over the Eastern Pacific decreases according to the both datasets. According to the E5, there is an increase in the RWB number over the Central Pacific in November. Over Eurasia, a decrease in the thickness of vorticity lines and in the RWB number was registered in December. However, taking into account insignificance of the breaking processes there in the subtropical jet in winter, the prediction that the jet stream area in December becomes less disturbed, is more reliable.

The most significant changes were obtained for the whole summer season. On average for the summer for the both datasets, there is a confident increase in the RWB number over Europe and a decrease over the Eastern Atlantic (Figs. 4a and 4b), the E5 data with the most significant trends are given. This is consistent with the results of most studies of changes in blocking events in the Euro-Atlantic sector [24]. For the C-type events, the number of reliable results, as well as of breakings of this type is much smaller. According to the both reanalyses, there is a summertime decrease in the cyclonic RWBs over the Eastern Atlantic, but their number in July grows according to the EI. In summer, the number of the C-type RWBs also considerably decreases over East Asia, especially in July, but only according to the EI (Fig. 4c). This trend coincides with the trend towards an increase in the RWB number over the Western Pacific, which is observed
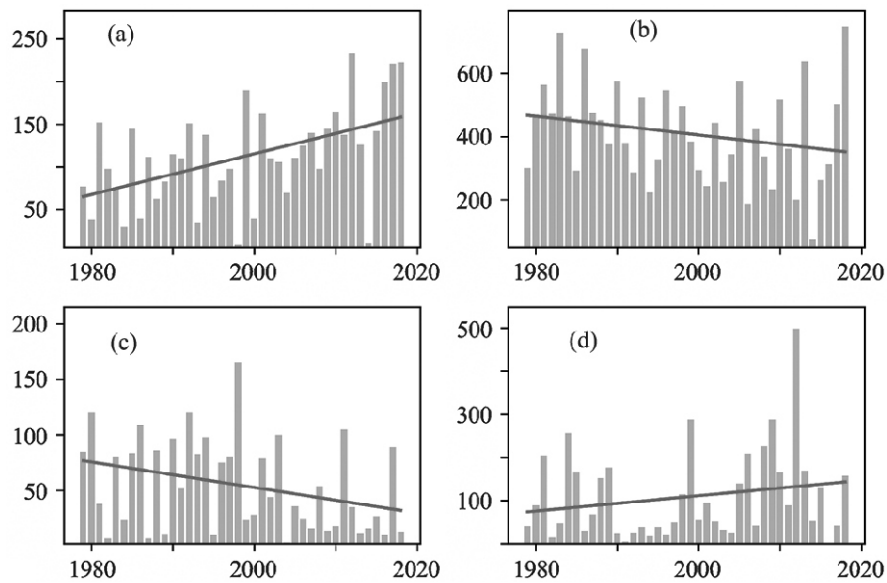
Fig. 4. The change in the number of AC-type Rossby wave breakings in summer over (a) Europe, (b) the Atlantic and (d) Pacific oceans, as well as (c) in the number of C-type breakings over East Asia according to the (a, b) ERA5 and (c, d) ERA-Interim. (a) Tr = 2.38, p = 0.001; (b) Tr = –2.96, p = 0.164; (c) Tr = –1.15, p = 0.042; (d) Tr = 1.78, p = 0.212.

both for July (according to the changes in the vorticity zone thickness) and the whole summer (Fig. 4d). In November, an interesting tendency was found over Europe: until the late 1990s, the cyclonic RWBs were absent here, but since the early 2000s their frequency has become noticeable, this feature is confirmed by the both reanalyses.

To conclude the regional analysis, the authors note that in some cases it would be correct to consider switching between the regimes with higher and lower RWB frequencies and their physical prerequisites rather than trends. The same conclusion was made by the authors of [1], who analyzed regional changes in the number of blocking events in Western Siberia.

4. CONCLUSIONS

Based on the method for identifying and clustering Rossby wave breaking events presented in [2], the climatology and variability of anticyclonic (AC-type) and cyclonic (C-type) breaking in the subtropical jet stream region are investigated. For this purpose, data on potential vorticity at the 350 K isentropic surface from the ERA-Interim and ERA5 reanalyses for 1979–2018 with a resolution of 0.75 were used. In general, the results of applying the methods for the two datasets are consistent, but there is great uncertainty for cyclonic breakings, especially on a regional scale during the periods of maximum RWB frequency (summer, autumn). The pattern of cyclonic breaking for the analyzed reanalyses needs further detailed investigation on a synoptic level.

The obtained long-term RWB variability is generally consistent with the results of the published studies. For the AC type in all seasons except autumn, two main zones of the maxima prevail: Atlantic and Pacific. During the year, only the position of the centers of these zones changes, the maximum is observed in summer. A more complex and less consistent distribution as compared to the previous studies has a frequency of C-type breaking. Its maximum is also observed in summer, the zones of maximum C-type RWB frequency are shifted to the north relative to the AC-type RWB centers. One of the key features, in our opinion, is the climatic maximum frequency of C-type RWB in East Asia, which is probably caused by the summer monsoon development in East Asia.

The intensity of AC-type breaking for the entire Northern Hemisphere is in good agreement for the two datasets and demonstrates a significant reliable positive trend. This is consistent with the data obtained in [15], but the trend found in the present study is more pronounced. Cyclonic RWBs are less consistent according to the two reanalyses, and only the ERA-Interim shows a significant negative trend component. This is due to the general difficulty of determining geometry of the C-type RWB during the period of maximum cyclone activity over the continents, especially over Eurasia.

We analyzed the variability of the regions for which changes in the frequency of Rossby wave breaking and in the thickness of the vorticity zone between the lines of 2–6 PVU are observed. In the Euro-Atlantic sector in summer, the frequency of AC-type breaking decreases over the Eastern Atlantic and increases over Europe. Together with the growth of the RWBs of the same type in May, an unfavorable situation is developing in Europe with an increased frequency of blocking events and number of severe weather events associated with heat waves and precipitation. The consistent and possibly related changes in the AC- and C-type RWB parameters were found in the Asia-Pacific. In summer, there is a decrease in the number of C-type breakings over East Asia and an increase in the number of AC-type breakings over the Eastern Pacific. A decrease in C-type frequency without significant changes in AC-type occurrence in East Asia probably explains significant changes in the thickness of the mean vorticity area. However, these changes were detected only for the ERA-Interim reanalysis and require further analysis.

FUNDING

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