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Atmospheric rivers as an indicator of circulation variability: between the Atlantic and the Black Sea region

Oleksandr Shcheglov¹,  <https://orcid.org/0000-0001-5702-6285>, e-mail: shcheglov@uhmi.org.ua

PhD (Geography), Senior Researcher

Vitalii Shpyg¹,  <https://orcid.org/0000-0003-1055-7120>, e-mail: vitold82@i.ua

PhD (Geography), Head of the Department of Atmospheric Physics

Nikita Fomichev²,  <https://orcid.org/0009-0004-2246-2326>, e-mail: nikitaformich2002@gmail.com

Student, Department of Meteorology and Climatology

Ivan Dudarenko²,  <https://orcid.org/0009-0000-0766-3622>, e-mail: dudarenkoivan18@gmail.com

Student, Department of Meteorology and Climatology

¹ Ukrainian Hydrometeorological Institute of the State Emergency Service of Ukraine and the National Academy of Sciences of Ukraine, Kyiv, Ukraine

² Taras Shevchenko National University of Kyiv, Kyiv, Ukraine

ABSTRACT

Introduction. Atmospheric rivers (ARs) are a key mechanism of water vapour transport in the mid-latitudes, shaping precipitation regimes in many coastal regions of the world. Their impact on Western Europe is well studied; however, the role of ARs in Eastern Europe and their relationship with large-scale circulation regimes remain insufficiently explored.

The purpose of the study. The aim of this study is to identify statistical relationships between the frequency of atmospheric rivers in the Atlantic–European sector and the main circulation indices, as well as to analyse the potential responses of these phenomena in Eastern Europe.

The research methodology. The methodology is based on the use of the AR Reanalysis Databases V3.0 (Guan, 2021), where the identification of atmospheric rivers was carried out following the approach of Guan & Waliser (2019), taking into account integrated water vapour transport (IVT). For the correlation analysis, the ERA-Interim–based dataset (1.5° × 1.5°) was employed; circulation indices (NAO, PE, EA/WR, SCAND) were obtained from CPC; and monthly precipitation totals were taken from the ClimUAd database (0.1° × 0.1°). These data were used to calculate correlation relationships and to construct maps.

Research results. Atmospheric rivers (ARs) in the Atlantic–European sector exhibit a distinct seasonality: their frequency peaks in winter and reaches a minimum in summer, with a pronounced impact on precipitation in Eastern Europe, particularly in the Carpathians and the Black Sea region. Statistically significant correlations between AR frequency and circulation indices (NAO, SCAND, EA/WR, PE) confirm the role of large-scale atmospheric dynamics in shaping AR trajectories.

The novelty of the developments. This study proposes to consider atmospheric rivers as manifestations of large-scale atmospheric circulation dynamics. Unlike most research that focuses on the direct AR effects in Western Europe, this work is the first to highlight the potential responses of atmospheric rivers in Eastern Europe, particularly along the northern coast of the Black Sea. For the first time, a correlation analysis between AR frequency and circulation indices (NAO, EA/WR, PE, SCAND) is conducted, along with an assessment of their influence on the region's monthly precipitation.

Practical significance. The results of this study can be applied to improve the understanding of atmospheric circulation as a driver of regional hydrometeorological anomalies. Identifying the potential impact of ARs on precipitation and cloudiness in Eastern Europe will enhance methods for long-term forecasting of the water balance and extreme weather events. This is of particular value for regions sensitive to precipitation deficits or sudden heavy rainfall, especially in the contexts of agriculture, water resource management, and risk management.

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Introduction

Atmospheric rivers (ARs) are narrow corridors (tens to hundreds of kilometres wide) of intense water vapour transport that play a key role in meridional moisture exchange and act as important triggers of extreme precipitation and strong wind events in coastal regions [34]. ARs transport a substantial portion of water vapour from the tropics toward the poles in the mid-latitudes, and they are a critical component of the global water cycle and the atmospheric energy balance. Certain coastal regions—for example, Western Europe, California, Chile, and the Caucasus—exhibit strong dependence on ARs in terms of moisture regimes and precipitation patterns [15, 19, 20, 22], as well as in shaping the state of the upper ocean layers in coastal zones [32]. ARs often enhance heavy precipitation, particularly on windward mountain slopes, i.e. through the orographic effect [7]. They also influence soil moisture recharge, mountain snow accumulation, and the corresponding river runoff regime [15, 28, 35]. For instance, the study [17] emphasise that ARs are a key driver of extreme precipitation and the mass balance of the Antarctic ice sheet.

Analysis of recent research. There are several approaches to identifying ARs, which are based on the calculation of specific indicators (IVT, IWV, VIMFC). The methodology and description of the formation features of this phenomenon are provided in [8, 28, 37]. Accurate information on AR dynamics has been obtained through field observations, particularly aircraft campaigns [26, 27]. Developed AR detection algorithms have enabled researchers to generate ready-to-use AR catalogues, such as [6]. For several regions, the relationship between ARs and precipitation is well documented [2, 13, 16, 19]. Precipitation is the key manifestation of ARs during their landfall or when crossing orographic barriers. ARs account for over 90% of the horizontal water vapour transport from the tropics to the mid-latitudes [8]. The large water vapour content concentrated in ARs creates highly favourable conditions for precipitation if uplift occurs (e.g., frontal zones or mountain ranges). ARs do not directly cause precipitation but act as a moisture supplier to frontal zones (warm fronts), cyclones, and their warm conveyor belts [3]. According to [35], about 80% of AR events in their dataset were associated with extratropical cyclones. ARs can also trigger stratiform precipitation events in areas of strong convection under local instability. For example, in [5] it is concluded that future research requires higher spatial resolution data (a few kilometres) and modelling of a larger number of cases to gain a deeper understanding of these processes. It is noted that ARs may occur under favourable conditions for the concurrent development of smaller-scale convective

phenomena (structures of the “AR rapids” type), which are evident in vertical cross-sections with a temporal resolution of 30 minutes and horizontal scales of 5–7 km. Given the importance of ARs in the climate system, their response to climate change is of particular interest. High internal variability driven by synoptic storms remains the main source undermining the predictability of extreme ARs [23]. It is also important to emphasise that different AR detection algorithms, data assimilation inhomogeneities, and other discrepancies among reanalyses (MERRA-2, ERA5, JRA-55) affect the results and the reliability of detected trends in AR changes and precipitation linkages, especially over land [10, 25]. Studies assessing future climate change suggest that ARs will become more frequent and intense under global warming [4, 14, 18, 24, 32, 35]. According to climate model analysis [35], future extreme ARs are generally expected to be associated with weaker storm systems, to be positioned farther from the centres of extratropical cyclones, and to develop less dependently on storm dynamics due to increased moisture supply under warmer conditions. Moreover, ARs have a more pronounced and longer-lasting impact on atmospheric moisture increases in the Arctic than the event duration itself, and this effect can be quantitatively distinguished from overall humidity changes [36]. Attempts to investigate AR impacts on more continental regions have yielded interesting results. For instance, [33] showed that ARs influence not only western coastal areas but also far inland. According to this study, under climate warming, ARs are projected to intensify and occur more frequently, with their landfall zones shifting northward, making these findings particularly relevant for precipitation forecasting and extreme-event risk assessment.

Unresolved aspects of the problem. While their role along the Western European coast is well documented (a detailed review of the issue is provided in [29]), much less attention has been given to the impact of ARs in the inland parts of the Atlantic–European sector, particularly in Eastern Europe [30]. According to available results, ARs were present in many cases of heavy precipitation in the northwestern region of the country; however, a considerable proportion of extreme precipitation events were not associated with ARs. Although the frequency of ARs in Eastern Europe, and specifically in the Black Sea region, is not as high as on the Western European coast, the Eastern Mediterranean and the Black Sea themselves act as substantial moisture sources, partly offsetting the general decline in AR occurrence with distance from the ocean. The relationship between AR frequency and large-scale circulation regimes, which control the trajectories and intensity of atmospheric moisture transport, also requires further clarification. In this article, we attempt to view ARs as manifestations of

large-scale atmospheric circulation mechanisms. To this end, we analyse how the frequency of AR events is related to circulation indices in the Atlantic–European sector (NAO, PE, EA/WR, SCAND), and we also investigate whether there are any detectable responses to ARs on the periphery of this sector, in Eastern Europe—particularly in terms of monthly precipitation over Ukraine.

Purpose of the article. The aim of this study is to identify statistical relationships between the frequency of atmospheric rivers in the Atlantic–European sector and the main circulation indices (NAO, PE, EA/WR, SCAND), as well as to analyse the responses of ARs in terms of precipitation over the territory of Ukraine.

Methodology and data. To determine the frequency of atmospheric rivers, we used the AR Reanalysis Databases V3.0 [6]. The AR identification methodology [9] is based on integrated vapour transport (IVT). The IVT index accounts for both the meridional and zonal components of air and moisture transport. In the catalogue, an AR is recorded if the following conditions are met: a) IVT exceeds the 85th percentile and is not less than $100 \text{ kg m}^{-1} \text{ s}^{-1}$; b) the orientation of the flow in the region of the specified IVT values deviates

by no more than 45° from the northward direction; c) the length of the AR is at least twice its width. For this study, we used the version of the database based on the ERA-Interim reanalysis, which has a spatial resolution of $1.5^\circ \times 1.5^\circ$. In the NetCDF file structure, the variable "shape" was employed to determine the spatial coverage of ARs. Data on the circulation indices NAO, PE, EA/WR, and SCAND [1, 11], calculated by the Climate Prediction Center, were obtained from [12]. We computed Pearson correlations between circulation indices and AR frequency at each grid point on a monthly timescale. To assess the correlation between AR frequency and monthly precipitation in Ukraine, we used the ClimUAd database with a spatial resolution of $0.1^\circ \times 0.1^\circ$ [21]. For visualisation, maps were generated using Python libraries.

Results

The frequency and trajectories of ARs potentially shape the seasonal and interannual structure of atmospheric moisture: changes in AR frequency or shifts in their pathways may lead to moisture redistribution across regions or to its deficit. To better understand the seasonal

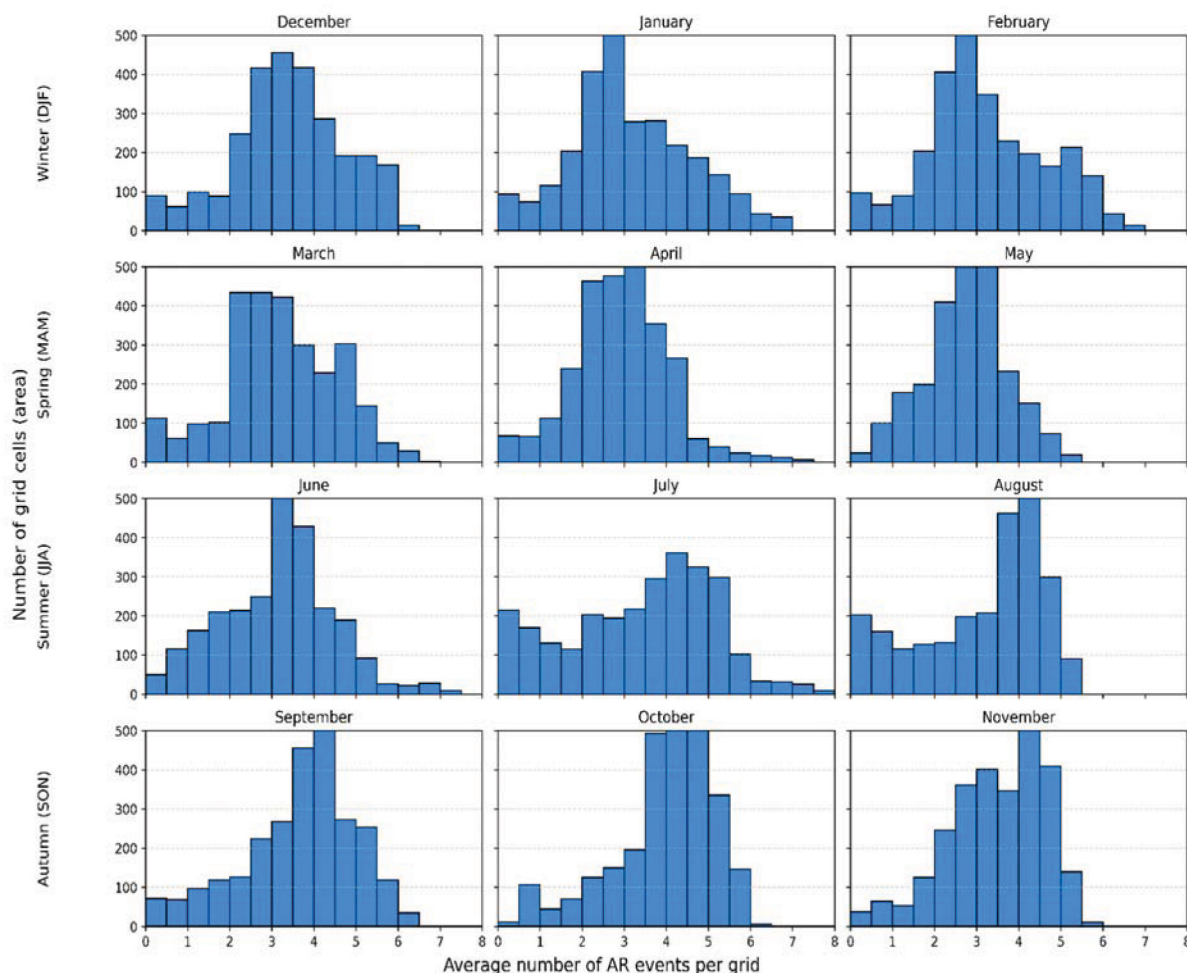


Fig. 1. Seasonal histograms of the mean monthly number of AR events per grid over the Atlantic–European sector ($30\text{--}80^\circ\text{N}$, $50^\circ\text{W--}70^\circ\text{E}$), 1990–2019

characteristics of AR occurrence in the Atlantic–European sector, we analysed the distribution of AR event frequency by month for the period 1990–2019. For this purpose, histograms were constructed to illustrate the spatial variability of AR counts at individual grid points within each month of the year. This approach makes it possible to identify not only the general seasonal trends but also the spatial heterogeneity and potential “hotspots” of AR activity throughout the year. Figure 1 presents histograms of AR event frequency in the Atlantic–European sector within 30°–80° N and 50° W–70° E, by month, for the years 1990–2019. In the histograms, the X-axis represents the mean number of AR events during a month, while the Y-axis shows the number of grid points (pixels/stations/cells) where AR events were observed within that month (corresponding to the value on the X-axis).

The winter months (December–January) are characterised by the highest number of grid with an average of 2–4 AR events per month (see Fig. 1). The distribution exhibits a long right-hand tail (up to 6–7 events), indicating the presence of individual locations with very high AR frequency (e.g., the

western coast of Europe or the Atlantic sector). The winter period corresponds to the peak of westerly transport activity in Europe, which also represents the main season of AR activity in the region. It should be noted, however, that the greatest recurrence of AR events occurs over the Atlantic Ocean.

In spring (March–May), the peaks remain fairly pronounced. The same mean values of about 3–4 ARs per month dominate, but March shows a leftward shift, whereas May tends toward a right-hand tail. Compared to winter, fewer grid cells exceed 4 ARs per month.

In summer, the maximum shifts slightly to the right (4–5 events per month), with August showing the most “right-skewed” distribution, reflecting higher AR intensity in some grid cells. Despite this shift toward more frequent AR occurrence in certain areas, extensive regions record fewer than 3 ARs per month. In practice, this is explained by the much lower incidence of ARs over the southern part of the continent (including the Mediterranean) during summer, while the main activity is concentrated in the north.

In autumn, a transition is observed from a left-skewed distribution in September to more right-

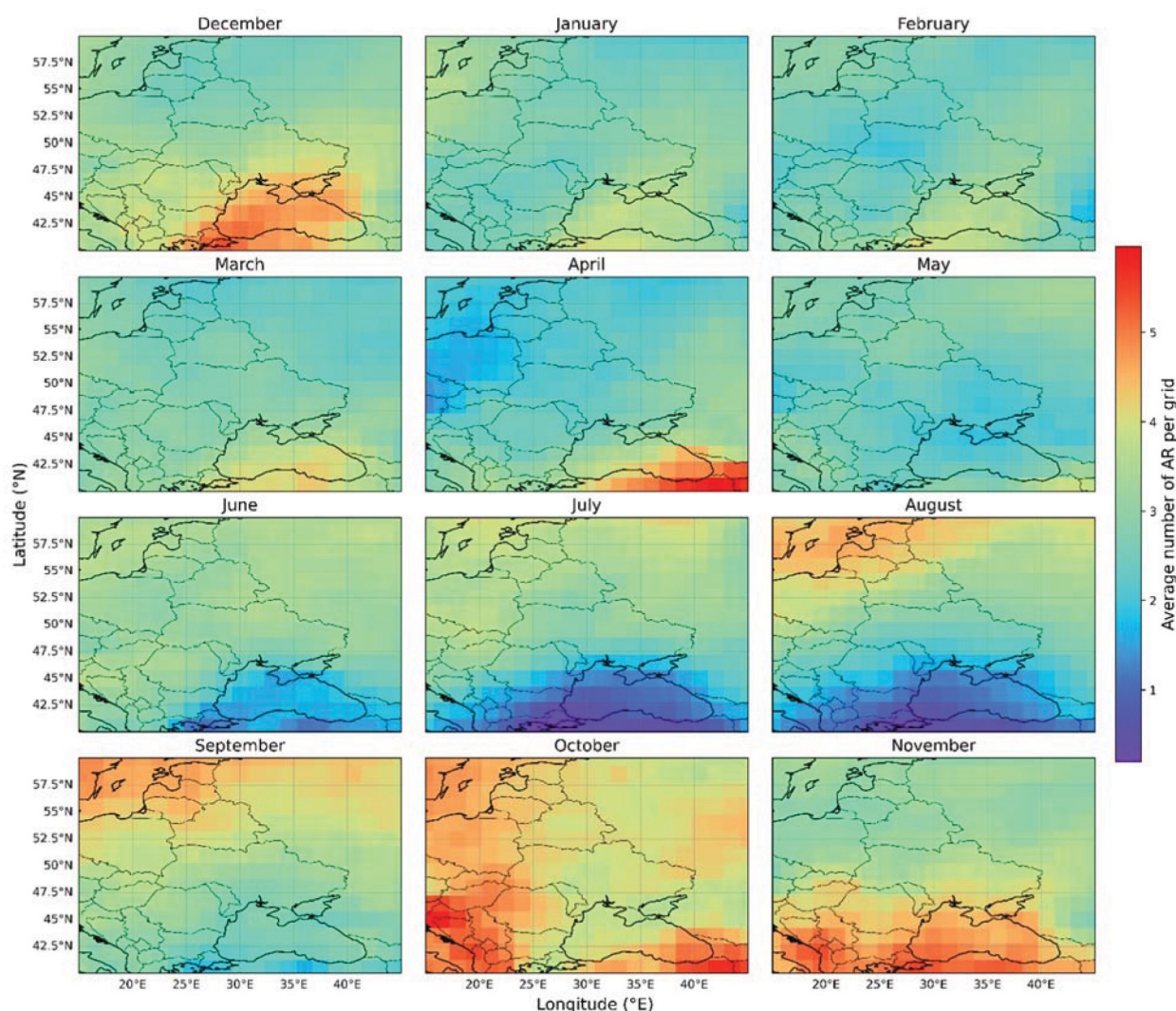


Fig. 2. Average monthly number of days with AR events in the Eastern Europe

skewed ones in October–November, indicating an increasing number of grid cells with elevated AR counts. Autumn is the period of most active AR occurrence over southwestern and central continental Europe.

Thus, atmospheric rivers in the Atlantic–European sector exhibit a clearly defined seasonality: their activity peaks in winter (December–February), while the lowest number of events is recorded in summer (July–August). Spring and autumn serve as transitional phases, with activity gradually intensifying in autumn, particularly in November. Spatial distribution is also heterogeneous: in winter, the long-tailed distribution indicates the existence of localised zones with high AR frequency.

Before examining the relationship between AR frequency in Eastern Europe, it is important to identify regional differences in AR occurrence frequency across the sector (Fig. 2). Spring–summer (April–August). During these months, a general decrease in AR frequency is observed across the entire region. The minimum values occur in June and July, when blue shades (1–3 AR days per month) dominate throughout, with the lowest frequencies

in the southern areas (southern Ukraine and the Black Sea coast). In August, a north–south gradient emerges, with higher AR frequency in the north (e.g., in the Baltic countries up to 4–5 ARs per month).

Autumn–winter (September–March) is the period of highest AR frequency, with maxima over southern Ukraine and the Black Sea coast. December and October are particularly pronounced, showing maxima exceeding 4–5 ARs per month in some areas. In November, AR frequency is moderate across most of the territory, with local maxima in the south. In January and February, AR frequency gradually decreases compared to December, though the spatial pattern of maxima over the southeast remains.

Transitional months (March, September). In March, frequency is similar to January–February but somewhat more evenly distributed, with a decline in the north. In September, a transition toward the autumn maximum is observed, with increasing AR frequency over central and southern Ukraine.

In summary, the southern part (Black Sea region) maintains a more stable maximum during the cold

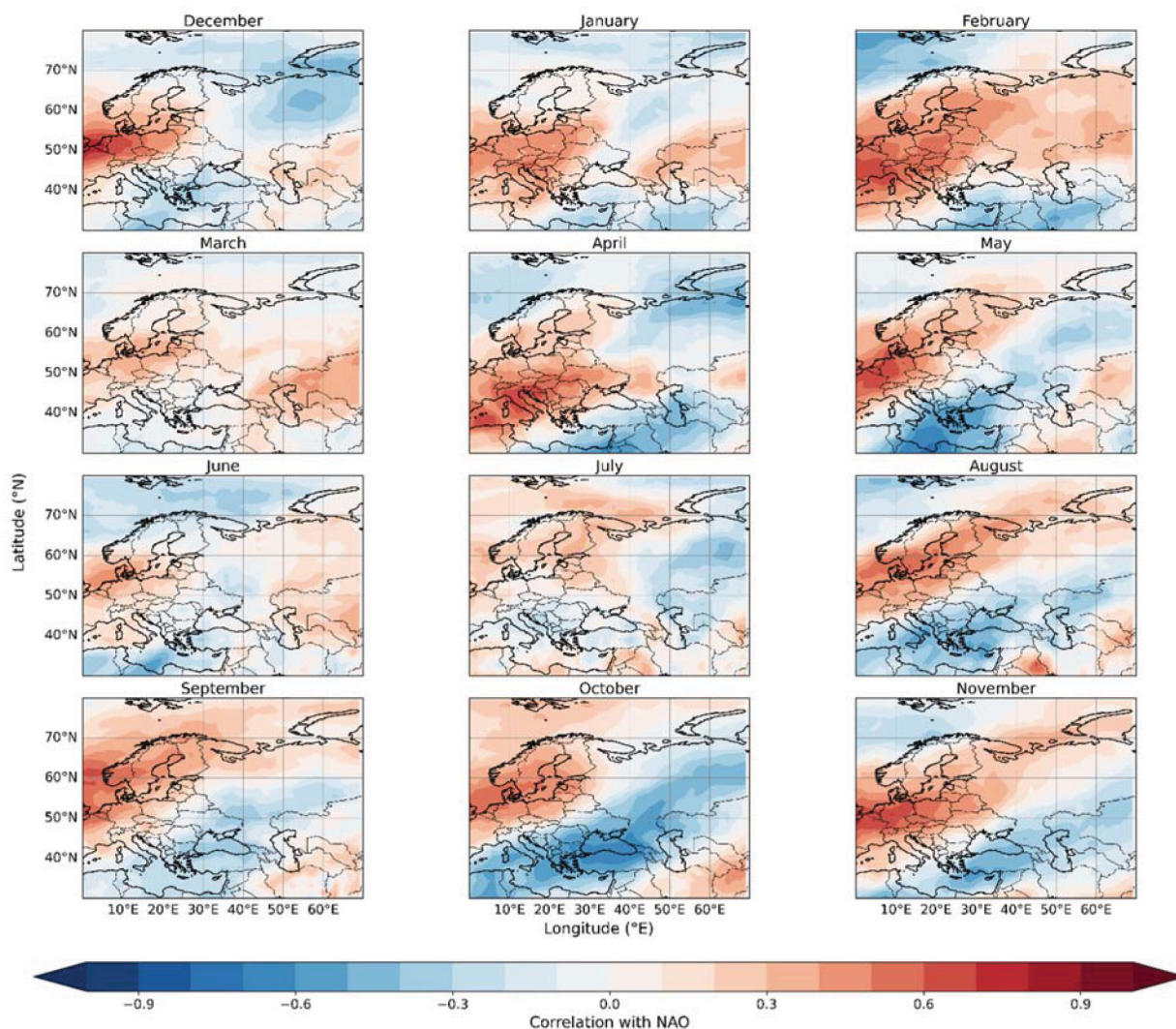


Fig. 3. Correlation maps between AR frequency at regular grid points and the NAO circulation index

season (October–March), likely reflecting the active role of Mediterranean and Black Sea cyclones in moisture transport. The northern areas (Belarus, northern Ukraine) show minimal AR frequency throughout the year, except for isolated increases in August and September.

Thus, AR seasonality in Eastern Europe is well defined: maxima occur in autumn and early winter (October–December), while minima are observed in summer (June–July). Spatial features of AR frequency indicate a dominance of AR activity in the southern part of the region, especially during the cold season, and a reduced role in the north. This pattern corresponds well with the seasonal activity of Mediterranean cyclones and the overall configuration of the westerlies that form ARs in winter.

Figure 3 shows correlation maps of AR frequency at grid points with the NAO index.

Given the pronounced seasonality of atmospheric rivers (ARs) in Eastern Europe, it is appropriate to investigate the extent to which changes in their frequency are linked to variations in large-scale circulation processes. Atmospheric circulation

indices, such as the North Atlantic Oscillation (NAO), strongly influence the position and intensity of the westerlies, which in turn are a key mechanism for AR formation. Therefore, the subsequent analysis focuses on the spatio-temporal correlation structure between monthly AR frequency and NAO values in order to identify potential dynamical linkages between these phenomena. As shown in Fig. 3, the spatial structure of the correlation response changes substantially throughout the year. A notable feature is the significant positive relationship between NAO and AR frequency over northwestern Europe during almost the entire year, with the exception of a few months (March, June, and July, when the coefficients are somewhat reduced). A second fairly persistent zone of negative correlation is observed over the eastern Mediterranean, the Balkans, Turkey, and the Black Sea region. The maps of monthly correlations between AR frequency and the NAO index clearly reveal a structure of alternating zones of positive and negative correlations oriented roughly southwest–northeast (SW–NE). This structure migrates throughout the year, changing its position and spatial extent, with the connection

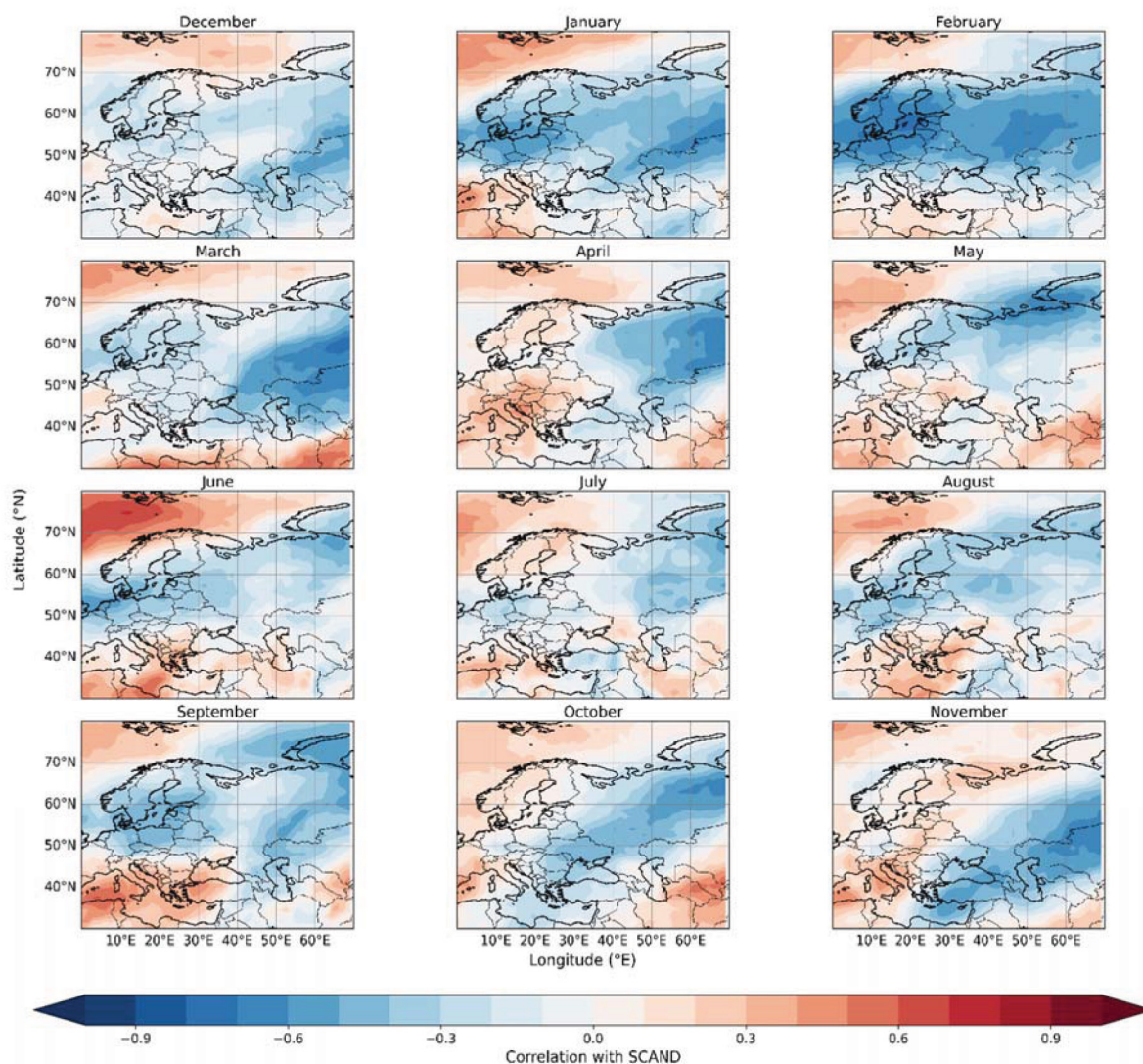


Fig. 4. Correlation maps between AR frequency at regular grid points and the SCAND circulation index

to ARs being stronger in some months (e.g., the autumn–winter period) and weaker in others (June–July). Overall, it reflects the long-term seasonal shifts in the climatic position of the jet stream, AR trajectories, and the influence of NAO.

In addition to NAO, other mid-latitude circulation patterns play an important role in shaping regional atmospheric conditions in Eastern Europe. One of these is the SCAND index (Scandinavian pattern), consisting of a primary circulation centre over Scandinavia and weaker centres of opposite sign over western Europe and eastern Russia/western Mongolia. The circulation state in these centres determines the position of zonal/meridional air transport in the region and can block or redirect cyclone pathways—thus potentially influencing AR occurrence.

Fig. 4 presents correlation maps between AR frequency at grid points and the SCAND index. A characteristic feature of the correlation between AR frequency and the SCAND index is that positive coefficients are mostly concentrated over oceanic areas, while negative ones dominate over the continental part of Europe. In the context of Eastern Europe, a certain negative response is observed in the northern part of the region during specific

months—January, February, June, and August–October. The southern parts of the region show negative correlations in October and November. In the remaining months, as well as in parts of the aforementioned periods, an extensive zone of negative correlation is evident to the east of Europe.

The Polar/Eurasia (PE) index, which is associated with variations in upper-level pressure over northern Eurasia, reflects shifts in the configuration of the Arctic front, which in turn may affect the pathways and frequency of atmospheric rivers. Although a certain pattern of alternating positive and negative correlations between PE and AR frequency can be observed, the correlation coefficients do not indicate a statistically significant relationship, particularly for Eastern Europe. Therefore, these maps are not included in the article.

The East Atlantic/Western Russia (EA/WR) index, which characterises wave-like oscillations extending from the Atlantic to western Siberia, can influence thermal contrasts and the stationarity of cyclonic activity, thereby determining favourable or unfavourable conditions for AR formation during transitional seasons. The monthly correlation between this index and AR frequency is shown in Fig. 5.

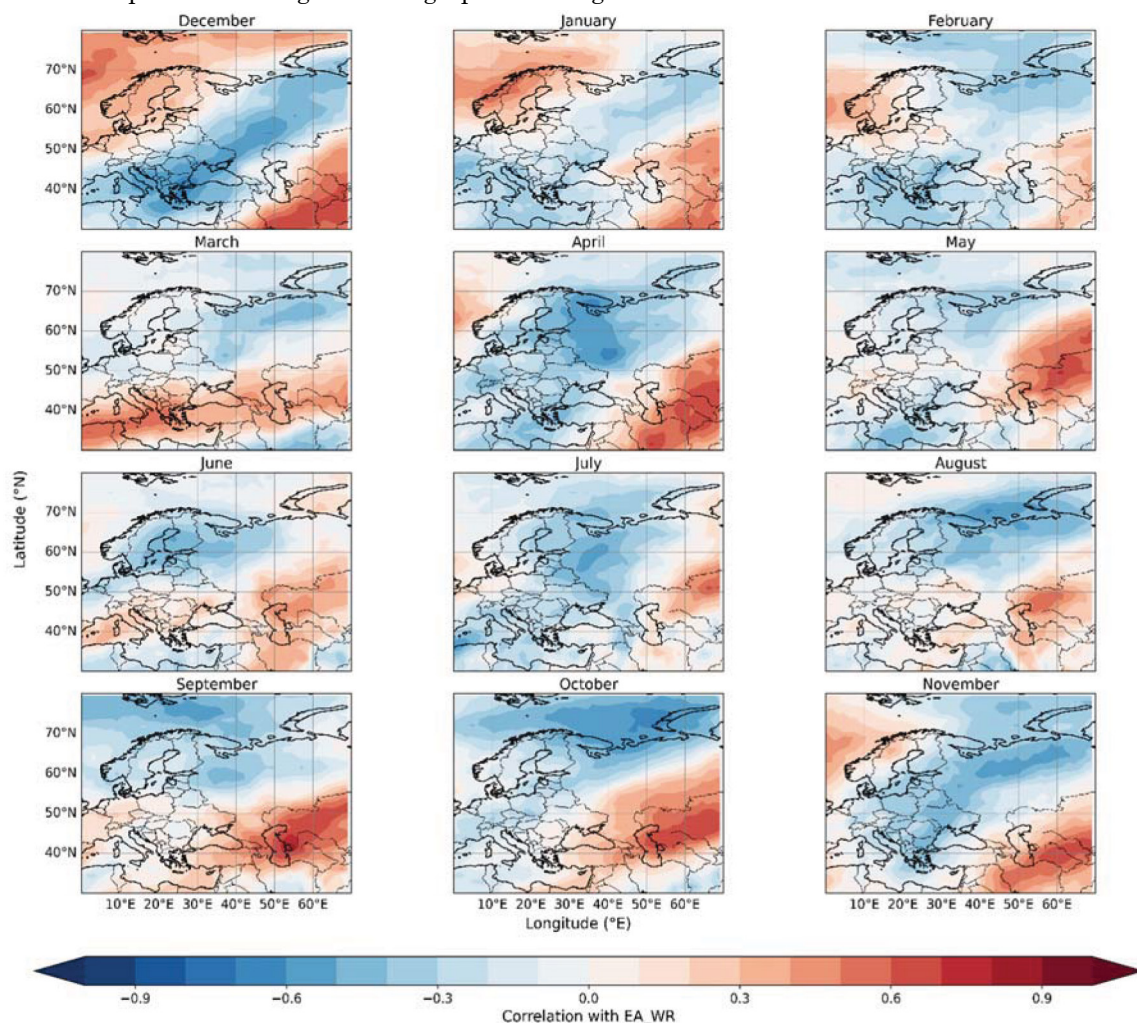


Fig. 5. Correlation maps between AR frequency at regular grid points and the EA/WR circulation index

The correlation maps between AR frequency and the EA/WR index exhibit a distinctive feature: alternating elongated zones of positive and negative correlations, oriented southwestward or zonally extended, with their positions shifting somewhat from month to month. This pattern can be explained by the seasonal reorganisation of mid-latitude circulation, particularly the displacement of major jet streams and atmospheric action centres (patterns). For Eastern Europe—primarily for Ukraine—the period from November to February shows the clearest signal, with a significant negative correlation between the EA/WR index and AR frequency. Over the broader domain, the zones of positive correlation are generally displaced either eastward or southward of Eastern Europe.

Finally, the article presents correlation maps between monthly precipitation totals from ClimUAd [21] and AR frequency (Fig. 6). As shown in Fig. 6, for the period from October to April a strong positive correlation is evident across most of Ukraine, particularly in the west and north. This indicates that an increase in AR frequency is accompanied by higher precipitation in these regions, with the strongest link observed in the Carpathians. In

summer (June–August), negative correlations (down to -0.5) are observed in the south and southeast, meaning that in years with higher AR frequency, these areas experience less precipitation. This may suggest that summer ARs do not reach this part of Ukraine, likely due to the blocking effect of the Carpathian Mountains as an orographic barrier, as well as the greater role of local convective processes during the summer season.

Thus, western and northern Ukraine are the most sensitive to the influence of ARs, especially in the cold season. Southern regions of Ukraine show an inverse relationship in summer, probably due to locally driven convective precipitation that is independent of ARs, combined with the orientation of the Carpathians along the pathways of moist airflows.

It is also noteworthy that there is a cyclic pattern, with ARs exerting the strongest influence in winter, a weakening of this effect in summer, and a renewed increase in autumn. Therefore, although extreme precipitation events are not always necessarily linked to ARs [30], from a climatic perspective, on monthly or longer timescales, precipitation anomalies correlate well with AR frequency over Ukraine.

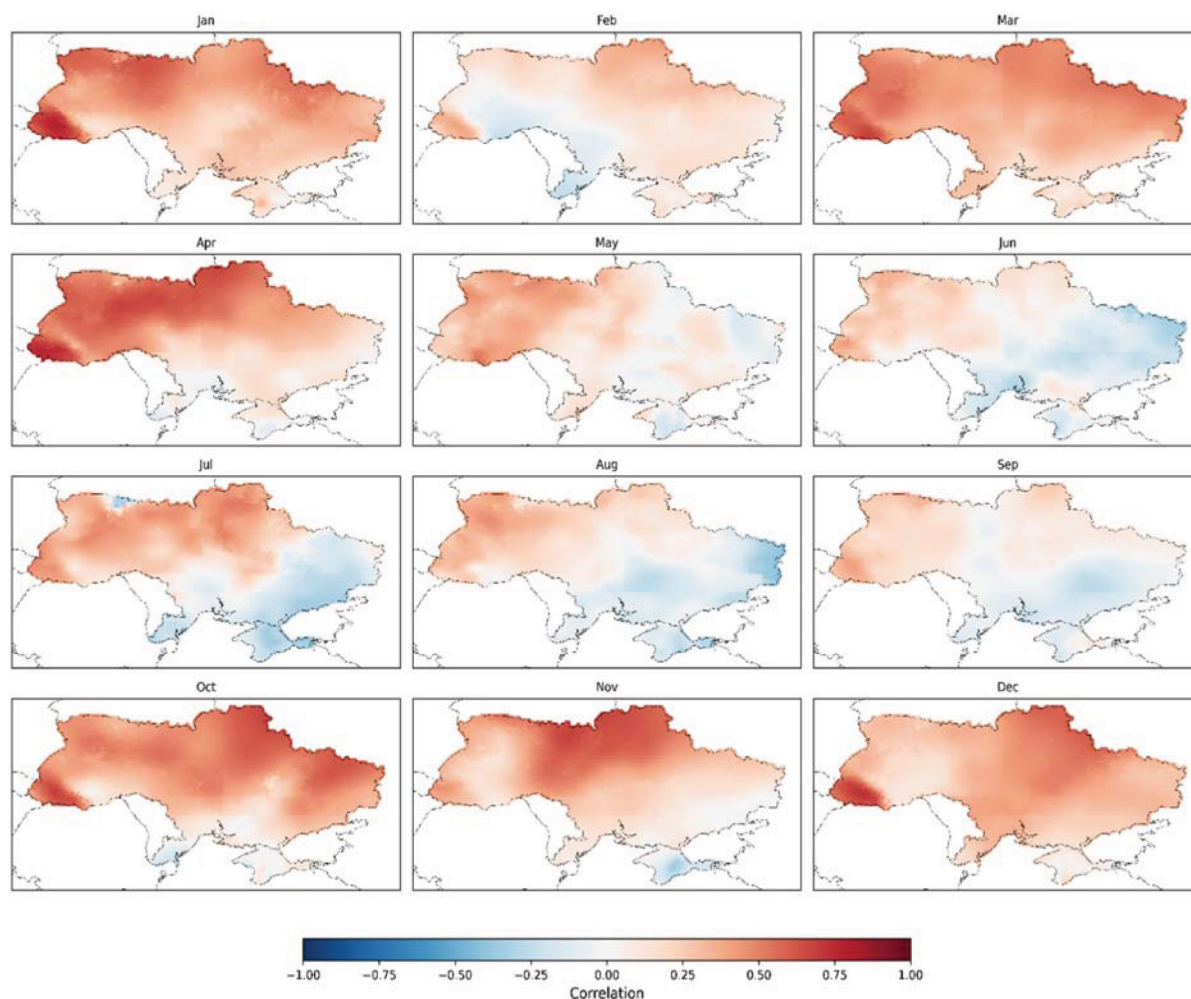


Fig. 6. Correlation between AR frequency in the region ($20\text{--}45^\circ\text{ E}$, $42\text{--}60^\circ\text{ N}$) and monthly precipitation totals (based on ClimUAd data)

Conclusions

Thus, the maximum AR activity in the Atlantic–European sector occurs in winter (December–February), when westerly transport is most intense. The minimum activity is observed in summer (June–July), when most of the region is under anticyclonic control. Spring and autumn act as transitional periods, with November showing a sharp increase in AR frequency. In Eastern Europe (particularly the Black Sea region), AR activity also peaks in the cold season, while summer is characterised by a minimum number of events.

In Western Europe, ARs are most frequent, corresponding to landfall from the Atlantic. In Eastern Europe, their role is less pronounced, but local maxima are detected along the Black Sea coast and in the southern regions of Ukraine, especially in autumn and winter. In the northern part of the region (Belarus, northern Ukraine), ARs are less significant, except during the transitional months (August–September).

In this study, we assessed the correlation between monthly AR frequency and monthly values of atmospheric circulation indices. For NAO, a stable positive correlation with ARs is observed in northwestern Europe and a negative correlation in the Eastern Mediterranean and the Black Sea

region, reflecting the control of the jet stream over AR trajectories. For SCAND, predominantly negative correlations over continental Europe highlight the blocking role of the Scandinavian pattern. For EA/WR, the strongest negative relationship in Eastern Europe is observed in winter (November–February). For PE, the relationships are weaker but indicate a potential influence of Arctic front displacements on AR trajectories.

During autumn and winter, increased AR frequency is strongly associated with positive precipitation anomalies in western and northern Ukraine, particularly in the Carpathian Mountains. In summer, however, southern and eastern Ukraine show an inverse relationship (more frequent ARs correspond to less precipitation), which can be explained by the predominance of local convective rainfall.

The results of this study can be used to improve physico-statistical long-term forecasting of extreme events (heavy rainfall, droughts) in Eastern Europe. The increase in AR frequency is also expected to coincide with greater cloud cover and reduced solar radiation, indicating that ARs may affect the regional radiation balance. Identifying the influence of ARs on humidity and precipitation has practical value for agriculture, water resource management, and risk management in the Eastern European region.

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Конфлікт інтересів: автори повідомляють про відсутність конфлікту інтересів

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Conflict of Interest: The authors declare no conflict of interest

Declaration of use of generative artificial intelligence: The authors confirm that no AI tools were used during the preparation of the manuscript.

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Атмосферні річки як індикатор мінливості циркуляції: між Атлантикою та Чорноморським регіоном

Олександр Щеглов¹,  <https://orcid.org/0000-0001-5702-6285>, e-mail: shcheglov@uhmi.org.ua

к. геогр. н., ст. наук. співробітник

Віталій Шпиг¹,  <https://orcid.org/0000-0003-1055-7120>, e-mail: vitold82@i.ua

к. геогр. н., зав. відділу фізики атмосфери

Нікіта Фомічев²,  <https://orcid.org/0009-0004-2246-2326>, e-mail: nikitaфомич2002@gmail.com

студент кафедри метеорології та кліматології

Іван Дударенко²,  <https://orcid.org/0009-0000-0766-3622>, e-mail: dudarenkoivan18@gmail.com

студент кафедри метеорології та кліматології

¹ Український гідрометеорологічний інститут Державної служби України з надзвичайних ситуацій та НАН України, Київ, Україна

² Київський національний університет імені Тараса Шевченка, Київ, Україна

АНОТАЦІЯ

Метою статті є виявлення статистичних зв'язків між частотою атмосферних річок в Атлантико-Європейському секторі та основними індексами циркуляції, а також аналіз потенційних відгуків цих явищ у Східній Європі. Методологія дослідження базується на використанні каталогу атмосферних річок (Guan, 2021), де ідентифікацію атмосферних річок здійснено за підходом Б. Гуана та Д. Валайзера (Guan & Waliser, 2019) з урахуванням інтегрального перенесення водяної пари (IVT) на основі даних реаналізу ERA-Interim. Для кореляційного аналізу використано індекси циркуляції NAO, PE, EA/WR, SCAND, а також місячні суми опадів із бази даних ClimUAd. Встановлено, що атмосферні річки в Атлантико-Європейському секторі характеризуються чіткою сезонністю з найвищою частотою їхньої появи взимку та мінімумом влітку. Виявлено просторово неоднорідні зв'язки між повторюваністю AP та основними типами великомасштабної атмосферної циркуляції. Для індексу NAO додатна кореляція з повторюваністю AP спостерігається в Північно-Західній Європі, а від'ємна – у Східному Середземномор'ї та регіоні Чорного моря, що може бути пов'язано зі змінами положення та інтенсивності струминних течій і їхнім впливом на траєкторії AP. Для індексу SCAND переважно від'ємні значення коефіцієнта кореляції над континентальною Європою можуть свідчити про вплив блокуючих процесів на повторюваність і траєкторії AP. Для індексу EA/WR найбільший обернений зв'язок у Східній Європі спостерігається протягом періоду листопад–лютий. Для індексу PE зв'язки слабші, але вказують на потенційний вплив зміщень арктичного фронту на траєкторії AP. Статистично значущі зв'язки між частотою AP в окремих регіонах та індексами циркуляції підкреслюють роль великомасштабної динаміки атмосфери у формуванні траєкторій AP. Виявлено, що в осінньо-зимовий період збільшення кількості випадків атмосферних річок у Східній Європі тісно корелює з додатними аномаліями опадів на заході та півночі України, зокрема в Карпатах. Влітку, навпаки, на півдні та сході України спостерігається зворотна залежність (вища частота AP пов'язана з меншою кількістю опадів), що можна пояснити зміною механізму формування основної частки опадів у загальній сумі за рахунок переважання локальних конвективних процесів, що супроводжуються сильними опадами.

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