

INTEGRATED VAPOUR TRANSPORT CLIMATOLOGY
1994–2023 AND A CASE STUDY OF AN ATMOSPHERIC
RIVER EVENT IN NOVEMBER 2023 IN BULGARIA

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Abstract

In recent decades, floods and droughts have intensified globally, with Atmospheric Rivers (ARs) being major vapour transport streams that cause extreme precipitation in regions like California, but their impact in Bulgaria remains largely unexplored. This study aims to establish the climatology of Integrated Vapour Transport (IVT) over Bulgaria for the period 1994–2023 and to present a case study of a high-impact weather event. The analysis reveals a distinct seasonal cycle, with maximum IVT values in summer and minimum values in winter. In 2023, monthly mean IVT exceeded the 30-year climatological mean in eight months, with the strongest anomalies observed in autumn – particularly in September and November. On 4th November 2023, a cyclone brought heavy rainfall to Bulgaria, associated with a pronounced IVT anomaly and a well-defined AR structure. IVT anomaly maps and vertical profiles of water vapour transport indicate a moisture plume extending from the Atlantic Ocean, across the Mediterranean Sea, toward the Balkans. This work provides the first long-term climatological assessment of IVT and ARs over Bulgaria, filling a regional research gap and offering new insights into moisture transport and its role in Southeastern Europe's hydrometeorology.

Key words: Integrated Vapour Transport (IVT), IVT climatology, Atmospheric River (AR)

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Introduction. The term “tropospheric river” was first used in 1992 by NEWELL et al. [1] to describe a long (about 2000 km) and wide (about 300–500 km) water vapour stream in the atmosphere. Later, RUTZ et al. [2] defined a threshold of IVT of $250 \text{ kg m}^{-1} \text{ s}^{-1}$ above which AR-like structure could be found. A global review of AR as a major factor for water vapour transport from tropics poleward through the mid-latitudes is done by GIMENO et al. [3]. Authors analysed distribution, structure and dynamics of ARs and showed that occurrence of these kinds of atmospheric structures can be the cause of significant and catastrophic floods. First studies of ARs were in the 1990s and were related to floods and droughts on the west coast of North America. In general, for this region the connection between ARs, floods and water resources is well documented and is being studied in depth to achieve optimal control of water resources and floods. For example, according to GUAN et al. [4] and DETTINGER et al. [5], between 25 and 50% of California’s water resources are due to the presence of ARs. The number of studies on this topic has grown significantly over the past decades [6]. In 2015 alone, over 200 papers were published [7], and that led to development of ARs forecasting methods and algorithms. In 2018, a project was created for joint cooperation and development of AR tracking methods (Atmospheric River Tracking Method Intercomparison Project – ARTMIP) [8]. The goal of this international initiative is to develop algorithms and definitions for AR research. In addition, recent studies by the San Diego Oceanographic Research Center [9], 9 ARs were predicted and reported to reach California for the period December 2022 – January 2023.

ARs usually occur over water areas such as oceans and seas. During their movement, they reach coastal regions, where air masses with a high moisture content in the lower part of the troposphere rise along the slopes of high mountains [10], and create and support unstable atmospheric conditions leading to heavy and extreme precipitation. The main source of ARs that transport synoptic scale moist air masses over Europe is the Atlantic Ocean. LAVERS and VILLARINI [11] found that AR had an impact on the entire west coast of Europe producing one third of all precipitation in parts of Europe. Mediterranean cyclones are also source of ARs as they collect and transport moisture. FROIDEVAUX and MARTIUS [12] demonstrated a strong link between ARs and floods in northern Switzerland. The study shows that 10 out of 14 floods were linked to extremely high values of IVT, and AR directed perpendicular to the Alps. These results led to development of an operational system for flood warnings for medium range (6 to 10 days ahead). ARs and their link to intense rainfall and flood events are still not well studied in Bulgaria. There have been only a few studies on this topic in the last 5 years. The first study is by LASOTA et al. [13] where the authors discuss two case studies of hail events in Bulgaria including synoptic scale analysis of IVT. Results show that an AR formed over the Atlantic Ocean, reached the Western Mediterranean sea and then on 8 July, 2014, a strong hailstorm was registered over

Sofia. Another study by KOSTASHKI et al. [14] analyzes severe convection over Southeast Bulgaria on 17 September 2022. In that case study AR-like structure is moving over the Mediterranean Sea and IVT values over Southeast Bulgaria are two times higher compared to the mean value for the 1993–2022 period.

The aim of this paper is to compute IVT climatology for the 30-year period for Bulgaria and present a case study with highest weather warnings issued by the National Institute of Meteorology and Hydrology (NIMH). Using a climatological period of 30 years from 1993 to 2023 we analyzed IVT over Bulgaria and its link to an AR structure that transports water vapour from the Atlantic Ocean through Europe.

Materials and methods. To study water vapour distribution and direction we estimated and analysed IVT index. For that purpose we use ERA5 reanalysis data [15, 16]. Monthly and hourly data of specific humidity (q), zonal (u) and meridional (v) wind components at ten pressure levels (p) of 1000, 925, 850, 700, 500, 400, 300, 200, 100 and 50 hPa are downloaded to compute IVT index and vertical transport on single level (VT) using the following equations:

$$(1) \quad \text{IVT} = \frac{1}{g} \sqrt{\left[\int_{p=1000}^{p=0} q(p)u(p) dp \right]^2 + \left[\int_{p=1000}^{p=0} q(p)v(p) dp \right]^2},$$

$$(2) \quad \text{VT}(p) = \sqrt{[q(p)u(p)]^2 + [q(p)v(p)]^2},$$

where q is the specific humidity in kg/kg; u is the zonal component of the wind speed in the east direction, in m/s; v is the meridional component of the wind speed in the north direction in m/s; p is the pressure at ten different levels in the atmosphere: 50 hPa, 100 hPa, 200 hPa, 300 hPa, 400 hPa, 500 hPa, 700 hPa, 850 hPa, 925 hPa, 1000 hPa.

We estimated and analysed IVT at an area with coordinates: 60° North, 30° West, 30° South and 40° East. Thus we include the Atlantic Ocean and Mediterranean Sea, which are the main areas of interest and where AR-like structures can be found. First, we compute monthly mean IVT values over the climatological period of 30 years – from 1994 to 2023 and compare results to 2023 IVT monthly means. Next, we estimated the monthly IVT averaged over Bulgaria (coordinates 44.5° North, 22° West, 41° South and 29.5° East). To deepen 2023 IVT analysis and its anomalous behaviour in the autumn we choose a day with a Meteoalarm code, issued from the Bulgarian National Institute of Meteorology and Hydrology [17]. Based on hourly data we estimated the IVT anomaly over Europe and compared it to 30-year mean. Additionally, we computed the water vapour vertical profile at a specific point over Bulgaria and compared the results to the 1994–2023 period. Studied area and location of VT profile are shown in Fig. 1. Finally, to verify the AR presence over Bulgaria on a day with an extreme weather event occurrence, we used a numerical database from AR catalogues, developed from ERA5-based Dataset for Atmospheric River Analysis (EDARA)

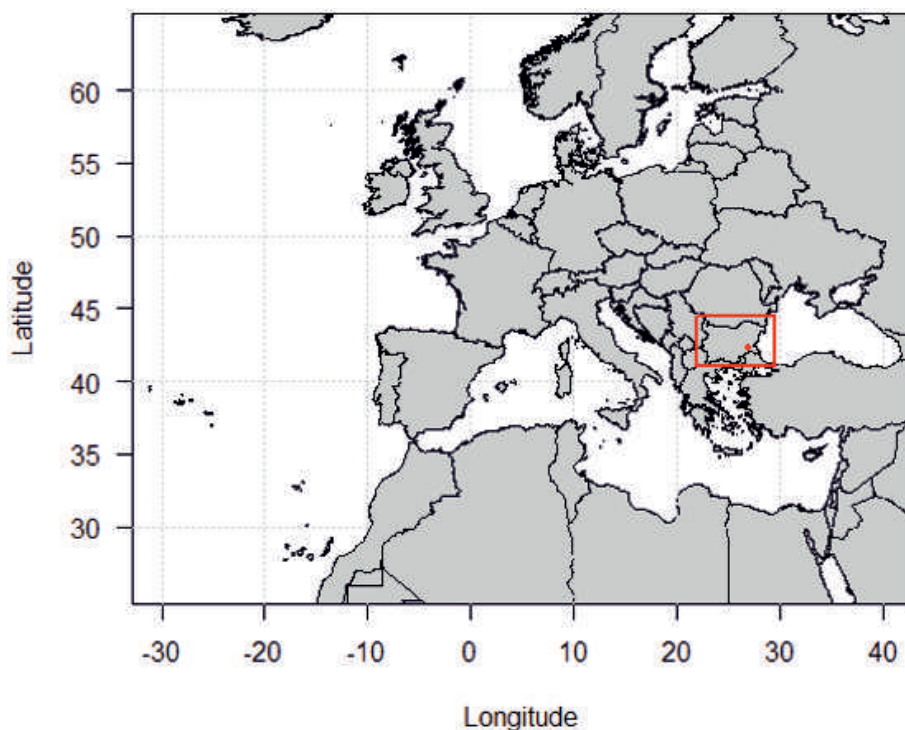


Fig. 1. Studied area, territory over Bulgaria (red rectangle) and location of vertical profile (red point)

project [18]. The dataset (EDARA) is available at [19] and is based on two algorithms, created by GUAN and WALISER [20]. This dataset can be used to perform various types of AR analyses, such as severe weather case studies. To analyse if there is a link between AR occurrence and extreme weather precipitation event on 4th November over Bulgaria we downloaded, processed and analysed 4 variables from EDARA database, namely Vertical integral of northward water vapour flux, Vertical integral of eastward water vapour flux, Atmospheric river shapes detected by the tARget-v3 algorithm, Atmospheric river shapes detected by the modified tARget-v3 algorithm (Q_v , Q_u , ARS and MARS).

Results. IVT climatology: 1994–2023. As the primary focus of this study is the geographical territory of Bulgaria, the monthly IVT was calculated as a spatial average over Bulgaria (Fig. 2). The corresponding domain is shown in Fig. 1. Results show that atmospheric moisture transport has a seasonal cycle over Bulgaria. Monthly mean IVT has maximum values in summer and minimum in winter months. IVT peaks in July and August, with more than $80 \text{ kg m}^{-1} \text{ s}^{-1}$. In the following months IVT is decreasing, reaching its minimum, with values of $34\text{--}36 \text{ kg m}^{-1} \text{ s}^{-1}$ in January and February. Monthly mean IVT for 2023 shows a different behaviour compared to the 30-year averaged data. Minimum values of

Monthly IVT over Bulgaria (1994–2023 Mean $\pm$ Range, 2023 Line)

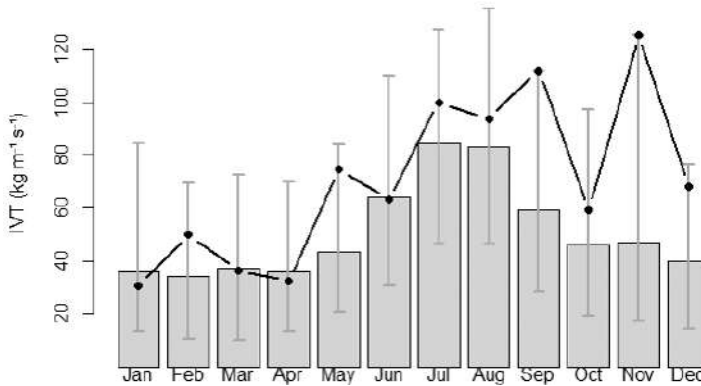


Fig. 2. Monthly IVT over Bulgaria 1994–2023 mean (bars) with maxima and minimum (grey lines) and 2023 mean (black line with dots)

IVT are observed in January and April ($31 \text{ kg m}^{-1} \text{ s}^{-1}$ and $32 \text{ kg m}^{-1} \text{ s}^{-1}$). In 2023 there are only four months (January, March, April and June) with values close to the mean. All other months have higher IVT values than the averaged over the 1994–2023 period. Also differently from the 1994–2023 period, 2023 IVT shows a peak not in the summer but in the autumn months. September and November 2023 monthly mean IVT values stand out with the highest estimated for the corresponding month over the studied period – $112 \text{ kg m}^{-1} \text{ s}^{-1}$ and $126 \text{ kg m}^{-1} \text{ s}^{-1}$, respectively. These results correspond to the Meteolarm warnings issued by NIMH, Bulgaria. For November 2023 ten precipitation warnings are issued, six of which are orange and red alarm levels indicating heavy rainfall, extensive flooding and landslides.

Case study: 4th November 2023. Throughout November 2023 the atmospheric conditions over Bulgaria are dynamic and bring unstable weather. On 3rd November 2023 a cyclone formed over the central Mediterranean Sea. On the next day as a result of its movement in a westerly direction it passed through the northern part of the Balkan Peninsula bringing a lot of rainfall all over Bulgaria. Detailed description of synoptic situation is given by NIMH [21]. At 00 UTC on November 4th maximum IVT anomaly above $1000 \text{ kg m}^{-1} \text{ s}^{-1}$ is observed in the Atlantic Ocean and is associated with a large cyclone approaching the west coast of Europe. As seen from Fig. 3a there is a wide and long band with high IVT anomaly values from the Azores, through the Iberian Peninsula, western and central Mediterranean to the Black Sea and north to the Scandinavian Peninsula. There are also high values above $250 \text{ kg m}^{-1} \text{ s}^{-1}$ in the area from Tunisia, through southern Greece, Southeast Bulgaria, and West Black Sea. These results of IVT anomalies of above $250 \text{ kg m}^{-1} \text{ s}^{-1}$ are associated with an AR-like shape structure transporting water vapour from the Atlantic Ocean through Europe. High values of IVT over the Balkans can be found at an area with length of more

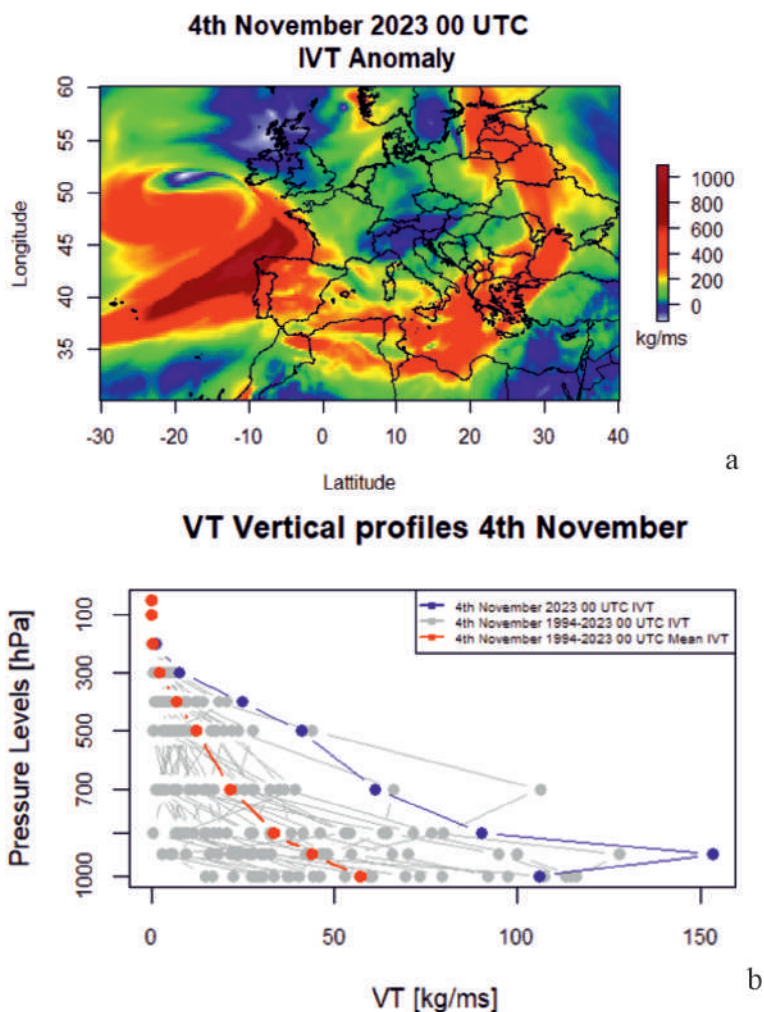


Fig. 3. 00 UTC on 4th November 2023: a) IVT anomaly and b) VT vertical profiles of climatological mean (red line with dots), 2023 (blue line with dots) and individual years (grey line with dots) over Southeast Bulgaria

than 1000 km and a width of several hundred km, which also indicatively shows a presence of AR. Furthermore, the vertical profile of water vapour was derived at the location in Bulgaria (indicated in Fig. 1) corresponding to the maximum IVT value on that day – $513 \text{ kg m}^{-1} \text{ s}^{-1}$, exceeding the climatological mean by $386 \text{ kg m}^{-1} \text{ s}^{-1}$. In addition, the vertical profile of water vapour transport at 00 UTC on 4th November over Southeast Bulgaria compared to the 1994–2023 mean and to each of the individual years is shown in Fig. 3b. It is seen that in 2023 VT values are higher than the climatological mean at all pressure levels from 1000 hPa to 200 hPa. Interestingly, the VT at low pressure levels of 925 hPa and 850 hPa are the highest over the studied period. Estimated IVT distribution and

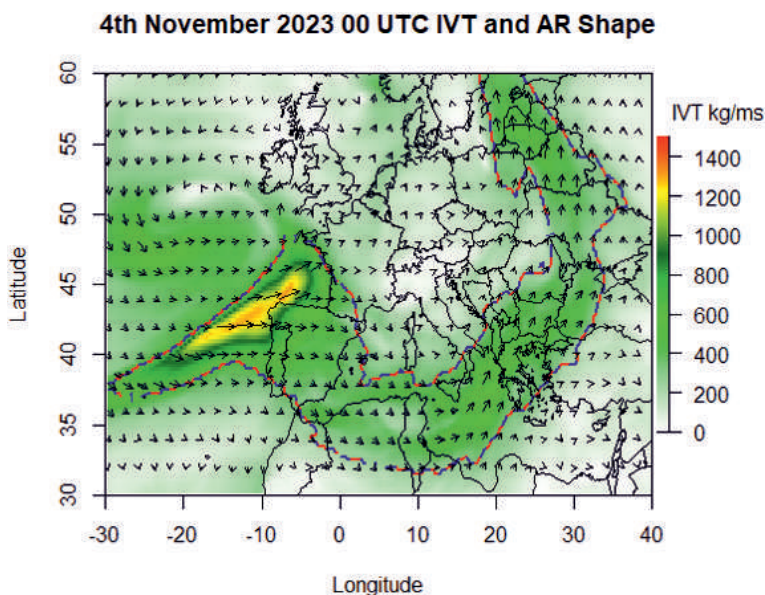


Fig. 4. November 2023 atmospheric river boundaries computed with the tARget-v3 and mtARget-v3 algorithms (red and blue dashed lines, respectively). The colour map with vectors shows IVT distribution and direction

direction as well as the AR shapes are shown in Fig. 4. High values of VT in the low troposphere and IVT anomaly that is shown in Fig. 3 are consistent with the IVT and AR shape maps derived from EDARA.

Discussion and conclusions. IVT and ARs play a central role in shaping weather patterns over Bulgaria by interacting with regional climatic systems, particularly Mediterranean cyclones and the Black Sea. Most high-impact precipitation events in Bulgaria are associated with Mediterranean cyclones that develop over the western or central Mediterranean and track northeastward toward the Balkans. Acting as a moisture conveyor belt, ARs continuously supply water vapour from the Atlantic and Mediterranean, intensifying the cyclone's precipitation potential. Bulgaria's complex topography further modulates these processes by directing airflow and enhancing orographic precipitation. The study by KOSTASHKI et al. [14] supports these mechanisms, showing that during the 17 September 2022 storm near the Black Sea coast, IVT exceeded $400 \text{ kg m}^{-1} \text{ s}^{-1}$ well above the climatological mean and AR-like structure approached Southeast Europe, highlighting IVT's key role in driving extreme weather over Bulgaria. Monthly mean IVT analysis over Bulgaria for the period 1994–2023 exhibits a seasonal cycle. Lowest values are $34\text{--}36 \text{ kg m}^{-1} \text{ s}^{-1}$ and are registered in winter months (January and February). Maximum IVT values of $83\text{--}84 \text{ kg m}^{-1} \text{ s}^{-1}$ are observed in summer (July and August). In comparison to the 30-year climatology, in 2023 IVT monthly mean shows: 1) higher values in 8 out of 12 months, and 2) the highest monthly mean values in autumn months (September and Novem-

ber). On 4th November 2023, NIMH issued a red Meteocalarm warning code for a cyclone bringing heavy rainfall. Analysis of hourly IVT anomaly on 4th November 2023 shows that: 1) there are values above $250 \text{ kg m}^{-1} \text{ s}^{-1}$, which are associated with an AR structure transporting water vapour from Atlantic Ocean through Europe, and 2) high IVT values over the Balkans confirm the AR area criteria with length of more than 1000 km and a width of several hundred kilometres. Analysis of vertical water vapour transport on 4th November 2023 over Southeast Bulgaria shows higher than the climatological mean values at all pressure levels from 1000 hPa to 200 hPa. The values at pressure levels 925 hPa and 850 hPa are the highest over the studied 30-year period. High values of VT in the low troposphere and IVT anomaly are consistent with the IVT and AR shape maps derived from EDARA. Results show a link between AR structure transporting water vapour from the Atlantic Ocean through Mediterranean sea, to the Balkans and extreme weather events in Bulgaria.

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