Atmospheric river, a term encompassing different meteorological patterns

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Abstract

The study of atmospheric rivers (ARs) and their impacts on extreme precipitation are currently of great research interest in view of their clear socioeconomical implications. However, studies of this type generally contain caveats. The first of these is of a meteorological nature, and is concerned with the diversity of the different meteorological patterns that can be associated in the phenomenological definition, in that there is no guarantee that all so-called ARs follow the same one. The second concern involves the initial definition of an AR, which implicitly assumes the subtropical origin of the atmospheric moisture that feeds it. To date, it has been observed that in many cases of ARs, most of the moisture originates in regions at higher latitudes. The aim of this article is to open a debate on these two aspects by using well-known examples of ARs which fit different meteorological patterns, and showing a climatology of the moisture sources that feed ARs.

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atmospheric rivers, extreme precipitation events, meteorological patterns
The number of important papers published annually on atmospheric rivers (ARs) and their impacts on extremes of precipitation continue to rise, and the topic has captured the attention of readers of some high impact-factor journals, for example the contribution to Nature Geoscience by Waliser & Guan (2017), and the “in-depth” commentary on this paper in Science, the paper by Zhang and Villarini (2018) in PNAS, the paper by Algarra et al. (2020) in Nature Communications, the paper on the impacts of ARs in Science Advances by Corringham et al. (2019), the review by Gimeno et al. (2016) in the Annual Review series, or the recent contribution by Payne et al. (2020) in Nature Reviews Earth and Environment. Furthermore, there has been ongoing research activity worldwide in this area, and an increasing number of papers have focused on the identification and climatology of ARs in different parts of the globe, using reanalysis and models for their characterization, including the effect of major modes of climate variability on the occurrence and distribution of these events in current and future climates.

Despite growing levels of interest in ARs, there are a couple of important caveats associated with all studies of these phenomena, which merit special scientific attention. ARs are generally defined based on phenomenological descriptions and objective threshold-based methods, and have been so almost since their initial description (Zhu & Newell, 1998); however, this constitutes no guarantee that all so-called ARs follow the same meteorological patterns (see Gimeno et al., 2014 for a review). What we may call an AR could in fact be something very different in meteorological terms, and a number of different patterns could be associated with ARs for different regions and seasons.

The vast majority of studies on ARs are focused on the analysis of their impacts in terms of associated precipitation and its extremes, amount and variability, as well as the location of hot-spot regions (both now and in the future) and predictability. However, ARs arriving at the same or different locations may correspond to different meteorological patterns (or weather systems), and this has important implications for the allocation of the amounts and distribution of precipitation associated with them. As an indication, let us assume two different weather systems (let us call them “A” and “B”), both associated with ARs affecting a same region, but with different precipitation patterns over the area. One of them (“A”) is associated with widespread but non-extreme precipitation, while the other (“B”) is associated with extreme and well-localized precipitation. To account a correct relationship between the total occurrence of ARs and their impact on the precipitation (and its extremes) it is necessary to know the frequency of occurrence of A-type or B-type. Additionally, if we expect changes in precipitation associated with ARs, these can be due to changes in the actual amount of moisture carried by the ARs, or changes in the frequency of occurrence of weather systems “A” or “B” over the region. These considerations are also relevant for studies of ARs and their impact on precipitation in future climates. We could conclude that there will be more or less ARs occurrence in the future over a location, but their impact on precipitation would be different depending on the changes in the occurrence of ARs linked to A-type or B-type weather systems. The science of ARs and the studies of their impacts in terms of precipitation (variability, amount, and location) would benefit greatly if we could classify them using the different synoptic patterns to which they are related.

The initial notion of an AR (Zhu & Newell, 1998) implicitly involves the concept of an extreme supply of moisture from a subtropical area. Over the years, this has been proved to be true in many cases. However, there are also many cases where moisture originates in regions far to the north of the principal sources (e.g., see Ramos et al., 2016a). The link between ARs and moisture sources is clear (Gimeno et al., 2012), therefore the analysis of moisture sources linked to ARs, to illustrate the clear differences between extratropical and high- and low-latitude ARs, would add a new perspective to the topic and enrich our understanding of them.

The recent definition of an AR (Ralph et al., 2018) in the AMS glossary (http://glossary.ametsoc.org/wiki/Atmospheric_river) partly solves these limitations by leaving open the question of whether the origin of the moisture is subtropical or extratropical, and by not linking all ARs with the development of extratropical cyclones: “A long, narrow, and transient corridor of strong horizontal water vapor transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources. Atmospheric rivers frequently lead to heavy precipitation where they are forced upward—for example, by mountains or by ascent in the warm conveyor belt. Horizontal water vapor transport in the midlatitudes occurs primarily in atmospheric rivers and is focused in the lower troposphere”. The definition in this regard is clear; moisture can be either tropical or extratropical in origin, and although they are typically associated with extratropical cyclones, this need not necessarily be the case in all instances.

While most of ARs are in fact intense moisture fluxes from subtropical areas associated with an upward warm stream (known by meteorologist as a warm conveyor belt [WCB]) of an extratropical cyclone, others clearly are not. The latter cases are, for instance, those ARs identified at low-latitude regions (near the tropics) and associated to...
monsoonal regimes, or even over central continental areas. “Monsoonal ARs” have been studied recently over India and it has been found that this particular “monsoonal ARs” are not connected with extratropical stormtrack activity (Laskhmi & Satyanarayana, 2020; or Lakshmi et al., 2019). However, regarding East Asia Summer Monsoon it was shown that, during the early stage of the monsoon, the ARs coincided with the strong south-westerly flow along the northern boundary of the regional subtropical high level pressure, while during the late monsoonal stage these ARs were more associated with extratropical cyclones (Park et al., 2021). On the other hand, “Continental ARs” often appear in global detection schemes. A notable example are the ARs found in South America parallel to the Andes mountain range (Lora et al., 2020, see their fig. 1). However, it is clearly documented the existence over this region of the well-known South American low level jet (SALLJ, Marengo et al., 2004), which is characterized as a narrow stream that channels the near-surface flow between the tropics and midlatitudes east of the Andes mountain range transporting moisture from the Amazon region into southern Brazil–Northern Argentina (Arraut et al., 2012; Algarra et al., 2019; Braz et al., 2021).

In this opinion piece, we will debate the two aspects mentioned above related to ARs, (i) their meteorological association (illustrating the differences using examples of known ARs with contrasting conceptual synoptic models), which has implications on the relationship AR-precipitation pattern and variability in the present and future, and (ii) their moisture origin, which may change regionally in a changing future climate having implications in the moisture amount transported by the ARs.

## 2 ARs, A PHENOMENOLOGICAL DEFINITION

The definition of ARs presented in Section 1 has generated debate about the precise meaning of the term. Over the last 20 years, various perspectives have been prominent in the technical community, some of the most common referring to ARs in the same sense as existing concepts such as the WCB (Ralph et al., 2018). The efforts made by several researchers to derive a definition of an AR are detailed in Ralph et al. (2018). In addition, according to Dettinger et al. (2015), exports of tropical moisture (TMEs) occur in zones of intense vapor transport out of the tropics. These TMEs can provide important amounts of vapor for ARs, although most ARs additionally incorporate moisture from midlatitude sources and convergences of vapor along their paths (Algarra et al., 2020; Ramos et al., 2016a).

In this sense, it is important to stress that the definition published in the AMS glossary clearly states that ARs are “typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone”, and a schematic summary of the structure of this type of AR is shown in Figure 1. This clearly illustrates the average characteristics of an AR based on dropsonde measurements and corresponding reanalysis data, and its location within the frontal system (Figure 1a). The vertical cross section is also shown (Figure 1b), in which the core of the water vapor transport in the AR is clear (orange contours and color fill). In addition, the most intense horizontal water vapor flux (depth of the ARs) corresponds to a region 3–3.5 km deep (lower troposphere).

With this definition in mind, the major areas affected by ARs generally correspond to the western regions of the continents (Algarra et al., 2020), with most of the impacts of extreme precipitation and floods in the western United States (e.g., Ralph et al., 2013; Corringham et al., 2019; Albano et al., 2020), western Europe (e.g., Eiras-Barca et al., 2016; Ramos et al., 2015), western South America (e.g. Valenzuela & Garreaud, 2019; Viale et al., 2018), western South Africa (Blamey et al., 2018; Ramos et al., 2019), and the polar regions (e.g., Gorodetskaya et al., 2020; Nash et al., 2018). In addition, the most intense ARs can be hazardous and have important socioeconomic impacts in the western United States (Corringham et al., 2019) and related regions globally, but also less extreme ARs can provide beneficial water supplies to watersheds (Dettinger, 2013; Eiras-Barca et al., 2021; Ralph et al., 2019).

Given the importance of the ARs in terms of their associated impacts and the critical role that the play in the water cycle, there is a wide range of methods to identify and track them. These different methods have been developed to answer specific research questions at a global or local scale, using different criteria such as geometry, threshold values of key variables, or even time dependence (Rutz et al., 2019). To understand and quantify uncertainties in the science of ARs based on the choice of detection/tracking methodology, a collaborative project was set in motion, namely the Atmospheric River Tracking Method Intercomparison Project (ARTMIP, Shields et al., 2018; Rutz et al., 2019). Most AR tracking methods are based on the analysis of vertically integrated water vapor transport (IVT), vertically integrated water vapor (IWV), or a combination of these. In recent years, machine learning techniques that do not require any thresholds have been also used. The main advantage of these proposed techniques is that they are threshold-free. Therefore, there is no need to include any—subjective—threshold criteria for the detection method. This facilitates objective
detection, and allows for comprehensive comparison between different large climate datasets (e.g., Muszynski et al., 2019; Prabhat et al., 2021; Xu et al., 2020). These techniques have also proven to be useful for improving ARs forecasts as shown in Chapman et al. (2019).

However, most algorithms do not take full account of the definition of an AR, specifically the reasoning that they are typically associated with a “jetstream ahead of the cold front of an extratropical cyclone”. To the best of our best knowledge, the only algorithm that accounts for this definition properly is that of Viale et al. (2018) for the sub-domain of South America, which imposes the restriction that an AR must be associated with a frontal system. This have implications for impacts and the attribution and modulation of the precipitation by the ARs in the present and future due to the expected changes on their latitude distribution and in the intensity and number of events (Gao et al., 2015; Ramos et al., 2016b; Shields & Kiehl, 2016), but also with the diverse associated meteorological systems such as cyclones, low-level jets, or monsoonal circulation (Jayasankar et al., 2021; Pepler & Dowdy, 2021; Torres-Alavez et al., 2021; Zhou et al., 2020).

3 | AR: ONE TERM VERSUS MULTIPLE METEOROLOGICAL PATTERNS

Most detection algorithms take no account of meteorological factors such as the association of ARs with extratropical cyclones or other systems. Instead, they rely solely on IVT and/or IWV, thus all they identify ultimately is the anomalous transport of moisture. In such schemes, ARs can be associated with different meteorological patterns (Gimeno et al., 2016), all linked to the intense transport of moisture such as in cyclones (Eiras-Barca et al., 2018; Gorodetskaya et al., 2014; Sodemann & Stohl, 2013), LLJ systems, or even monsoons (e.g., Arraut et al., 2012; Liang & Yong, 2020; Yang et al., 2017). In this section, we give two examples to illustrate these potential drawbacks of the detection algorithms, revealing that an AR can occur under unequivocally different meteorological patterns. To do this, we use a meteorological evaluation which merges synoptic configuration and numerical parameter fields (Box 1) for two
landfalling AR cases over the same geographical location. Both ARs impact the SE coast of the United States, coming from the Gulf of Mexico and flowing northwards to cross the Great Plains that occurred on May 1, 2010 12 h and July 8, 2010 18 h (Figure 2). Both cases were selected from the AR database of Guan & Waliser (2015) that located landfalling ARs over coastlines worldwide with no consideration of the meteorological conditions (further details of the method of AR detection can be found in Guan & Waliser, 2015).

The specific Guan & Waliser (2015) algorithm was the first one to implement a ARs detection scheme and is one of the most widely used global-scale ARs database, which has continuity in other efforts such as Mundhenk et al. (2016) or Skinner et al. (2020). Using the different global AR detection schemes available in the ARTMIP, Lora et al. (2020) analyzed the consensus and disagreement between them. Regarding the ARs frequency, the global catalogues show a high consensus, with the best degree of agreement in extratropical regions. Outside these regions, the ARs detection is highly dependent on the method used and should be treated with care.

Figure 3 summarizes schematically the meteorological configuration of both events. This figure is based on Figures 2 and 4, and figures included in the Supplementary material (Figures S1 and S2), and represents a set of key parameters (Box 1). Table 1 highlights the main differences between both situations in terms of these key parameters.

A typical cyclogenetic development is commonly detected using the mean sea level pressure (MSLP), and the pairing of thermal frontal parameter (TFP, at 700 hPa) and the equivalent thickness at 850–500 hPa to locate the possible occlusion and associated fronts (Figures 2a,b and 4a,b, also in Figure S1a,b), and complemented with the wind speed and temperature advection at 850 hPa, and vorticity advection at 500 hPa (Figure S1c,d). On May 1, 2010 case study a surface low level pressure can be observed at 50°N–100°W, with the configuration typical of a well-developed occlusion with associated cold and warm fronts. Focusing on the area of the AR, it is clear that there is a crowded zone of equivalent thickness isolines to the west of the maximum values of IWV associated with the WCB (a coherent warm and moist airstream, Pfahl et al., 2014), which forms the cold frontal cloud band. As a consequence of the position of

**BOX 1 Basic numerical parameters and their use in meteorological conceptual models**

A meteorological system is essentially described by a conceptual model that captures its key features by identifying the main physical and thermodynamics processes that take place during its evolution. The meteorological fields involved should demonstrate the main processes for the appropriate diagnosis and prognosis, and should be able to discriminate between different meteorological phenomena. To highlight the differences, some basic numerical parameter fields are widely used.

- The thermal frontal parameter (TFP) is used for frontal detection because it describes the changes in temperature at any tropospheric level, and it is always combined with the gradient of equivalent thickness, which is based on the temperature increase that would occur were all the water content condensed. The maximum TFP is located on the warm side of the areas of high thickness gradient.
- The positive (negative) vorticity describes the cyclonic (anticyclonic) rotation of a flow field, and for a given region if the positive vorticity increases with height and time (positive advection) it makes a contribution to upward motion, involving the possible formation of clouds.
- Contribution to upward motion also exists when warm advection takes place, while cold advection contributes to a sinking motion.

These parameters should be used to evaluate 2D surface maps, but the use of vertical cross-sections are a fundamental tool in creating a 3D view. Of particular interest are:

- the lines of equivalent potential temperature (isentropes), which are especially useful for revealing frontal zones where they are close together, when used in combination with the other parameters described as well as others such as:
- humidity, wind, or measures of stability or instability through wind convergence, because it is assumed that upward vertical motion exists if convergence occurs at the surface level, and as a consequence clouds could develop (and precipitation may occur).
this crowded zone, the TFP shows maximum values along 30°N–105W and 45°N–90°W. Across northern latitudes and perpendicular to the track of the AR there is also a sharp gradient in equivalent potential temperature and TFP, indicating a warm front. In the area behind the AR, within the cold front there is positive vorticity advection at 500 hPa, especially over the southern part of the MSLP trough, and in the occlusion point (the point at which a warm front, cold front, and occlusion meet according to the AMS glossary; https://glossary.ametsoc.org/wiki/Point_of_occlusion), and the vorticity advection is negligible east of the AR. The temperature advection at 850 hPa shows pronounced cold advection over eastern Mexico and the eastern Great Lakes, underlining the presence of a cold front there, while the marked warm advection in the area of the northern Great Lakes immediately ahead of the AR indicates the existence of the WCB. The wind pattern at 850 hPa shows a relative maximum over the area of landfall of the AR. In contrast, the July 8, 2010 case (Figures 2b and 4b) is not associated with any frontal structure; there are no maximum TFP values and no high gradient of equivalent thickness to the west of the maximum IVT and IWV in its vicinity. There is no question that this event does not correspond in any sense to a system such as the one described above. An isolated relative maximum of wind is detected at 850 hPa (Figure S1d) in the area of landfall of the AR. Following the algorithm used to detect LLJ systems proposed by Algarra et al. (2019), a Great Plains LLJ event is detected from 32.5°N–99°W to 42.5°N–85°W at local night time (white filled boxes in Figure 2b).

The use of vertical cross sections permits us to see the different thermodynamic structures and to refine even more the assignment to a synoptic conceptual model. Figure 4c,e shows that the May 1 case corresponds to a typical cold front with (i) the isentropes showing a vertical gradient zone near the surface and downwards with height through the whole troposphere (showing the frontal zone), (ii) a frontal zone within a positive vorticity advection, in which the advection increases with height; this is especially clear west of the AR landfalling point at 95°W, reaching a maximum just below the tropopause, and (iii) a positive temperature advection dominates within the frontal surface and predominates negative behind it. The remaining parameters (see Figure S2) corroborate this pattern with (iv) the wind increasing from the surface to a pronounced maximum near the tropopause, over 300 hPa, (v) vertical motion with negative values (upward motion) within and above the cold frontal zone, with weak positive values (downward motion) behind the cold frontal zone, (vi) the relative humidity higher ahead of the TFP maximum zone, with a backward tilt with

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**Figure 2** Meteorological configuration for two atmospheric rivers (ARs) that landfall on the SE coast of the United States and flow northwards on May 1, 2010 (a) and July 8, 2010 (b), selected from the database of Guan & Waliser (2015). The AR axes before landfall are denoted by the empty white boxes, the point of landfall is shown filled in. White filled boxes show the axis of the Great Plain low level jet detected as in Algarra et al. (2019). The white line denotes the positions of the vertical cross sections used in Figure 4 (and Figure S2). The arrows symbolize the integrated water vapor flux (IVT; kg m⁻¹ s⁻¹) from the surface to 300 hPa. The colored field represents the integrated vapor water (IWV; kg m⁻²). Black contours indicate the mean sea level pressure (MSLP; hPa), the center of the low level system pressure is highlighted with the letter L.
height, which is lower behind the surface of the frontal zone, and (vii) wind convergence predominant within the frontal zone and divergence above it.

On July 8 case the isentropes (Figure 4d,f) show an equivalent temperature structure that corresponds with a statically unstable region. The vorticity advection (Figure 4d) is symmetrical about the LLJ axis, with negative values to the left side of the LLJ core and positive on the right side. The maximum of moisture content is accompanying with a wind maximum centered at 800 hPa (Figure S2k,g respectively), absolutely compatible with an LLJ system. The maximum wind convergence occurs at low levels and the maximum vertical motion occurs at mid-levels in the LLJ exit region (Figure S2i,h).

4 | THE UNCERTAIN SUBTROPICAL ORIGIN OF THE MOISTURE IN ARs

The origin of moisture associated with AR events has been the subject of much recent debate. ARs are considered the main mechanism of meridional transport of moisture and latent heat on the Planet (e.g., Gimeno et al., 2016 and references therein). In this sense, the articles that point to the importance of moisture advection with (sub)tropical origin in
FIGURE 4  Meteorological configuration for two atmospheric rivers (ARs) that landfall on the SE coast of the United States and flow northwards on May 1, 2010 and July 8, 2010, selected from the database of Guan & Waliser (2015). (a,b) The AR axes before landfall are denoted by the red boxes, the point of landfall is shown filled in. Orange filled boxes in (b) show the axis of the Great Plain low level jet detected as in Algarra et al. (2019). The magenta line (A–B) denotes the positions of the vertical cross sections used in (c–f). The arrows symbolize the integrated water vapor flux (IVT; kg m$^{-1}$ s$^{-1}$) from the surface to 300 hPa. Colored contour in blue is the thermal front parameter (TFP) at 700 hPa, and green lines represent the equivalent thickness at 500/850 hPa (units: dam). (c–f) Vertical cross sections for A–B, the point of landfall is denoted with the red box in the abscissa in each plot. Contours in black represent the isentropes (units: °C). Colored contours denote: (c,d) vorticity advection (units: 10$^{-8}$ s$^{-2}$ 12 h$^{-1}$), and (e,f) temperature advection (units: °C 12 h$^{-1}$).
shaping the structure of the AR are numerous (e.g., Eiras-Barca et al., 2017; Knippertz et al., 2013; Ramos et al., 2016a; Ryoo et al., 2011; Sodemann & Stohl, 2013). However, the critical role played by the local convergence mechanism along the path has been also identified as essential for maintaining the structure and ensuring its continuity (Bao et al., 2006; Dacre et al., 2015). Much discussion has focused on the apparent discrepancy in determining whether the primary source of moisture associated with ARs is of (sub)tropical origin, or whether it can be explained by a local convergence mechanism. It appears reasonable that both mechanisms are real, and probably necessary, and that the relative contribution of each varies according to the dominant meteorological pattern for each event. In this sense, the recent contribution of Hu & Dominguez (2019) used the Eulerian moisture tracer tool coupled to the WRF model (WRF-VT) to show the complementary existence of the two mechanisms for the ARs that made landfall in the North-western US Coast in recent decades. In particular, they reported that ARs with a clear tropical contribution showed stronger pre-cold-frontal LLJs and stronger warm advection. They also stated that the events that have caused the most rainfall are those with a clear tropical connection, but even in these cases, most of the precipitation associated with these events was not of subtropical origin. A similar conclusion has been obtained by Nusbaumer & Noone (2018), making use of the water tracer and water isotope-enabled Community Atmosphere Model version 5 (CAM5) for both the modern era and the late 21st century. Particularly, they have found that more than 70% of the moisture associated with these events was not from tropical latitudes. Despite this, the injection of moisture associated with these events from tropical latitudes is expected to increase by more than 15% by the end of the century. These increasingly frequent results highlight the impossibility of attributing the entirety of moisture transport to a single mechanism. Real events are proven to combine both with variable relative contributions depending on different aspects.

Algarra et al. (2020), using the phenomenological and objective ARs database of Guan and Waliser (2015), identified 24 regions of maximum occurrence of AR landfall activity around the Globe. After a filtering process in which the regions mainly affected by monsoonal climatology were discarded, these authors made use of the Lagrangian dispersion model FLEXPART to determine the regions of maximum evaporative contribution to the structure of the AR, thereby identifying the main source regions from a climatological perspective. Further information about the methodologies

| AR landfalling date and position | May 1, 2010 12 h; 30° N–91.5° W | July 8, 2010 18 h; 28.5° N–97.5° W | Check in figure |
|---------------------------------|---------------------------------|---------------------------------|----------------|
| Great Plains LLJ detected       | No                              | Yes (at 32.5° N–99° W to 42.5° N–85° W) | Figures 2 and S1 |
| Maximum of TFP                  | Yes                             | No                              | Figures 4 and S1 |
| Gradient of equivalent thickness| Yes                             | No                              | Figures 4 and S1 |
| Maximum humidity                | Ahead of the TFP zone, and backward tilt with height | At surface and in vertical | Figures 2, 4, S1 and S2 |
| Vorticity advection in cross section | Increases with height, maximum just below the tropopause | | Figures 4 and S2 |
| Gradient in temperature advection in cross section | Negative behind the frontal zone | Symmetrical to the AR axis | Figures 4 and S2 |
| Vorticity advection field associated | Yes | No | Figure S1 |
| Gradient in temperature advection field | Yes | No | Figure S1 |
| Wind max growing with height    | Yes | No | Figure S2 |
| Wind divergence                 | Convergence within frontal zone, divergence above frontal zone | Convergence at low levels | Figure S2 |
| Maximum vertical velocity       | Within and above the cold frontal zone | Symmetrically to the AR axis at mid-levels | Figure S2 |
used can be found in Algarra et al. (2020). Here, we make use of the position of the centroids of the moisture contribution areas associated with each of the AR events analyzed. The positions of these centroids are representative of the regions most significant in terms of the contribution of evaporation for each event. Events fed mostly by tropical moisture show centroids located within tropical latitudes, while events with significant contributions from local convergence show centroids closer to the point of landfall.

Figure 5 shows the position of the aforementioned centroids, for the set of regions found after filtering for monsoon activity. The regions are displayed in four separate groups (a–d) for easier interpretation. The most notable results that can be obtained from this analysis are as follows: (1) most of the regions show a relevant variability in the positions of the centroids; (2) most centroids are located in an area comprising both (sub)tropical and midlatitudes; particularly if the region of interest is below 45°C. This indicates the notable variation in the relative contribution of advection of (sub)tropical origin and local convergence in each case; and (3) some regions (R1, R12, R13, R18, R22, R23) show most of their associated centroids far from what may be considered a (sub)tropical latitude. This shows that the connection between the baroclinic structure and the tropical latitudes should not be imposed in the characterization of ARs.

5 | CONCLUSIONS

Given that ARs are generally identified using objective thresholds and—more recently—machine learning methods based on phenomenological descriptions, there are two key assumptions made in the conceptualization of ARs, namely a similar meteorological pattern and the subtropical origin of moisture that feeds them; this cannot be seen in many of the ARs identified using these approaches. In this opinion piece, we have shed light on this issue and discussed these two aspects of moisture origin and associated meteorological patterns.

We have shown that not all ARs correspond with the same type of meteorological pattern. Consequently, the local impacts in terms of precipitation associated with ARs could be very different. The unequivocal relationship between the existence of ARs and intense precipitation is the argument of many current studies and future projections, in terms of precipitation intensity, frequency of events or spatial changes. However, the precipitation linked to these events is
not the same depending on the associated meteorological system, not even on one same region, where different meteorological systems may occur. Therefore, the observed and future precipitation patterns associated with ARs must take into account not only the simple occurrence or location of ARs, but also the frequency distribution among different weather systems associated to them. It is thus a great challenge to subcategorize the ARs according to the synoptic systems associated.

We have also shown that the (sub)tropical origin of the humidity associated with ARs is a common but not universal characteristic. A large number of the ARs detected and analyzed globally show the epicenter of the contribution of evaporation far from latitudes that can be considered subtropical. In addition, the local convergence is posited as a complementary mechanism to that of advection of (sub)tropical moisture, and it can play a major role in events to the north of the midlatitudes where many of the sources are located.

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CONFLICT OF INTEREST
The authors have declared no conflicts of interest for this article.

DATA AVAILABILITY STATEMENT
The data that support the findings of this study are available from the corresponding author upon reasonable request.

AUTHOR CONTRIBUTIONS
Luis Gimeno: Conceptualization (lead); funding acquisition (lead); project administration (lead); supervision (lead); writing & original draft (equal); writing & review and editing (lead). Iago Algarra: Data curation (equal); formal analysis (equal); methodology (equal); software (equal); validation (equal); visualization (equal); writing & original draft (equal); writing & review and editing (supporting). Jorge Eiras-Barca: Formal analysis (equal); investigation (equal); methodology (equal); software (equal); validation (equal); visualization (equal); writing & original draft (equal). Alexandre M. Ramos: Data curation (equal); formal analysis (equal); methodology (equal); software (equal); validation (equal); writing & original draft (equal). Raquel Nieto: Conceptualization (supporting); formal analysis (equal); funding acquisition (lead); methodology (equal); software (equal); validation (equal); visualization (equal); writing & original draft (equal); writing & review and editing (supporting).

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