

## Major mechanisms of atmospheric moisture transport and their role in extreme precipitation events

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**Abstract:**

We review the major conceptual models of atmospheric moisture transport, which describe the link between evaporation from the ocean and precipitation over the continents. We begin by summarising some of the basic aspects of the structure and geographical distribution of the two major mechanisms of atmospheric moisture transport, namely low-level jets (LLJs) and atmospheric rivers (ARs). We then focus on a regional analysis of the role of these mechanisms in extreme precipitation events, paying particular attention to the intensification (or reduction) of moisture transport and the outcome of this in terms of rainfall anomalies and subsequent flooding (drought), as well as considering changes in the position and occurrence of LLJs/ARs with respect to any associated flooding or drought. We then conclude with a graphical summary of the impacts of precipitation extremes, highlighting the use of this information to hydrologists and policymakers, and we describe some future research challenges including the effects of possible changes to ARs and LLJs within the context of future warmer climates.

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## 1.- INTRODUCTION

Each of the main components of the hydrological cycle plays a major role in the global climate system (1). Thus, considered from the perspective of climate change and variability, it is therefore of the utmost importance to obtain the best possible understanding both of the intensity of the hydrological cycle and of its evolution over time. Indeed, this could be said to represent one of the most important challenges for research in geoscience for **the next** century. Understanding the processes governing the evaporation of water from the oceans (2), and the transport of atmospheric moisture (3) are each particularly important, as is understanding the effects of each of these processes on the hydrological cycle (4) - all within the context of the current paradigm of global climate change (5).

The transport of moisture from the oceans to the continents makes up the atmospheric branch of the water cycle and forms the link between evaporation from the ocean and precipitation over the continents (1). A detailed study of this transport could provide us with both a better understanding of any observed changes and some physical evidence in support of the many available projections of future climates (e.g., 6-8). Our understanding of the transport of moisture is also motivated by obtaining a firmer grasp of the monsoonal precipitation that plays a significant role both in local continental evaporation and in the transport of vapour from adjacent oceanic regions (e.g., 9). A better understanding of the role of anomalies in the transport of moisture as observed during natural hydro-meteorological hazards is also required, in relation to extreme drought (e.g., 10) or intense precipitation (11).

A review of the conceptual models of moisture transport is required to underpin any study of the origins of continental precipitation. Of the two large-scale dynamical/meteorological structures known to play important roles, namely Low-Level Jet systems (LLJs) and Atmospheric Rivers (ARs), the former are known to be key in tropical and subtropical regions. The characteristics of LLJs were discussed by Stensrud (12) and their transport of moisture and their characteristics have been described in a number of regions (e.g., 13). ARs are also important in the transport of moisture, although these structures are mostly confined to extratropical regions (14). A large proportion of extreme precipitation events in western USA (e.g., 15) and western Europe (16) are now thought to be linked to the occurrence of ARs, including some famous historical floods (e.g., 17). Overall, the contributions of ARs and LLJs to total precipitation at the regional scale are not yet well quantified, and are likely to be larger than previously considered. Moreover, there has never been any attempt to unify our understanding of these processes at the Global level, and a global assessment is therefore one of our aims here.

The transport of moisture by ARs and LLJs is also connected to monsoonal regimes and to other important natural hazards. It has been suggested that there are two main sources of monsoonal precipitation, namely local continental evaporation and transport from adjacent oceanic regions (e.g., 18, 9). Several researchers have identified low levels of moisture transport during the active phases of monsoon regimes (e.g., 19). There is nevertheless a degree of uncertainty concerning the mechanisms involved in the anomalies in the transport seen during precipitation extremes and their consequences (i.e., drought or flooding). Drought occurs when there is significantly less moisture available than

normal for long periods, and the demand for water cannot be met (20) while the transport of large amounts of water vapour and its associated convergence may trigger extreme rainfall events and cause flooding (21). The persistence of drought could be due in part to a lack of transport to the continents (22) as seen during the most recent major drought in the Iberian Peninsula (10) and Southeastern Brazil (23).

In this review we will focus on the two major mechanisms of atmospheric moisture transport described above (LLJs and ARs) and discuss their roles in extreme precipitation events (**droughts and flooding**), paying particular attention to i) the intensification (or reduction) of moisture transport caused by each together with their role in rainfall anomalies and **flooding (drought)**, ii) changes in the position and occurrence of LLJs/ARs with respect to any associated in rainfall, changes and associated flooding and drought, iii) possible changes affecting ARs and LLJs within the context of future warmer climates.

## **2.- GENERAL OVERVIEW OF MAJOR ATMOSPHERIC MOISTURE TRANSPORT MECHANISMS**

### **2.1 Atmospheric rivers**

Atmospheric rivers (ARs) are relatively narrow atmospheric corridors along which much of the atmospheric water vapour is transported from the subtropics to the midlatitudes (24). It is generally accepted that more than 90% of the total midlatitude vertically integrated water vapour flux is transported by these structures. A wide range of alternative terms have been used for this meteorological phenomenon over the past few decades, including “tropospheric

rivers”, “tropical moisture exports” (25) or “moisture conveyor belts” (26). At a more regional scale ARs have also been given local names such as “Hawaiian fire hose”, “Pineapple Express” (27) or “Maya Express” (28). Nevertheless, the term “atmospheric river” is now widely accepted, implying the ability of these structures to transport water in the atmosphere at rates similar to those seen in the largest rivers of the world (24, 29). ARs supply water vapour, bringing large amounts of precipitation and often contributing to extreme precipitation events, causing flooding, inducing landslides and damaging ecosystems. However, ARs also play a critical role in water supply for regions such as California and Arizona in the United States of America (15, 30).

Over the past few decades, there have been several publications regarding the structure of ARs, and a complete list of observational and modelling results is presented by Gimeno et al. (14). In essence, ARs are shallow (having a height of 1 - 2.5 km) and narrow (about 300–500 km in width) plumes with high water vapour contents, stretching over distances of at least 2000 km, and are often associated with the pre-cold-frontal region of extratropical cyclones in the region of the warm conveyor belt (31). ARs are always associated with strong winds at low levels of the atmosphere while a low-level jet (LLJ) is positioned ahead of the maximum moisture flux (Fig 1a) due to the temperature gradient across the cold front. This produces a concentrated band of intense low-level specific humidity and a vertical distribution of equivalent potential temperature (32, 33) showing subsidence at low levels ahead of the AR, a low-level potential instability on the rear part of the front, and a moist-neutral stratification in the area of the AR. In the context of ARs, it is important to highlight the relationship between warm conveyor belts (WCBs) and tropical moisture exports (TMES) as recently proposed

by a small group of experts at the International Atmospheric Rivers Workshop, at which a consensus was reached on the definition of each component (34): "... the WCB refers to the zone of dynamically uplifted heat and vapor transport close to a midlatitude cyclone. The vapor is often transported to the WCB by an AR, and the result of the uplift is heavy rainout that generally marks the downwind end of AR conditions if the AR hasn't experienced orographic uplift (upslope flow) and rainout over mountains earlier along its approach to the WCB. TMEs are zones of intense vapor transport out of the tropics, vapor that is frequently conducted by ARs toward cyclones and WCBs. TMEs can provide important vapor sources for ARs, but most ARs also incorporate midlatitude sources and convergences of vapor along their path."

Two main approaches are generally used to detect ARs using an objective analysis. The first is based on the computation of the Integrated Water Vapour (IWV) (e.g., 33, 15, 35); the second uses the vertically integrated horizontal water vapour transport (IVT) between two atmospheric levels (e.g., 24, 16, 36-37). A recent review presented an exhaustive summary of the main methodologies used (14).

Typically, between 3 and 5 ARs occur in each hemisphere at the same time. Intense ARs with particular meteorological relevance in terms of precipitation are more frequent in winter. Even though the IWV in the ARs is sometimes greater in summer, the vapour flux is stronger in winter due to the stronger flows associated with extratropical cyclones. During the cold season ARs are associated with a winter planetary wave number of 4-5 (24). Regions affected by extratropical cyclones are therefore potential areas of AR occurrence. In the last decades maps showing the general distribution of ARs have been produced (e.g., 24, 38)



and these were also summarised in the recent works of Gimeno et al. (14) and of Guan and Waliser (37). Figure 2 illustrates the main regions of their occurrence. ARs are generally detected along the eastern borders of the Atlantic and Pacific oceans, in the western north and south Atlantic, on both sides of the Indian Ocean (in South Africa and Australia), and on the coast of Japan. There are additional “river fluxes” over regions such as the Indian Peninsula and the Caribbean, but these are related more to monsoonal regimes and low-level jets, therefore strictly speaking they are not ARs.

Through orographic lifting, ARs can produce large amounts of precipitation when they reach coastal areas. However, this is not the only mechanism inducing the upward motion of moisture; other processes such as synoptic and mesoscale systems can play an important role in the intensification of precipitation via the associated convective motion, and mesoscale frontal waves can modify the stability or the duration of ARs (39). The last few years have seen an increasing number of studies showing the continental areas particularly affected by ARs (e.g., 14, 37). Three areas have emerged from this work in particular, namely the west coast of North America (39, 37), Western Europe (16, 37), and southwestern South America (37). Moreover, and as seen in Figure 2, several other locations are affected by ARs as previously detected and analysed, and these are further addressed in Section 3 together with their impacts. Figure 2 shows that ARs also have a high impact in regions such as the Gulf of Mexico, Greenland, Antarctica, and other areas that have received relatively little attention in the previous literature, such as Australia and New Zealand, southwestern South Africa, the pacific coast of Asia, and northeastern North America (37).

Several authors have shown how a few major modes of climate variability may significantly influence the occurrence of ARs. The Arctic Oscillation (AO) and the Pacific/ North American teleconnection pattern (PNA) in their negative phases increase the number of winter ARs in the western USA in comparison with the positive phases of these modes (90% and 50%, respectively) (37). A regional study of the British Isles showed that the impact of the Scandinavian (SCAN) negative phase contributes to increasing ARs in this area (42). The North Atlantic Oscillation (NAO) impinges its 'seesaw' behaviour on the occurrence of ARs in Europe (43), with an increase in ARs affecting the South of the continent during its negative phase, and when the NAO is in its positive phase the increase occurs instead in northern Europe. For the particular case of the Iberian Peninsula, the East Atlantic teleconnection pattern (EA) plays a more determinant role than the NAO regarding the inter-annual variability of the frequency of ARs (36). During an EL Niño event (the warm phase of the El Niño–Southern Oscillation (ENSO)), the frequency of ARs increases over subtropical and extratropical regions, with the opposite behaviour during La Niña (the cold phase). During an El Niño event more anomalies in terms of the number of ARs are seen over the northeastern Pacific, the north Atlantic, and the Gulf of Mexico. The impact of land falling systems is stronger in terms of precipitation in northwest USA and western Canada, but shows a decrease over California (37, 26). During the neutral phase of the ENSO, the transport of moisture from the tropics to the pole is favoured, and ARs appear to be more common (44, 26). Future changes in the occurrence of ARs in the context of climate change, including heavy and prolonged precipitation episodes associated with ARs, have also been being

modelled under future climate scenarios (e.g., 45, 46) in order to analyse future changes in ARs and to highlight any possible implications.

## **2.2 Low-level jets**

The wind corridors of the lower atmosphere are generally termed low-level jets (LLJs), and these carry much of the moisture transport from low to high latitudes or from warm oceans towards continental areas (Fig 2). Different definitions of LLJs are found in the literature (47). LLJ was firstly defined as a 'significant' wind maximum within the first 1.5 km of the atmosphere, decreasing by at least five knots to the next minimum at a higher level (48). The extensively adopted criterion of Bonner (49) is quite similar and includes the magnitude and vertical shear of the wind, which must exceed  $12 \text{ ms}^{-1}$  and decrease by at least  $6 \text{ ms}^{-1}$  to the next higher-level minimum or to the 3 km level, whichever is lower. Whiteman et al. (50) adopted Bonner's definition but added a weaker category of LLJs.

LLJs are primarily a warm-season phenomenon, and the mechanisms that drive them differ between coastal and inland jets (47). Coastal LLJs are generally in geostrophic balance and are associated with topography and with daily cycles of land–sea contrast (e.g., 51). In contrast, jets located inland within continents are generally driven by topographic and/or inertial effects, or may result from secondary circulations associated with upper-level flows (52). Topography may influence the behaviour of an inland jet in different ways. For example, several LLJs are the result of channelling through gaps in the terrain via the Bernoulli effect (e.g., over central Iran: 53). Barrier Jets flow parallel to the topography and often result from geostrophic adjustment (e.g., the South American LLJ: 13, 18).

The most commonly studied LLJs are those that achieve their maximum strength at night, forming at least in part from the decoupling of the planetary boundary layer (PBL) after sunset, hereafter we term these nocturnal low-level jets (NLLJs) (54). NLLJs tend to have maxima near local midnight, with the height of the jet core ranging from 300 to 600 m above ground level (AGL), with a mesoscale and synoptic-scale extent. Two major mechanisms favour the generation of NLLJs; the first depends on the decoupling and eventual recoupling of the lower troposphere to the surface through diurnally varying eddy viscosity driven by changes in solar heating (48), while the second is related to the response to changes in horizontal **baroclinity** arising from spatial contrasts in insolation and horizontal variations in the topography.

The lack of data at high temporal and spatial resolutions means that the proper study of NLLJs remains a particular challenge. There are a few exceptions for some systems where high resolution observational data are available, such as for the Great Plains of North America LLJ (e.g., 55-56), or where concerted field campaigns have been used, such as for the South American LLJ (e.g., 57). However, to overcome the problem of data scarcity, Rife et al. (54) made use of 21 years of global downscaled reanalysis data with a horizontal resolution of 40 km at hourly intervals to document the characteristics of NLLJs over the whole planet. An index of NLLJ activity was proposed based on the vertical structure of the temporal variation of the wind. Based on the methodology proposed by a Whiteman et al. (50), two criteria must be satisfied simultaneously: the first requires the winds at 500 m AGL (near jet level) to be stronger at local midnight

than at local noon, and the second requires the wind speed at the core of the jet (500 m AGL) to be stronger than that at a higher level (4 km AGL). This technique was used to resolve not only all the NLLJs known previously (12), but also some newly identified jets, including over Ethiopia, Venezuela, Guyana, Syria, Iran, Tarim Pendi, Tibet, the Brazilian Highlands, and the Great Rift Valley in Africa. Figure 2 shows the mean characteristics (strength and direction, the position and the velocity of the core jet) ) for each of these 18 NLLJ considered. Most of the NLLJs occur in the Northern Hemisphere because of the stronger land-sea temperature contrasts generated by the larger continental expanses. Also, NLLJs predominantly occur within 30° of the equator. Equatorwards of 30°, diurnal land-sea variations produce inertia-gravity waves that can propagate far from their origin (58). Polewards of 30°, the atmospheric response is more localised (e.g., a land-sea breeze).

Numerous authors have documented the linkage between NLLJs and rainfall in different regions, such as in the Great Plains (e.g., 59, 56), in South America (e.g., 60), in Africa (61), India (62), and the western Pacific (63). Monaghan et al. (64) introduced a statistical approach to categorising nocturnal precipitation extremes as a function of NLLJ magnitude, wind direction, and wind frequency. According to this study “Relationships between NLLJs and nocturnal precipitation extremes exist in at least ten regions around the world, including the US Great Plains, Tibet, northwest China, India, Southeast Asia, Southeast China, Argentina, Namibia, Botswana, and Ethiopia. For many jets, a physical linkage exists between the jet exit region and enhanced precipitation because mesoscale ascending motion often occurs near the exit of the NLLJ, where the jet encounters either an upward slope in the terrain or a frontal zone”. However, this relationship

with the jet exit region is unclear for other NLLJs, such as those in Guyana, Venezuela, Australia, India, and Brazil. These regions have a prominent coastal influence, and the diurnal cycle within the coastal zone tends to produce convection onshore during the day and offshore at night.

### **3.- REGIONAL STUDIES**

#### **3.1 North America**

The seasonality of the precipitation over the continental United States is strongly modulated by the transport of moisture from the subtropical and tropical oceans to the continental land mass. Early observational studies showed that a significant moisture flux into the United States during the summer season arrives as a southerly flow from the Gulf of Mexico (65). Station observations provided further evidence that from April to September, the south-central United States experiences nocturnal southerly wind maxima (sometimes in excess of 20 m/s) between 200 and 1000 m above the surface, known as the Great Plains Low-Level Jet (GPLLJ). The GPLLJ arises due to the strong pressure gradient at the western edge of the Atlantic subtropical high and interactions with the complex terrain of the Rocky Mountains and the diurnal variations of eddy viscosity within the boundary layer (66).

The GPLLJ plays a critical role in the hydrological cycle of the central United States. In a 2-month (May-June) Global Circulation Model (GCM) simulation, the GPLLJ was shown to bring in roughly one-third of all the moisture entering the continental United States (66). The jet has been extensively linked to precipitation throughout the region (56). Summer rainfall shows an early evening peak over

the Rocky Mountains and a near-midnight peak in the central Plains of the United States with more than 25% more precipitation falling by night than by day – all associated with the GPLLJ (56). In fact, parts of the Midwest and the central Plains receive more than 30% of their total night-time rainfall during the strongest LLJs, which are relatively infrequent (56). LLJs are most frequent in a large region extending from the Mexico-USA border to the upper Midwest, on the eastern slopes of the Rocky Mountains (49). However, the continental part of the enhanced LLJ-associated rainfall is variable and migrates from the north-central states in May to the south and eastern states in July and August. This migration follows an enhanced moisture flux and synoptic-scale patterns (56).

There is a well-known inverse relationship between the GPLLJ and the Gulf of California Low-Level Jet (GCLLJ), the latter influencing precipitation in the southwestern United States (55). When the GCLLJ is strong and precipitation increases over Arizona, the GPLLJ is weak and precipitation decreases over the Great Plains; however, the relationship is not symmetrical, and a strong GPLLJ is not related to a weaker GCLLJ (55). GCLLJ events are characterised by strong southerly winds that extend along the entire Gulf of California throughout the bottom 1-2 km of the atmosphere and extend into Arizona, southeast California and southern Nevada (67). The high winds of the GCLLJ can cause dust transport and reduced visibility, but when associated with moisture transport the jet is locally called a “gulf surge” event and brings a much-needed drop in temperature and an increase in moisture to the Arizona desert (68-70). Gulf surges are one of the principal mechanisms responsible for the strong advection of moisture and precipitation during the North American Monsoon season (70). Furthermore, recent research has found that a large proportion of gulf surge events are related

to tropical cyclones, suggesting a mechanism by which tropical cyclone moisture can be channelled into the southwestern United States (69, 71-74).

Periods of extreme precipitation over the central United States are linked to intensified GPLLJ moisture transport and moisture convergence downwind of the GPLLJ (75). Indeed, the GPLLJ played a critical role in the 1993 floods that affected the USA Midwest when the region experienced an increased **the** incidence of very strong LLJs in late June and early July (75, 76). However, extreme flooding in the Midwest is not just a regional phenomenon; it is also part of large-scale patterns that link the tropics and the midlatitudes via long-range moisture transport from areas as remote as the Caribbean Sea (77). Moisture sources for the extreme flooding events of 1993 and 2008 were both associated with this significant pathway known as the “Maya Express” that extends from the Caribbean Sea to Central America and then joins the GPLLJ as it enters the United States (77, 78). Understanding these events as part of a large-scale pattern of moisture transport is in line with the idea that the GPLLJ is the northerly branch of the Caribbean Low-Level Jet (CLLJ) as it crosses the Yucatan Peninsula and veers north into the United States (79). The Maya Express is essentially the local name for the AR structures that have recently been linked to the most extreme spring and summer flooding events throughout the region (80). Unlike the GPLLJ or the GCLLJ, ARs are not confined to a specific region and have no clear diurnal cycle. Perhaps the best known is the “Pineapple Express”, which can be clearly identified from satellite imagery as a long filament of water vapour connecting the Hawaiian Islands with western North America.

ARs have been extensively associated with extreme winter precipitation and flooding events throughout the western coast of the United States, undoubtedly



the region that has been the focus of the most attention (81-82, 15) – in stark contrast to ARs in central USA, which are spring and summer phenomena. In an analysis of four major watersheds in the western state of Washington, almost all the annual peak daily flow events were associated with ARs, and these events were characterised by above-normal temperatures that led to significant rain – as opposed to snow – causing flooding in the region (83). The role of the orientation of an AR in relation to topography has been shown to be a critical factor affecting the probability of flooding (83-84).

More recently, ARs have been linked to extreme floods in more inland locations of the southwestern USA (85-86, 30, 84). However, ARs in the southwestern United States can differ greatly from those affecting the west coast because moisture can be transported at mid-levels in association with cutoff lows off the coast of California and Baja (87, 30) While ARs are linked to extreme rainfall and flooding, they also play a critical role in water resources in the southwestern United States – this region is critically dependent on winter precipitation, and just a few of these extreme storms can bring most of the annual rainfall (15). These studies of ARs have led to a number of significant conclusions about their impacts, including i) the recognition that ARs cause of the majority of the flooding seen in rivers all along the west coast of the USA (39); ii) ARs represent the source of 30–50% of all the precipitation in this region (15); iii) ARs are frequently the cause of the end of drought periods on the west coast (40); iv) the megaflood seen in central California on Christmas Eve 1861 was produced by intense ARs (41).

### 3.2 Central and South America

Several jets modulate the climatology of Central and South America. The low-level jets identified over this region are the Caribbean LLJ (CLLJ) (88 for a review), the CHOCO Jet (89 for a review) and the South American LLJ (SALLJ) (13). South America is also affected by ARs at tropical and subtropical latitudes (90).

The precipitation over the Pacific coast of Colombia is determined by the low-level westerly (CHOCO) jet. The trans-equatorial winds blowing over the Pacific Ocean acquire a west-east trajectory and penetrate into Colombia as a LLJ (89). The CHOCO LLJ has a long pathway; it has been detected as far south as 30°S near the Chilean coast (91). The jet has a wind maximum at 900-1000 hPa, and is associated with strong land-ocean temperature gradients and therefore with a **baroclinicity** surface. This jet presents a very strong annual cycle, being imperceptible in February-April and intensifying from May to a peak in October-November (89). The long-term average transport of moisture has been estimated to be about 3800 m<sup>3</sup> s<sup>-1</sup>, which helps explain the existence of one of the rainiest areas of the planet along the Pacific coast of Colombia, and the development of strong erosion on the Western Cordillera of the Colombian Andes. The CHOCO LLJ is also able to transport moisture into southern Central America during boreal summer and autumn (92). Due to its position, the flow is highly modified by the ENSO phenomenon.

Over the Caribbean Sea, the Caribbean low-level jet (CLLJ) is located between northern South America and the Greater Antilles. This jet is responsible for the moisture transport from the tropical Atlantic Ocean into the Caribbean Sea and the Gulf of Mexico (east-west direction); its axis is located at 15°N, and the

intensified winds are confined below 600mb, with maximum values below 925 mb. The flow reaches the eastern Pacific, crossing Central America (90). It exhibits a very marked seasonal pattern after splitting into two main branches when it reaches the western Gulf of Mexico; during boreal summer the first of these branches turns to the north reaching central USA and becoming the GPLLJ. During boreal winter, the northeast trades blow across the **Isthmus**, and three distinct wind jets form caused by the major gaps in the Central American mountain range, one of which then merges with the CHOCO jet. The CLLJ is the regional climate modulator during summer when the jet is intensified, being responsible for the maximum precipitation over the Caribbean coast of Nicaragua and Costa Rica when convergence occurs in the jet, with reduced precipitation in the case of low-level divergence (88).

The easterly trade winds from the Atlantic Ocean penetrate into northern South America and flow along the eastern border of the Andes, crossing Amazonia and reaching the La Plata River Basin. This flow develops the structure of a LLJ, and is called the South American LLJ (SALLJ).

Moisture transport into and out of the Amazon basin has been studied since the 1990's using a variety of upper air and global reanalysis data sets, as well as data from climate model simulations. During the wet season in particular, moisture is exported from the Amazon basin and transported via the South American LLJ (SALLJ) along the Andes, contributing to precipitation over the La Plata Basin (29, 93-97). Changes in land use – particularly deforestation in the Amazon basin – alter the rate of evapotranspiration and affect the water cycle (98, 99). Some authors have suggested that the dominant sources of monsoonal precipitation are local continental evaporation and the transport of vapour from adjacent

oceanic regions (e.g., 18). The resulting reduction in regional moisture supply may have important consequences for the stability of Amazonian rainforests (100).

ARs are also important for the transport of moisture in extratropical regions (14). Applying this concept to the South American case, the trade winds flowing into Amazonia form an AR, as does the moisture that flows east of the Andes towards the subtropics (29, 96). The discharge of the AR east of the Andes to the subtropics over 20 dry seasons varied between 10 and 23 Gt day<sup>1</sup>, comparable to the discharge of the Amazon River. The two most important contributions were the flow from Amazonia and zonal flow from the Atlantic, followed closely by local net soil evaporation. The flow from Amazonia had the greatest effect on the variability of the total discharge. The heavy winter orographic precipitation events over Central Chile (Andes area) are strongly related to an intense water vapour transport from the southern Pacific in the form of an AR associated with extratropical cyclones (101). The most intense rainfall tends to occur near and above the crest of a mountain range (102).

### **3.3 Europe**

The intra- and inter-annual variability of European precipitation are both strongly affected by the transport of moisture from the North Atlantic and the Mediterranean into Europe (8). However, while the North Atlantic moisture source affects the whole of Europe mostly in winter, the Mediterranean source affects southern Europe in both winter and summer. One of the major mechanisms associated with moisture transport from the North Atlantic towards Europe are

ARs, usually embedded in the trailing fronts of extratropical cyclones. Despite the importance of the ARs in atmospheric moisture transport, the analysis of their contribution to precipitation in Europe has generally been restricted to a few specific extreme events (e.g., 28, 103). Only in the past few years have any long-term climatological studies been published (e.g., 36, 43).

ARs are responsible for about 20–30% of all the precipitation in parts of western Europe, with the maximum being recorded in autumn and winter (mainly in France and the Iberian Peninsula), the effects of ARs generally being felt further inland (e.g., Poland) than in the western USA. This is most likely a result of the blocking role played by the higher mountainous terrain in the latter, which acts as a barrier to inland penetration (104). In addition, there is a strong relationship between ARs and the occurrence of annual maximum precipitation days in Western Europe, which is particularly pronounced along the coast of Western Europe, where some areas had eight of their ten highest annual maximum precipitation days related to ARs (43).

In terms of local climatological studies, three areas have received particular attention: 1) the British Isles (16, 42); 2) the Iberian Peninsula, where daily precipitation extreme events were associated with ARs in different domains (36); and 3) Madeira Island, where precipitation over a 10-year period was associated with meridional water vapour transport in ARs during the winter (105). ARs have also been detected using different reanalysis datasets such as Era-Interim, NCEP/NCAR reanalysis (36, 42), and even 20<sup>th</sup> Century Reanalysis (17).

Lagrangian analysis has also been applied to ARs in Europe at different time scales. Sources of water vapour producing precipitation over Norway and the link with ARs were investigated over a 5-year period (21). A similar approach was

used - to analyse moisture origin and meridional transport in ARs and their association with multiple cyclones in December 2006 (106). - A Lagrangian climatology of tropical moisture exports (in AR-like structures) to the Northern Hemispheric Extratropics was developed (25) by analysing forward trajectories leaving a box between 0° and 20°N for the period 1979-2001. A backward trajectory approach was applied to study the AR moisture transport that reached different parts of Western Europe (107).

The importance of ARs in different extreme precipitation events in Europe was also analysed in detail to evaluate the extreme precipitation event that took place in the city of Lisbon (Portugal) in November 1983 (103), which produced flash flooding, urban inundations, and landslides, all of which caused considerable damage to infrastructure and led to some fatalities. This work showed that this unusual event was clearly associated with the transport of tropical and subtropical moisture by an AR associated with an extratropical cyclone. Two historical floods in the Iberian Peninsula are clearly associated with ARs, the first in December 1876 affected the south-western sector of the Iberian Peninsula, leading to the highest discharge ever recorded in two large international rivers (Tagus and Guadiana), with a significant socio-economic impact (17). The second affected the north-western sector of the Iberian Peninsula on 20–28 December 1909 and corresponds to the hydro-geomorphological event with the highest number of flood and landslides recorded in Portugal over the period 1865–2010 (108). This event also caused important social impacts in parts of Spain, especially in the Douro basin, having triggered the highest floods for more than 100 years at the river mouth in the city of Oporto (109). The intense precipitation and flash flood event of 20 February 2010 in Madeira caused more than 40 deaths, with many

missing and injured, together with a vast range of material losses, including the destruction of houses, industries, roads, bridges, and several thousand vehicles (110).

LLJs are not significant in terms of atmospheric moisture transport in Europe. Some LLJs can be identified, mainly offshore, such as in the Iberian Peninsula (111) or in Norway (112). These have some relevance for offshore wind installations and energy production.

### **3.4 Africa**

The climate of tropical Africa is dominated by the movement of the ITCZ and the monsoonal regimes that affect west and much of east Africa. To the north of this monsoon-influenced region lies the Sahara desert. To its south, southern Africa is essentially a narrow, peninsula-like landmass surrounded on three sides by oceans. Its climate, its marine and terrestrial ecosystems, and its economy are all strongly influenced by this land-sea configuration and associated marine influences. **While the Indian Ocean** has traditionally received the most scientific attention as the major oceanic moisture source for southern African summer rainfall (113), the South Atlantic and the Southern Ocean also play important roles (114). Most of the landmass receives the bulk of its rainfall during the austral summer, but the western part of South Africa mainly receives winter rainfall and the south coast experiences rainfall throughout the year. On the other hand, a bimodal rainfall regime occurs near the equator in Tanzania and the Eastern Congo Basin.

The seasonality of this precipitation is largely controlled by movements in the Inter-tropical Convergence Zone (ITCZ) and the subtropical semi-permanent anticyclones over the South Atlantic and South Indian Oceans. At seasonal scales, the major oceanic moisture sources for summer rainfall are the tropical western Indian Ocean (115), the subtropical South West Indian Ocean, and to a lesser extent the tropical southeast Atlantic Ocean (116). Inflow from the latter is facilitated by the development of a thermal low over northern Namibia / southern Angola in the Angola low in austral spring, which typically persists until late autumn. A secondary convergence zone links this feature with the meridional arm of the ITCZ that passes through the Congo Basin.

As is common elsewhere in the tropics and subtropics, the rainy season is made up of a number of wet and dry spells. Wet spells over South Africa during summer tend to be associated with an inflow of moisture from the tropical South East Atlantic that converges over the land mass with the mean easterly moisture inflow from the Indian Ocean (116).

Upstream planetary wave activity and associated ARs have been implicated in studies of heavy precipitation over South Africa brought by tropical temperate troughs (TTTs) (117). During summers with good rainfall, the Angola low is prominent and often acts as the tropical source region for the TTTs. The role of planetary waves is also highlighted in the evolution of TTTs, as well as the prime moisture source for these systems, which is the tropical Indian Ocean (117). The tropical southeast Atlantic typically acts as a secondary source. Additionally, the importance of latent energy build-up over the Mozambique Channel is also suggested for TTT development (118).



In the southern half of South Africa, most flooding events tend to result from cut-off lows (e.g., 119), but elsewhere in the sub-continent, tropical storms / cyclones are largely the cause (e.g., 120), particularly over Mozambique, Madagascar, Mauritius, and occasionally northeastern South Africa. Furthermore, mesoscale convective complexes (121) have led to flood events in the past, as have intense TTT events (122). Strong low-level jets (LLJ) transporting moisture from warm oceanic areas have often been implicated in these events. For cut-off lows, LLJs crossing the warm Agulhas Current and reaching the coastal mountains were found to be an important factor in flood events in the Western and Eastern Cape regions of South Africa (119, 123). These events also appeared to show ARs extending south from the Mozambique Channel over the southwest Indian Ocean and feeding into the flood regions in South Africa. Moisture inflow from the northern Agulhas Current / southern Mozambique Channel contributed towards heavy rainfall associated with Mesoscale Convective Complexes (MCCs) over KwaZulu-Natal / southern Mozambique (124), and from the northern Mozambique Channel for the intense TTT flooding that occurred in Mozambique in January 2013 (122).

In East Africa, a LLJ structure has recently been the focus of some attention (47). The so-called Turkana jet occurs in the Turkana Channel of northern Kenya. The jet occurs semiannually from May to October, being strongest during the June–September dry season, with typical core speeds of about 10–15 m s<sup>-1</sup>. The rainfall seems to be modulated by the jet, with strong jets suppressing rainfall during the summer rainy season and favouring aridity in northeast Kenya, southern Somalia, and southeastern Ethiopia.

### **3.5 Australia and New Zealand**

Australian climate is characterised by a vast arid center, encompassed by a wet tropical region in the north and temperate areas in the southwest and southeast. The monsoon is the most significant source of moisture to the northern areas of Australia. It occurs from November to April and handles approximately 90% of the total annual precipitation (125, 126).

The primary source of moisture and rainfall over the southern parts of Australia comes from synoptic systems during wintertime, e.g. cold fronts, embedded and cut-off lows. In the southern mid-latitudes, Tasmania and New Zealand experience a marked contrast of cloudiness and rainfall from west to east due to their mountainous topography and exposure to westerly winds. Rainfall is highest during austral winter over Tasmania and northern parts of New Zealand but is more evenly distributed throughout the year in the southern parts.

The large-scale transport of moisture in the Australian – New Zealand region is predominantly zonal and occurs to a great extent over the equator and mid-latitudes, with zonal migration of those bands throughout all seasons. The warm pool located in the equatorial western Pacific including the Coral Sea (e.g., 6) and north Tasman Sea are important sources of moisture for eastern Australia, which in conjunction with prevailing easterly winds during summer months provide enhanced onshore flow and orographic uplift favouring the occurrence of heavy rain along the eastern seaboard of Australia (127).

Unlike the so-called "Pineapple Express", the transport of moisture via ARs is not common in Australia. When ARs occur in the Australian sector, they are not confined to any region in particular, but in some cases they can be associated

with the 'Koorin LLJ', 'Southerly Busters', Northwest Cloud bands or LLJs created during the interaction of tropical moisture processes with extratropical weather systems. The strongest and most frequent LLJ in Australia was observed in Daly Water in the Northern Territory and it is referred to as the Korin nocturnal LLJ (128). The Koorin jet is associated with easterly winds typically between 15 to 30 ms<sup>-1</sup>s in the atmospheric boundary layer, and is strongest at night between June and August. It does not show a long, thin flow like those associated with synoptic events or certain terrains, instead it shows a broader horizontal extent than many common LLJs around the world (129). The Southerly Buster is a change in southerly wind that occurs mostly between October and February due to the interaction of a cold front with the Great Dividing Range in southeastern Australia (130, 131). It produces strong gusts of wind and a dramatic drop in temperature of 10-15 C in less than one hour. Sydney experienced its strongest Southerly Buster event on 18 December 1948 when a maximum wind gust of 113 kmh<sup>-1</sup> was recorded at the city airport. A Southerly Buster event in early February 1977 showed a coastal jet with a width of about 150 km over New South Wales, resembling an AR event (130).

ARs events can sometimes be generated along with the development of cut-off lows in the Australian sector. Cut-off lows in the Southern Hemisphere occur preferentially over southern Australia and New Zealand between 60°E and 130°W (38, 132), mostly from May to October. A classical formation of a cut-off low was observed in late August 1997, which interacted with a tropical water vapour channel resembling an AR event (133). In that particular case, an LLJ event transported moisture from the Coral Sea to higher latitudes, producing a

narrow moist tongue from the tropics to extratropical regions across southeast Australia. The narrow tongue provided an extra supply of moisture to the cut-off low and intensified the weather system, causing heavy rainfall over southeastern South Australia. Many cut-off low episodes in southern Australia are developed and strengthened by interactions with blocking highs located to their east over the Tasman Sea. In New Zealand, an AR event occurred in early March 1988 during the extratropical transition of tropical cyclone Bola, causing severe damage and flooding in the North Island (134). Heavy rainfall exceeding 800 mm in 5 days was recorded in Gisborne Ranges, in northeast New Zealand.

### **3.6 Indian / South Asian region**

The Asian Summer monsoon is a major feature in the general circulation. The southwest monsoon or the summer monsoon provides about 80% of the mean annual rainfall to the various meteorological sub-divisions of the Indian continent and is one of the most outstanding meteorological phenomena of them all (135). In a typical monsoon season, the monsoon sets in over the Kerala coast by 1st June and covers the entire Indian subcontinent by 15th July, withdrawing from northwest India by 1st September. Each monsoon is unique in three important aspects, namely 1) Monsoon onset over the Kerala coast, 2) Active and break in monsoon conditions within the monsoon life cycle (onset-active-weak-break-active-withdrawal) and 3) The amount of monsoon rainfall. There have been several studies of the source of moisture for the southwest monsoon rainfall, with the Arabian Sea (e.g., 136), and cross-equatorial flow (e.g., 137) considered the major sources. It is now widely recognised that inter-hemispheric cross-equatorial flow plays a major role in monsoon activity over the Indian subcontinent.

A study of the role of low-level flow in monsoon activity over the Indian subcontinent using 850 hPa winds showed the importance of low-level flow into the Indian subcontinent (Equatorial Indian Ocean) during active (break) monsoon conditions in two contrasting monsoon years, 1987 (deficit) and 1988 (excess) (138). A strong cross-equatorial LLJ with a core around 850 hPa exists over the Indian Ocean and South Asia during the summer monsoon season (June-September) (62). Their study showed that the axis of the LLJ was away from (towards) the Indian subcontinent during monsoon onset and break (active) **during monsoon conditions.**

The roles of the Southern Hemispheric Equatorial Trough (SHET) and the Eastern Equatorial Indian Ocean (EEIO) on monsoon activity have been studied using a suite of *in-situ*, satellite and reanalysis datasets (139). This study revealed that the EEIO is the warmest region in the north Indian Ocean compared with the Arabian Sea and the Bay of Bengal. The **SST** over the EEIO increased by about 1 C during the period 1951 – 2007, which in turn altered the large-scale ocean-atmosphere circulation processes and intensified the SHET and the moisture convergence in the region. This then resulted in a weakened southwest monsoon flow; i.e., a decrease in moisture transport from the Indian Ocean to the Indian subcontinent. By analysing daily rainfall data, the study also showed an increase in the prolonged break in monsoon conditions during the peak monsoon months of July and August in recent decades. These decadal-scale changes are consistent across several ocean-atmosphere parameters. While it can be concluded that the increasing trend of break monsoon conditions over the subcontinent is related to ocean-atmosphere processes, further study is needed

fully to comprehend the causative mechanisms that have altered the ocean-atmosphere coupled system.

The convective systems over the Northwest Pacific (NWP) region were found to play an important role in all aspects of the monsoon such as the monsoon over Kerala (MOK), active-break cycles, and the amount of monsoon rainfall (140). This study revealed that the convective systems were absent for about five pentads prior to and after the MOK during excess monsoon years. It also showed that there were twice as many convective systems over the NWP than over the Bay of Bengal region during deficit monsoon years and prolonged breaks in monsoon conditions. Such a scenario occurred in 2009 when there were about 18 convective systems over the NWP compared to only three in the north of the Indian Ocean (of which two formed in the Bay of Bengal). 2009 contained one of the lowest monsoon rainfalls in recent years with a seasonal deficit of 23%, making it second only to 1972, which had a deficit of 24%.

#### **4.- SUMMARY AND FUTURE CHALLENGES**

The analysis of the impacts of ARs and LLJs at the regional scale requires an explanation capable of representing the pan-global nature of the phenomena involved. This is attempted in Figure 3, which summarises in a graphical way the general impacts of precipitation extremes linked to ARs (blue) and LLJs (red), thereby providing useful information for hydrologists and policymakers.

Some of the most interesting potential future directions of AR studies lie perhaps in the area of multi-scale interactions, given that the dynamic processes that cause ARs span a wide range of spatial scales, from planetary-scale circulations

to mesoscale frontal waves (141). Furthermore, once an AR makes landfall, much smaller hydrological scales (watershed to hill slope) become relevant. Further work to understand the dynamical processes that lead to the formation of ARs (which would remove the subjectivity inherent in their identification) is also sorely needed. In this regard, the work of Newman et al. (142) moves away from the traditional definition based on shape to one that includes all “episodic poleward-moving moisture plumes”, which is more in line with traditional definitions of atmospheric phenomena. In addition, Dacre et al. (143) analysed selected cases of water vapour transport within a climatology of North Atlantic winter extratropical cyclones, introducing some scepticism to the widely accepted paradigm of the structural definition of ARs. They discussed the possibility that ARs are formed by a cold front that ‘sweeps up’ water vapour in the warm sector as it catches up with a warm front. This causes a narrow band of moisture to form with a high water vapour content ahead of the cold front at the base of the warm conveyor belt airflow. In this framework, water vapour in the warm sector of the cyclone, rather than the long-distance transport of water vapour from **the subtropics**, is responsible for the generation of filaments with a high water vapour content. However, the origin of the warm sector associated with most of the water vapour observed in ARs is at odds with recent results obtained using Lagrangian methods (107). The use of Lagrangian analysis is useful for assessing more precisely the sources of moisture associated with ARs. Ramos et al. (107) analysed 35 years of data allowing them to pinpoint the moisture sources for ARs arriving in 5 different domains in western Europe (Iberian Peninsula, France, UK, Southern Scandinavia & the Netherlands, and Northern Scandinavia). Their results confirm the important role played by the long-range advection of moisture

linked to ARs from **subtropical** areas between the Caribbean Sea and northern Africa. Future studies of ARs should also allow a more in-depth evaluation of the moisture sources for ARs from a Lagrangian point of view for other regions as well. There are also some important improvements needed for future studies of LLJs, particularly the need to increase the number of observations and the collection of data in specific places in order to better understand their structure and physical mechanisms. A better exploration of the role of complex terrain on LLJ development and its impact continues to be a challenge.

Most of the extreme precipitation events that occur in western Europe and the western USA are associated with winter AR events and in South America with LLJs. Both ARs and LLJs have been implicated in flooding events in subtropical southern Africa. Any study that aims to evaluate the changes in flood risk in these domains must take into account the potential role of AR response under different future climate change scenarios. For example, using multiple simulations (45) showed that the North Atlantic ARs affecting the UK are expected to become stronger and more frequent under different future scenarios. Likewise Warner et al. (144) showed that precipitation caused by extreme ARs will increase in the western USA under warmer climate scenarios. For LLJs, integrations using regional models have been used to good effect to evaluate **the impacts** associated with LLJs; for example Soares and Marengo (145) suggested for 2071-2100 for the A2 scenario that there could be a greater intensity of moisture transport from tropical regions available to feed the mesoscale convective systems in the subtropical La Plata Basin, due to the intense southward flow associated with a faster SALLJ bringing more moisture from the Amazon Basin southwards. A more intense SALLJ in a warming climate suggests an increased



transport of moisture from the north to the southeast of the Andes compared with at present, and an increase in the frequency of rainfall extremes in southeastern South America around the exit region of the LLJ.

Finally, special consideration should be given to the role of ARs in the highly sensitive (to climate change) regions of the Arctic and the Antarctic in future studies. For example, heavy snow accumulation in east Antarctica during 2009 and 2011 contributed significantly to the mass balance of the Antarctic ice sheet surface. Precipitation during these two years was associated with a few ARs that contributed to nearly 80% of the outstanding ice sheet surface mass balance (146).

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## Captions

Figure 1. Conceptual model of an Atmospheric River (AR) over the Northern Pacific coast in North America and of a Low-Level Jet (LLJ) over South America.

**(1) ATMOSPHERIC RIVER:** Schematic view of the positions of the polar-cold-front (in black) and the associated Low-Level Jet (LLJ, in dark blue). The orange arrow shows the AR. The integrated total column of water vapour (IWV)  $\geq 2$  cm is shown in green and the associated rain-rate enhancement (RR)  $\geq 0.5$  mm/h along the AR is shown in red. The precipitation area associated with the AR is denoted by the broken blue line. The pink line a–b marks the limits where the profiles for the bottom-left box are integrated: in red the vertical structure of the moisture flux, in green the moist static stability, and in blue the wind speed.

**(2) SOUTH AMERICAN LOW LEVEL JET (SALLJ):** Schematic view of the moisture transport into South America from the tropical (blue arrow) and subtropical (green arrow) South Atlantic Ocean that form the LLJ along the Andes. Thin orange arrows represent the northeast trades. The precipitation area associated with the LLJ is denoted by the broken blue lines. In the top-right-hand box, a typical vertical profile of a LLJ is shown including wind speed (in blue, m/s), specific humidity (red, g/kg) and temperature (green, °C).

// This figure is a new version of previously published plots. For the ARs we use figures adapted from Figure 23(a) in the Reference 33 and Figure 13(b) in the Reference 32. For the SALLJ we use Figure 1 in the Reference 18, and Figure 1(b) in the Reference 147.

**Figure 2. The global geographical position of ARs and LLJ.**

**(1) ARs:** Areas of ARs occurrence are shown by the large orange arrows.

Each arrow denotes the direction of flow. The figure is based on the References 24, 38, and several maps of Integrated Total Column of Water Vapour (IWV) composites. Orange circles denote the frequency (days/year) of AR landfall (37).

**(2) (2) LLJs:** Red and blue arrows show the locations of Night Low-Level Jets (NLLJ) detected by the Reference 54 in summer (red for the northern hemisphere and blue for the southern). The name of the jet (coloured box close to the arrow), its typical height (bottom-left, in m AGL) and its typical speed (bottom-right, in m/s) at the jet core are also displayed. The size of the arrow is scaled with respect to speed. These characteristics together with the position of the jet core were obtained from Table 2 in the Reference 54. In magenta, other LLJs with high climatic relevance are shown: the Great Plains Low-Level Jet (GPLLJ), Gulf of California Low-Level Jet (GCLLJ), Caribbean LLL (CLLL), Choco LLJ, South American LLJ (SALLJ), Turkana LLJ, Somali LLJ, Korin jet and Southerly Buster.

**Figure 3. Summary of the general impacts of extremes linked to ARs (in blue) and LLJs (in red) in terms of precipitation (broken line), intense precipitation (dashed contour), floods and landslides (coloured contour), snow (light blue dots) and drought (in brown for ARs and in red for LLJs).**

Figures:

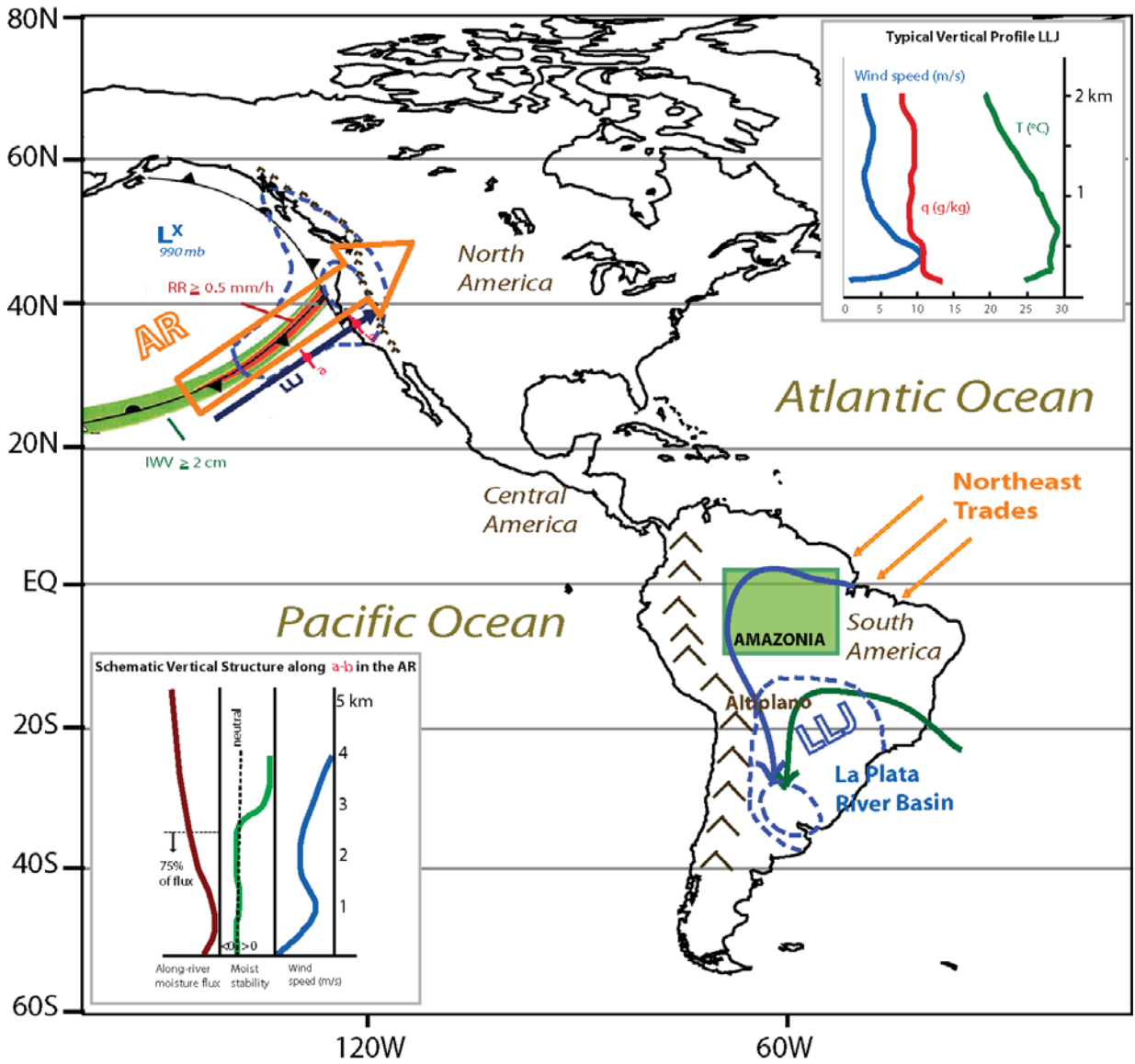


FIGURE 1

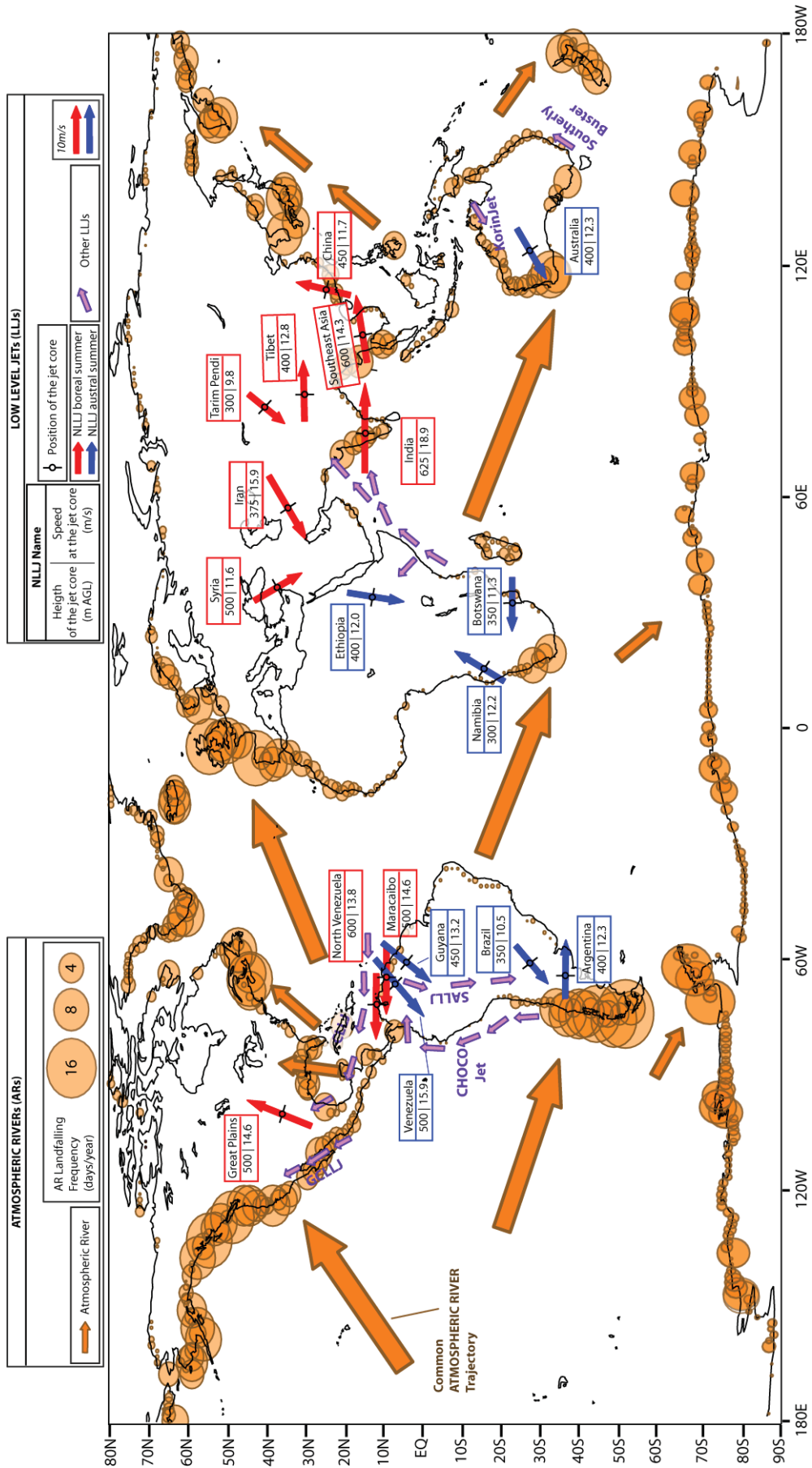


FIGURE 2



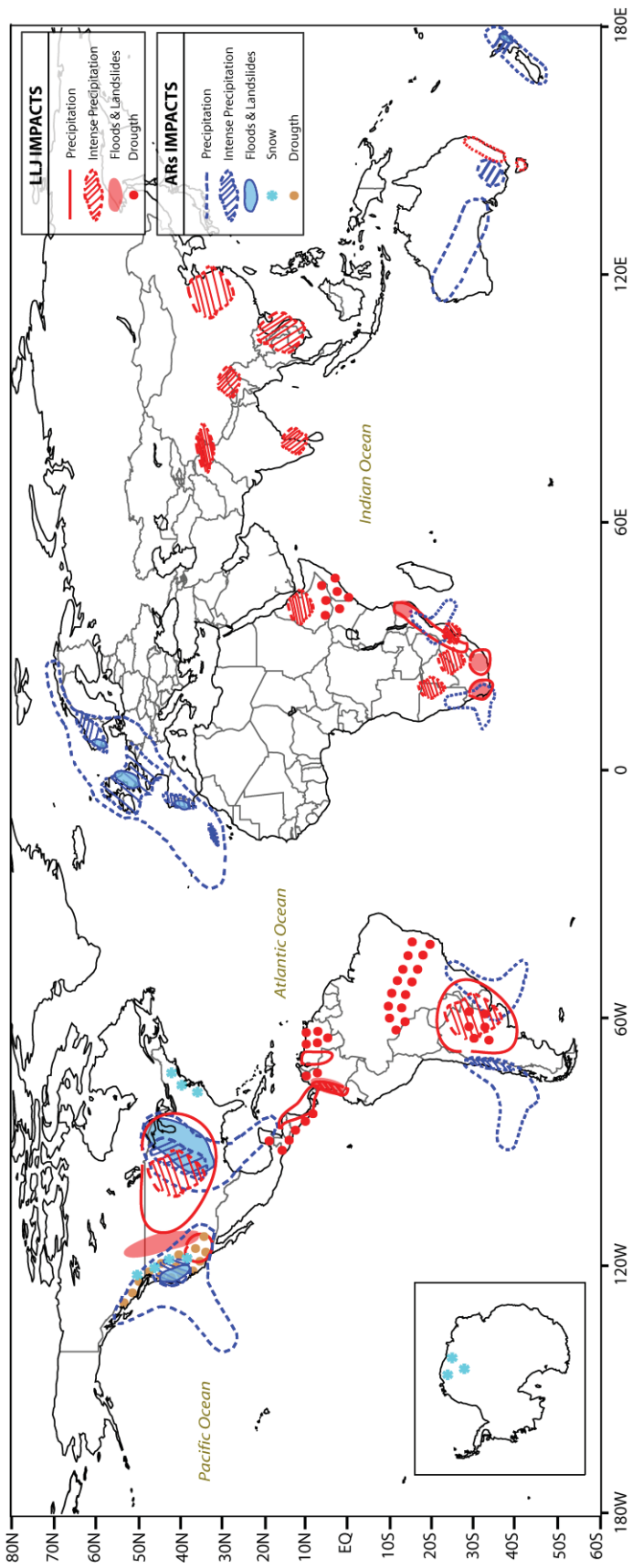


FIGURE 3