

## Atmospheric rivers in the Australia-Asian region: a BoM–CMA collaborative study

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**Abstract.** The name ‘atmospheric river’ (AR) could easily be misinterpreted to mean rivers flowing in the sky. But, ARs actually refer to narrow bands of strong horizontal water vapour transport that are concentrated in the lower troposphere. These bands are called ‘atmospheric rivers’ because the water vapour flux they carry is close to the volume of water carried by big river systems on the ground. ARs can cause heavy rainfall events if some physical mechanisms, such as orographic enhancement, exist to set up the moisture convergence and vertical motions necessary to produce condensation. In recent decades, these significant moisture plumes have attracted increasing attention from scientific communities, especially in North America and western Europe, to further understand the connections between ARs and extreme precipitation events which can trigger severe natural disasters such as floods, mudslides and avalanches. Yet very limited research has been conducted in the Australia-Asian (A-A) region, where the important role of atmospheric moisture transport has long been recognised for its rainfall generation and variations. In this paper, we introduce a collaborative project between the Australian Bureau of Meteorology and China Meteorological Administration, which was set up to explore the detailed AR characteristics of atmospheric moisture transport embedded in the A-A monsoon system. The project in China focused on using AR analysis to explore connections between moisture transport and extreme rainfall mainly during the boreal summer monsoon season. In Australia, AR analysis was used to understand the connections between the river-like Northwest Cloud Band and rainfall in the region. Results from this project demonstrate the potential benefits of applying AR analysis to better understand the role of tropical moisture transport in rainfall generation in the extratropics, thus achieve better rainfall forecast skills at NWP (Numerical Weather Prediction), sub-seasonal and seasonal time scales. We also discuss future directions of this collaborative research, including further assessing potential changes in ARs under global warming.

**Keywords:** atmospheric river, extreme rainfall, monsoon, narrow band of strong moisture transport, Northwest Cloud Band, weather and seasonal forecasts.

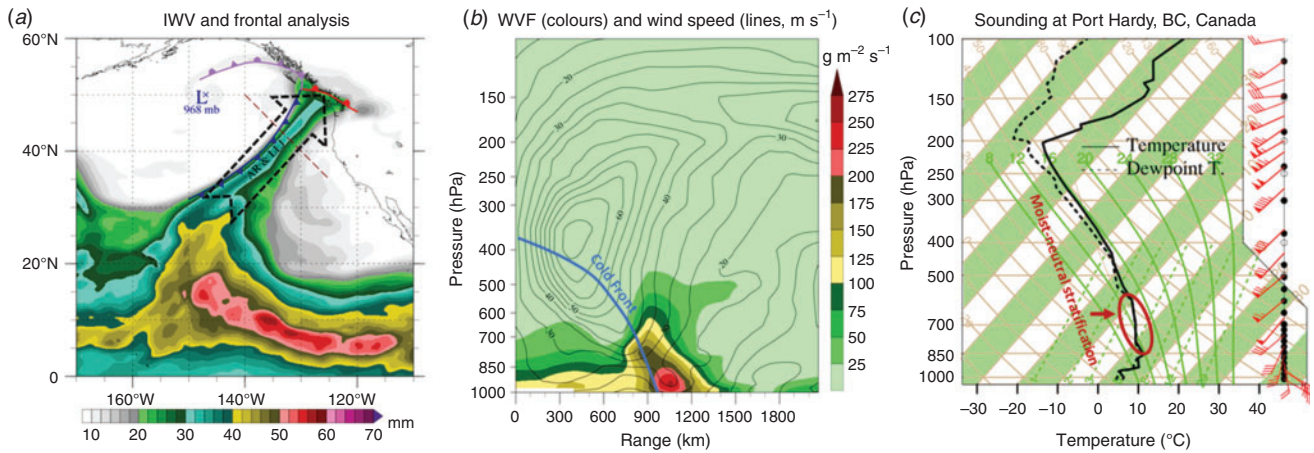
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### 1 Introduction

Atmospheric rivers (ARs) have received increasing attention from meteorological and hydrological communities in recent decades due to the close association of ARs with extreme rainfall events, mainly occurring on the western coasts of North America (Zhu and Newell 1994; Ralph *et al.* 2004, 2006; Neiman *et al.* 2008a, 2008b; Smith *et al.* 2010; Dettinger *et al.* 2011; Warner *et al.* 2012, 2015; Gershunov *et al.* 2017, 2019; Mo *et al.* 2019), South America (Garreaud 2013; Viale *et al.* 2018) and Europe (Lavers *et al.* 2011, 2012; Lavers and Vilarini 2013, 2015). As Ralph *et al.* (2017) pointed out, there has been a rapid increase in scientific publications on ARs, from a few in the 1990s to over 200 per year in recent years. The analogy to ‘river’ could be misleading, because it can be misinterpreted as suggesting there are rivers in the sky operating like these on the ground, with fixed channels and tributaries. Instead, the term

refers to narrow bands of strong horizontal water vapour transport concentrated in the lower troposphere, which can cause extreme rainfall when these moisture belts meet with some dynamical lifting mechanisms, such as orographic uplift. Nevertheless, the terminology of AR, which was coined by Zhu and Newell (1994, 1998), has now been widely accepted in the scientific literature (Gimeno *et al.* 2014; Ralph *et al.* 2017). These bands are called ‘atmospheric rivers’ because if the water vapour flux carried within them were to precipitate out, the volume of water would be equivalent to that transported by big river systems on the ground (Zhu and Newell 1994).

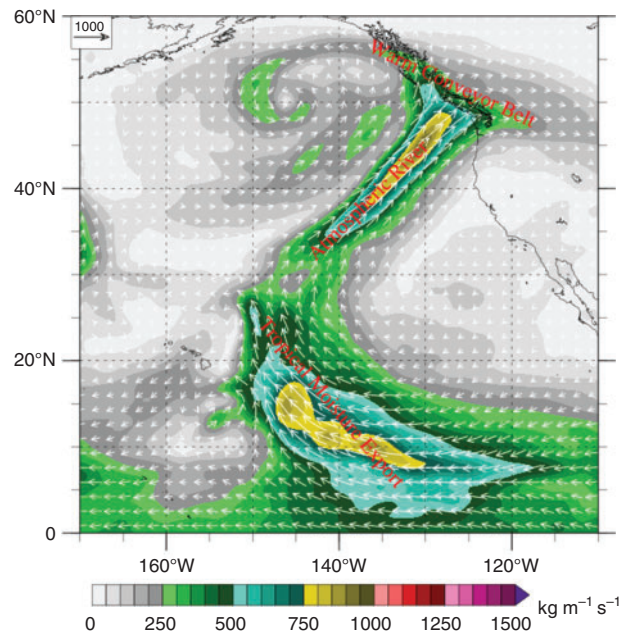
Fig. 1 shows the characteristics of a typical AR making landfall in western Canada at 0000 UTC 29 January 2018. It fits well with the conceptual model for the ARs over the Northeast Pacific shown in Gimeno *et al.* (2014) based on an observational campaign over the west coast of North America (Ralph *et al.*



**Fig. 1.** Conceptual model based on a typical AR making landfall on the west coast of North America at 0000 UTC 29 January 2018. (a) Vertically integrated water vapour (IWV) associated with a polar cold front along with LLJ (low-level jet), with the AR being schematically depicted by the dashed arrow. (b) Cross-section through the AR along the northwest-southeast red line in (a) for horizontal water vapour flux (WVF, coloured shading) and wind speed (black lines with contour interval  $5 \text{ m s}^{-1}$ ). Note that the core of the AR is below the 850-hPa level and is co-located with a pre-cold frontal low-level jet. (c) Vertical structure of the AR shown as the Skew- $T$  log- $P$  diagram of the sounding profile observed at Port Hardy, BC, Canada ( $50.68^\circ\text{N}$ ,  $127.36^\circ\text{W}$ ).

2004). This AR, bounded by the 20-mm contour of vertically integrated water vapour (IWV), was a long (expanding well beyond 2000 km in length), narrow (on average with  $\sim 500$ – $800$  km width) and shallow (1–2.5 km in depth) band of strong horizontal water vapour transport in the lower troposphere. It was associated with a strong pre-cold frontal low-level jet (LLJ) as documented by many other studies (Ralph et al. 2004, 2005; Neiman et al. 2008a, 2008b; Gimeno et al. 2014). Another important feature in Fig. 1 is that, at the AR head (shown at Port Hardy, BC, Canada), the sounding profiles of temperature and dewpoint temperature suggest that its vertical distribution followed closely to a near moist-neutral stratification. On the west coast of North America, AR centres are usually located at a level lower than the coastal mountains. Therefore, when they make landfall on the coast, the orographic enhancement of rainfall can lead to extreme precipitation events (Ralph et al. 2004, 2006; Neiman et al. 2008a, 2008b).

Nevertheless, when the AR concept was first introduced in the 1990s, there were debates on the differences between ARs and other concepts already used for describing moisture sources and transport in extratropical rainfall generation, such as the warm conveyor belts (WCBs) and tropical moisture exports (TMEs). The distinct and complementary concepts used in exploring atmospheric moisture transport outside the tropics were not properly defined until an international AR workshop in 2015 (Dettinger et al. 2015), where consensus was reached. As shown in Fig. 2 which follows another conceptual diagram in Dettinger et al. (2015), it is now generally agreed that a WCB refers to a zone of dynamically uplifted heat and moisture transport close to a midlatitude cyclone. The atmospheric moisture is often transported into the WCB by an AR. TMEs are zones of intense atmospheric moisture transport out of the tropics, and that tropical originated water vapour is frequently conducted by ARs toward cyclones and WCBs. Note that TMEs provide important vapour sources for ARs, but most ARs also incorporate



**Fig. 2.** Schematic diagram showing the connection between tropical moisture export (TME), a warm conveyor belt (WCB) associated with a mid-latitude cyclone, and a landfalling AR shown as the vertically integrated vapour transport (IVT) valid at 0000 UTC 29 January 2018. The vectors show the zonal and meridional components of IVT and the shaded colors show the magnitudes of IVT ( $\text{kg m}^{-1} \text{s}^{-1}$ ).

midlatitude sources and convergences of vapour along their paths (Sodemann and Stohl 2013; Dettinger et al. 2015).

Numerous studies in the last decades have documented the AR contribution to large-scale water vapour transport and extreme precipitation events in orographically favoured

locations around the world (Smirnov and Moore 1999; Gyakum 2000; Ralph *et al.* 2004, 2005, 2006; Neiman *et al.* 2008a, 2008b; Roberge *et al.* 2009; Lavers *et al.* 2011, 2012; Newman *et al.* 2012; Lavers and Villarini 2013; Guan and Waliser 2015; Mahoney *et al.* 2016; Ralph *et al.* 2017; Browning 2018; Zhang *et al.* 2019). However, this relatively new meteorological terminology has not been generally adopted in the Australia-Asian (A-A) region, except for a few recent studies (Hirota *et al.* 2016; Paltan *et al.* 2017; Yang *et al.* 2018). It is well known that weather and climate in the Asian region are dominated by monsoonal flows that bring warm and moist air from the tropics into the subtropical and extratropical areas (Ding 2004; Zhang 2010) through several channels (Chen *et al.* 1991; Chang *et al.* 2004; Ding 2004; Wang 2006), but it is unclear to what extent such transport is realised as ARs and/or other mechanisms. We note that several recent studies started to analyse ARs in the Asian monsoon region (Hirota *et al.* 2016; Yang *et al.* 2018), but it is unclear whether the established AR conceptual model can be directly applied in the A-A monsoon system and to what extent the monsoon rainfall intraseasonal variations are associated with its AR activities.

Another attraction of conducting AR analysis in the Australian region is a significant weather phenomenon known as the Northwest Cloud Band (NWCB). As described by Tapp and Barrell (1984), in satellite weather images the NWCB is a river-like, long and narrow band (typically extending over 2500 km and existing for two to four days) that often originates in the warm and moist Indian Ocean, south and west of Indonesia. It thus bears a strong similarity to the AR phenomenon. Wright (1997) showed the NWCB as one of the synoptic patterns that results from tropical–extratropical interactions. Studies from Frederiksen and Balgovind (1994) and Frederiksen and Frederiksen (1996) further linked the formation of NWCB with sea surface temperature (SST) gradients in the Indian Ocean. Using a general circulation model, Frederiksen and Balgovind (1994) simulated an increased frequency of NWCB with enhanced SST gradients between the Indonesian Archipelago and the central Indian Ocean and with enhanced influx of warm tropical air from northwest Australia. In a follow-up study, Frederiksen and Frederiksen (1996) used a two-level primitive-equation model to demonstrate that an enhanced SST gradient can produce instability modes resembling circulation changes surrounding the onset of NWCB.

Although NWCBs are likely to produce extensive rainfall over Australia, their effectiveness in generating heavy precipitation is still under debate (Ummenhofer *et al.* 2011). The complex relationship between NWCB and rainfall could partly be attributed to the different atmospheric moisture sources that support the formation of the cloud band. Early studies, such as Hill (1977), stressed the importance of tropical thunderstorm activity in injecting tropical warm and moist air into the midtroposphere, which is then advected south-eastwardly along the band. However, Tapp and Barrell (1984) showed that tropical convection is not always evident near the origin of NWCB. Early studies of Hill (1964, 1969, 1977) also showed the importance of a second NWCB-supporting moisture source off eastern Australia. Therefore, AR analysis has the potential to offer some insight into the formation of NWCB, its moisture

source and transport, and how these processes affect its rainfall effectiveness.

Given the lack of assessment of ARs and the importance of their moisture transport in affecting the weather and climate in the A-A region, a bilateral project on AR research was conducted over 2017–2019 under a cooperation agreement between the China Meteorological Administration (CMA) and the Australian Bureau of Meteorology (BoM). This collaborative project was designed to fill the gap in AR research and apply this diagnosis for supporting weather and climate services in the region. Some preliminary results were presented at the 2018 Australian Meteorological and Oceanographic Society-International Conference on Southern Hemisphere Meteorology and Oceanography (5–9 February, Sydney, Australia), and a special issue of the Journal of Southern Hemisphere Earth Systems Science has been arranged to publish these results to promote AR studies in the region. The main purpose of this paper is to provide a scientific background on AR research, list key scientific questions addressed by this project, report on the project's progress and discuss future directions.

The remainder of this paper is organised as follows. Section 2 gives a brief overview of ARs, their detections and current applications in regions outside the A-A region. Section 3 reviews key scientific questions addressed by our BoM-CMA collaborative project and highlights some important results from the project. In Section 4, the limits from current studies and future directions of this collaborative project are discussed.

## 2 Atmospheric rivers: an overview

### 2.1 A brief historical perspective

As shown in Fig. 1, an AR can be generally defined as a long, narrow and transient corridor of strong horizontal water vapour transport (American Meteorological Society 2019). The concept of a ‘river’ in the sky was introduced in the early 1990s to describe some filamentary structures of atmospheric water vapour transport. In a pilot study, Newell *et al.* (1992) showed the presence of these moisture filaments, which have lengths many times their widths and persist for many days while being transported through the lower atmosphere. They termed these features ‘tropospheric rivers’, given that some of them may carry as much water as the Amazon River. The name ‘atmospheric river’ was used in a later article by Zhu and Newell (1994) (also see Newell and Zhu 1994). The great importance of ARs in large-scale water vapour transport was further recognised by Zhu and Newell (1998), who showed that ARs may carry essentially the total meridional moisture transport observed in the extratropical atmosphere, despite occupying only about 10% of the total longitudinal length at a given latitude.

Before the AR concept was widely known and accepted, some studies used the term ‘Pineapple Express’ to describe the strong LLJs blowing from the Hawaiian area (where pineapples are grown) towards the west coast of North America (e.g. Lackmann and Gyakum 1999; Mo *et al.* 2009). Other names used for describing the strong water vapour transport in the atmosphere include ‘moisture conveyor belt’ (Bao *et al.* 2006), ‘Maya Express’ (Dirmeyer and Kinter III 2009) and ‘tropical moisture export’ (Knippertz and Wernli 2010). Nevertheless, since the



influential paper by Ralph *et al.* (2004), the term ‘atmospheric river’ has been adapted and received great publicity in the meteorological and hydrological communities. Numerous recent studies have demonstrated that ARs play a crucial role in determining the occurrence of floods, breaking of droughts and managing water resources in many parts of the world (Gimeno *et al.* 2014; Ralph *et al.* 2017 and references therein). As illustrated in Fig. 2, the general view now is that ARs provide the link between moisture sources in the tropics (TMEs) and the moisture embedded within the middle-latitude WCBs, and ARs are directly responsible for some heavy precipitation events (Sodemann and Stohl 2013; Dettinger *et al.* 2015).

In the A-A monsoon region, Zhu and Newell (1998) found that persistent monsoon circulations are supported by transient filamentary water vapour fluxes. These features may be considered as semipermanent ARs. Joseph and Moustauoui (2000) used a simple, dynamically consistent model to demonstrate the development of filamentary moisture transport in a monsoon-like flow. He *et al.* (2007) described some patterns of strong large-scale moisture transport in the A-A monsoon region as ‘great moisture rivers’. They found that the precursory signals in the seasonal transition from the winter to summer pattern could be revealed by the establishment of a strong southerly total moisture transport value exceeding  $100 \text{ kg m}^{-1} \text{ s}^{-1}$ . The terminology of AR has been adopted in some recent studies in the A-A monsoon region (e.g. Hirota *et al.* 2016; Paltan *et al.* 2017; Yang *et al.* 2018). However, there is still a lack of understanding about whether ARs embedded in the large-scale monsoonal flow are an important mechanism for moisture transport in the monsoon system and to what extent AR activities have contributed to monsoon intraseasonal rainfall variations.

## 2.2 Methods for atmospheric river detection

The two most frequently used approaches to detect and define ARs are integrated water vapour (IWV) and integrated vapour transport (IVT), which can be defined as:

$$\text{IWV} = g^{-1} \int_0^{p_s} q dp, \quad \text{IVT} = |\mathbf{Q}|, \quad \mathbf{Q} = g^{-1} \int_0^{p_s} q \mathbf{V}_h dp, \quad (1)$$

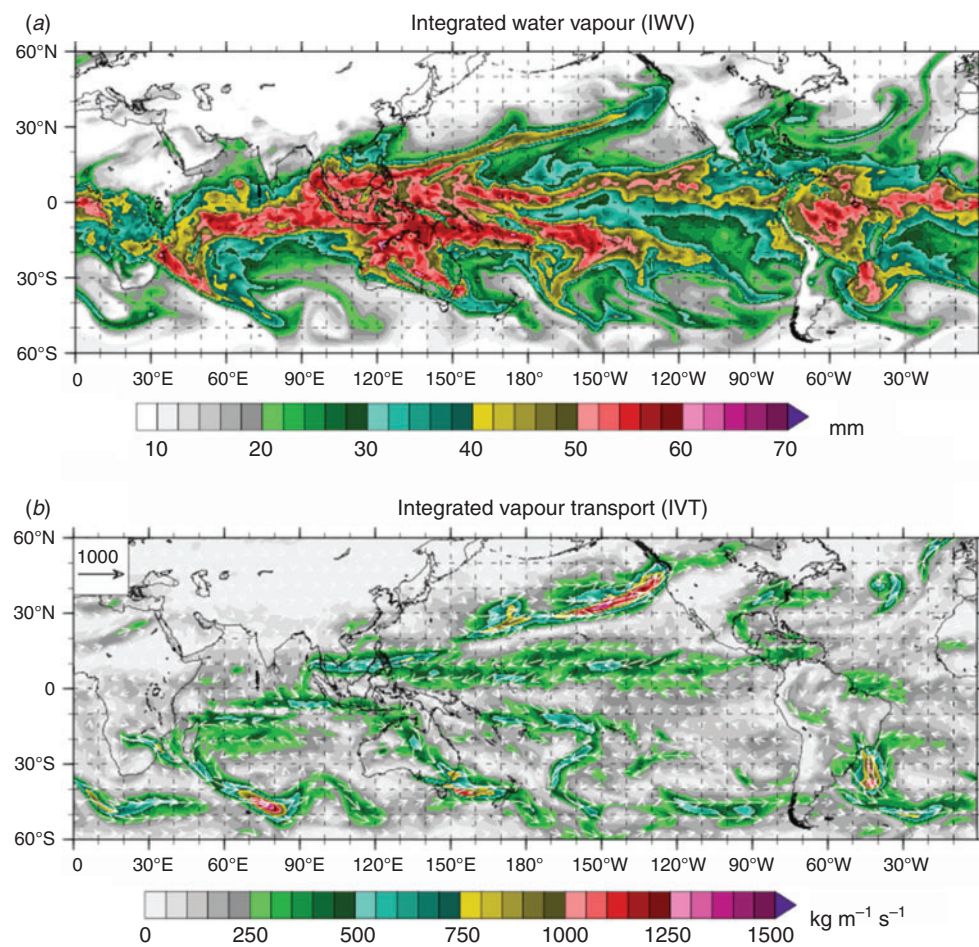
where  $g$  is the acceleration of gravity,  $q$  is the specific humidity,  $\mathbf{V}_h$  is the horizontal wind vector,  $\mathbf{Q}$  is a two-dimensional IVT vector,  $p$  is the pressure taken as the vertical coordinate, and  $p_s$  is the surface pressure. The vertical integrations in Eqn 1 are carried out from the Earth’s surface to the top of the atmosphere. Therefore, the IWV represents the total mass of water vapour per unit area above the Earth’s surface. It is also called the ‘precipitable water’. The IVT is the magnitude of  $\mathbf{Q}$ , representing the total horizontal transport of water vapour per unit area above the Earth’s surface. Note that both IWV and IVT are dominated by conditions in the lower troposphere because of the rapid decrease of specific humidity with altitude. In practice, it suffices to carry the vertical integration up to the 300 hPa level in the upper troposphere, but for the convenience of operational application implementation, one can choose to simply take the IWV value integrated from the surface to the top of the atmosphere, as this variable is often saved in numerical model outputs.

Ralph *et al.* (2004) showed that the IWV derived from meteorological satellite observations can be used as a proxy for detecting the presence of ARs: an AR is defined as an elongated area with a minimum IWV threshold of 20 mm, a minimum length of 2000 km and a maximum width of 1000 km. Their analysis found a close correlation between IWV and IVT in the midlatitudes, and the identified ARs were typically associated with the pre-cold-frontal LLJs within oceanic extratropical cyclones (Ralph *et al.* 2005). This IWV-based AR definition has been successfully applied in many subsequent studies (Ralph *et al.* 2006; Neiman *et al.* 2008a, 2008b; Guan *et al.* 2010; Dettinger *et al.* 2011; Ralph *et al.* 2011; Ralph and Dettinger 2012). An automated objective algorithm for the AR identification based on IWV has also been developed by Wick *et al.* (2013).

Because the IWV-based AR definition does not include wind information, it does not address the fundamental processes for water vapour transport. When both wind and moisture data are available, IVT is a more appropriate variable for the AR definition (Zhu and Newell 1998; Lavers *et al.* 2012; Lavers and Villarini 2013; Wick 2014; Guan and Waliser 2015; Mahoney *et al.* 2016; Mo and Lin 2019). A range of definitions and thresholds are used in various studies, and currently there is an intercomparison project to compare results from these studies (Shields *et al.* 2018). Rather than using a fixed threshold, Guan and Waliser (2015) developed a technique for objective AR detection using varying thresholds based on the IVT distributions calculated from reanalysis data covering a long period (normally over 30 years). They used the 85th percentile of IVTs with geometry requirements of  $>2000 \text{ km}$  length and a length/width ratio  $>2$  as the AR-defining threshold. There is merit in such a definition, as the magnitude of atmospheric moisture transport and its impacts on rainfall may vary with different climate backgrounds. For operational applications, a simpler definition can also be given as an elongated area with a minimum IVT threshold of  $250 \text{ kg m}^{-1} \text{ s}^{-1}$ , a minimum length of 2000 km and a length/width ratio  $>2$  (e.g. Wick 2014; Mo and Lin 2019).

Mahoney *et al.* (2016) pointed out that the IVT-based AR definition is particularly useful for distinguishing the strong moisture transport corridor where the climate background is moist, such as in southeast USA. This is likely also true in the A-A monsoon region. As an example, Fig. 3 shows the IWV and IVT distributions at 1800 UTC January 2017, derived from the Japanese 55-year Reanalysis (JRA-55) (Kobayashi *et al.* 2015; Harada *et al.* 2016). Based on the IWV-based definition, we can readily identify a strong AR from the tropical western Pacific towards the west coast of North America in Fig. 3a (Mo *et al.* 2019). In addition, several ARs can also be identified in the extratropical areas of the South Indian Ocean, the South Pacific Ocean and the Atlantic Ocean. There is an indication of a weak AR along the south coast in Australia. On the other hand, the AR signal over the southeast USA is poorly defined. By comparison, as corridors of strong water vapour transport, the ARs are better distinguished by the IVT-based definition in Fig. 3b. In particular, the ARs across the southeast USA and Australia can be readily recognised in Fig. 3b.

As pointed out by Shields *et al.* (2018), different methods used to detect ARs on numerical model gridded datasets and/or



**Fig. 3.** The (a) IWV and (b) IVT distributions based on the JRA-55, valid at 1800 UTC January 2017.

reanalysis data can vary substantially in the derived AR characteristics (including frequency, duration and intensity) due to the different chosen methods. It is hard to choose one against another without a reference dataset to compare. Therefore, in the BoM-CMA project, we dedicated significant resources to conduct manual AR detections by combining IVT calculations from six-hourly JRA-55 data ([https://jra.kishou.go.jp/JRA-55/index\\_en.html](https://jra.kishou.go.jp/JRA-55/index_en.html)) with manually checked daily synoptic charts and satellite images. This effort was to make sure that the detected ARs not only satisfy certain thresholds often used in the automatic schemes but they also actually exist as recognisable weather patterns in an operational weather forecasting environment. Detailed description is provided by [Wu et al. \(2020\)](#) in this special issue. Our AR dataset covers the AR events in Australia and China domains for 1977–2016. This will serve as the reference dataset in our future selection of a suitable automatic detection algorithm that will allow us to implement the AR diagnosis in operational systems.

In general, the strength of precipitation is directly associated with the convergence of water vapour transport, rather than the strength of moisture transport ([Benton and Estoque 1954](#); [Mo and Lin 2019](#); [Mo et al. 2019](#)). Along the west coast of North America, when an AR approaches a mountain barrier, the

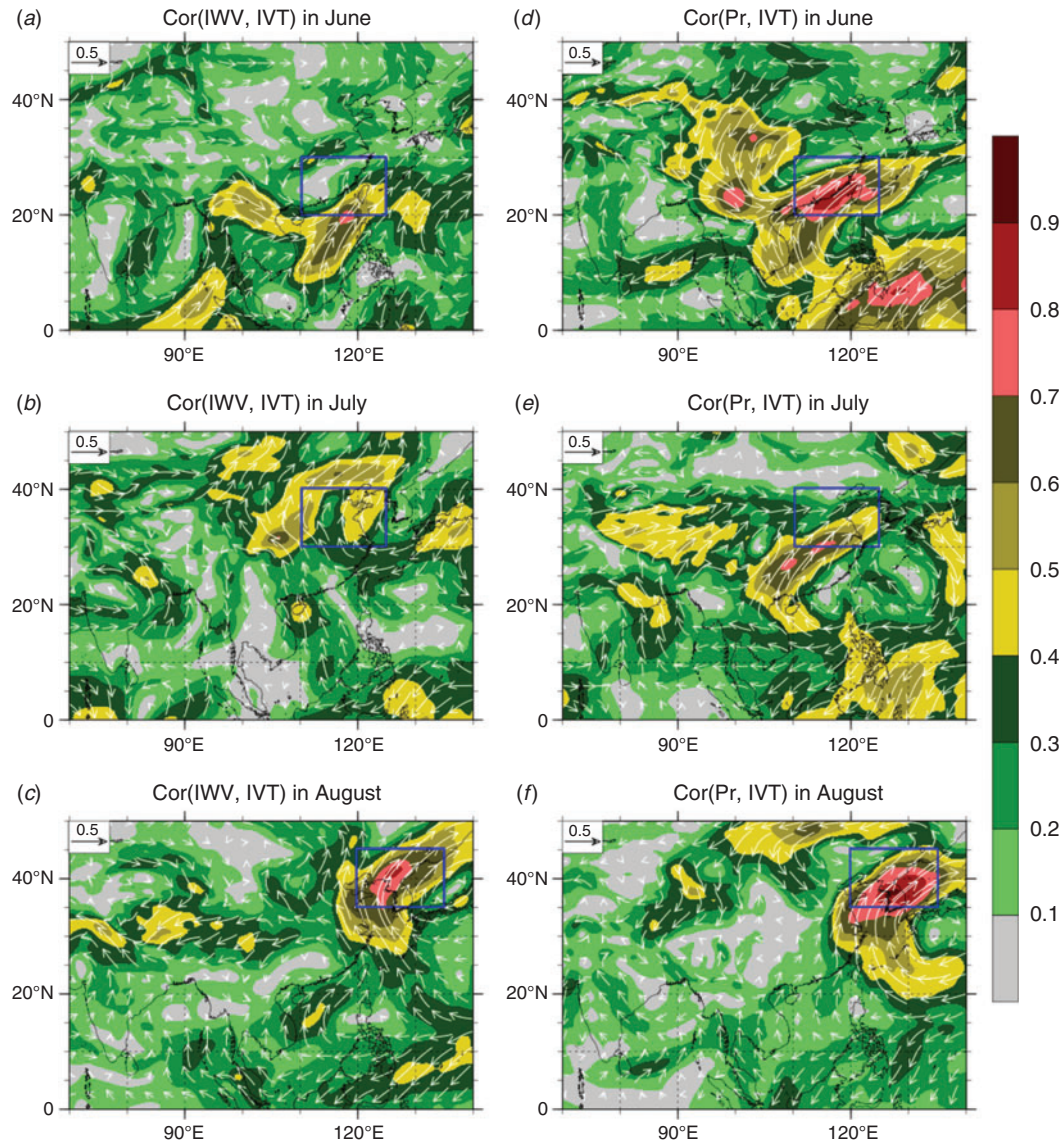
deceleration of air motion can lead to strong moisture convergence on the windward side. This, together with the orographic uplift, can lead to heavy precipitation in the mountains and lowlands alike ([Lackmann and Gyakum 1999](#); [Mo et al. 2019](#)). In addition, horizontal convergence and uplift may also be generated by other mechanisms, such as midlatitude frontal systems and blockings (e.g. [Mo and Lin 2019](#)). Different dynamical mechanisms for AR-induced heavy precipitation in the A-A region will be further explored in this BoM-CMA project through several case studies ([Chen et al. 2020](#); [Xu et al. 2020a](#)).

### 3 Key scientific questions in this research

Although several studies have used global reanalysis datasets to document ARs in the global context (e.g. [Guan and Waliser 2015](#); [Gimeno et al. 2016](#); [Waliser and Guan 2017](#)), there is a lack of detailed analysis focusing on the ARs in the A-A region. In this section, we highlight some fundamental features of moisture transport in the monsoon region and discuss how AR diagnosis can be used to further improve our understanding of the monsoon system and the skills in forecasting monsoon rainfall at NWP, seasonal and climate time scales.

As pointed out in a review paper by [Gimeno et al. \(2016\)](#), there are two main moisture sources for precipitation, namely





**Fig. 4.** (a)–(c) Correlation vectors of monthly mean IVT vectors with the monthly mean IWV (precipitable water) averaged over the selected areas in East Asia (marked by blue lines) in June, July and August. (d)–(f) Same as in (a)–(c) but with the monthly precipitation averaged over the selected areas. The vector magnitudes, ranging from 0 to  $2^{1/2}$ , are colour-shaded.

(i) continental evaporation/transpiration; and (ii) moisture transported from adjacent oceanic regions. [Van der Ent \*et al.\* \(2010\)](#) assessed the contribution of water recycling through land evapotranspiration to the generation of precipitation across the globe and estimated approximately 15–30% as the continental water recycling rate over the A-A summer monsoon region. Therefore, atmospheric moisture originating from tropical warm oceans plays a dominant role in supporting and sustaining rainfall over land.

Weather and climate in our region are dominated by the A-A monsoon, with a remarkable seasonal wind reversal. In the East Asian subtropical monsoon, the prevailing winds change from north-easterly in boreal winter into south-westerly ([Chen \*et al.\* 1991](#); [Ding 2004](#); [Chang \*et al.\* 2004](#); [Wang 2006](#); [Zhang 2010](#)).

Associated with these monsoonal flows is a huge transport of warm and moist air out of the tropics, which produces heavy summer monsoon rainfall in the areas where strong moisture convergence occurs. The relationships of moisture transport (represented by IVT vector) with water vapour content in the atmosphere (represented by IWV) and rainfall over East Asia in the summer season can be seen in [Fig. 4](#). The left panel shows the correlation vectors of monthly mean (June, July and August) IVT vectors with the area-averaged monthly mean IWV from the JRA-55 over three selected regions for the 30-year period of 1979–2018. The right panel shows the same correlation vectors, but with the area-averaged monthly precipitation from the Climate Prediction Center Global Unified Precipitation data ([Chen \*et al.\* 2008](#); [NOAA 2019](#)). To highlight intraseasonal

rainfall migration and the associated moisture transport in the course of the East Asian monsoon development, the three selected regions used in Fig. 4 are: (i) the southern domain (110°E–125°E, 20°N–30°N) in June when early monsoon rainfall is mainly located in southern China; (ii) the central-northern domain (110°E–125°E and 30°N–40°N) in July when heavy monsoon rainfall occurs in the Yangtze River and North China Plain area; and (iii) the far northeast domain (120°E–135°E and 35°N–45°N) in August when the monsoon rainfall advances further into northeast China, the Korean Peninsula and Japan. We see that the summer atmospheric water content and heavy rainfall in the East Asian region are driven by strong moisture transport from the tropics. There are clear correspondences to the well-known three preferred moisture channels for tropical moisture affecting the East Asian summer monsoon rainfall and its northward migration (Chen *et al.* 1991; Ding 1994, 2004; Chang *et al.* 2004): (i) the south-westerly flow from the Bay of Bengal; (ii) the southerly flow from the South China Sea region; and (iii) the anticyclonic south-easterly flow on the west flank of the Western Pacific Subtropical High (WPSH).

At the early stage of the East Asian summer monsoon, the large amount of IWV and high precipitation over South China (Fig. 4a and d) are supported mainly by the steady warm and moist south-westerly flow across the Bay of Bengal, Indochina Peninsula. At the same time, warm and moist airflow from South China Sea region provides another important moisture source. As the summer monsoon further develops and moves north-eastward in July and August, moisture carried by the anticyclonic flow of the WPSH becomes the dominant source for sustaining the heavy monsoon rainfall in subtropical and extra-tropical regions of East Asia.

The critical importance of the WPSH (its position, size and intensity) in influencing the summer rainfall in East Asia has been documented by many studies (e.g. Wang *et al.* 2013; Ying *et al.* 2017). To a large extent, it is the co-influence between the Tibetan Plateau and a semistationary WPSH that gives rise to the preferred moisture channels across East Asia during the boreal summer season. From the patterns displayed in Fig. 4, one can see some AR-like features, i.e. an elongated band of strong moisture transport. However, it is unclear if these bands reflect the collective effect of ARs occurring in the region for conveying moisture into the extratropics. It is also unclear whether there are different features between these East Asian ARs and the ones in North/South America. Consequently, the main tasks for this project in the East Asian region are defined around the following scientific questions:

- (i) What is the role of ARs in moisture transport in the Asian summer monsoon season, and are monsoon extreme rainfall events and their intraseasonal variations (active and break phases) associated with AR activities embedded within the large-scale monsoon flow?
- (ii) What are the main characteristics of ARs embedded in the Asian monsoon system, which are mainly located inside continental East Asia, in contrast to the ones in North/South America? So far, most of the published AR studies have focused on moisture transport from the subtropics into the midlatitudes. In contrast, the AR studies in this

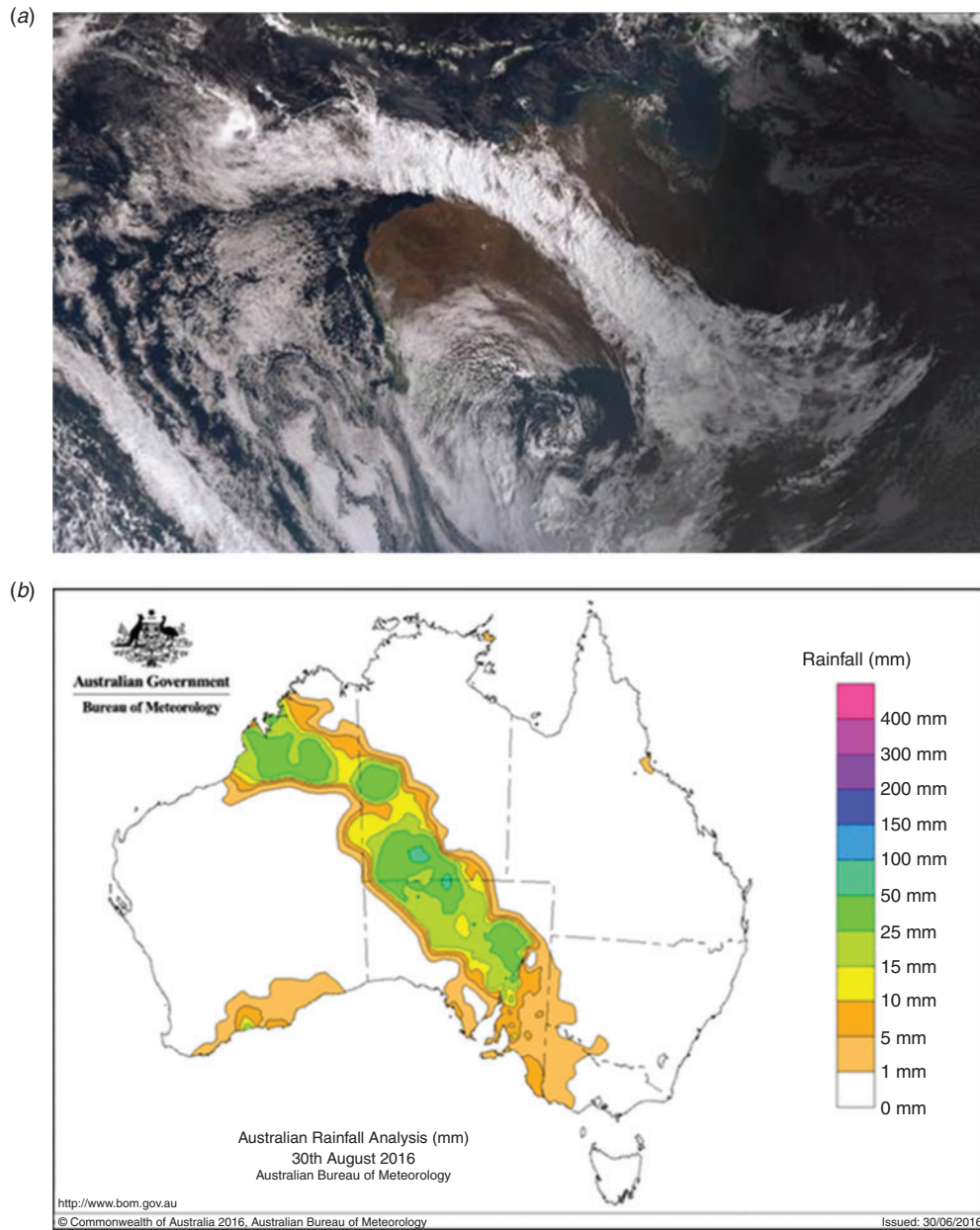
project focus on detailed features of moisture transport embedded in the overall monsoon circulation, mainly in the subtropical area.

- (iii) How skilful are current numerical weather prediction (NWP) models in forecasting ARs in the region, and can the AR forecast skill help us to indirectly extend our forecasts of extreme rainfalls during the Asian summer monsoon season?
- (iv) What are the underlying drivers for the intraseasonal, seasonal and interannual variations of ARs in the A-A region, and what is the potential predictability of these ARs?

Although several studies, such as Waliser and Guan (2017) and DeFlorio *et al.* (2018), showed the AR occurrence in the Australian region, how it impacts on the regional weather and climate is far from clear. In contrast to the significant orographic blocking and the massive WPSH dominating the west Pacific which form the preferred channels for moisture transport into the East Asia, the topographic influence over the Australian continent is relatively weak. Therefore, ARs in Australia require stronger interactions between midlatitude cyclonic systems and subtropical systems to produce these long and narrow bands of moisture transport. Another key feature of our AR analysis in the Australian region is that we try to link moisture transport through ARs to some prominent synoptic patterns. As discussed in the Introduction, the river-like NWCB is an important weather phenomenon affecting large-scale rainfall in the continent. As an example, Fig. 5 shows a classic NWCB occurrence during 28–30 August 2016. Associated with this NWCB was a band of northwest–southeast rainfall across the continent. In this special issue, Chen *et al.* (2020) will provide a detailed analysis of the AR and NWCB features during this event.

In recent years, several studies identified the linkage between NWCB and SST conditions in the tropical Indian Ocean. Modelling and theoretical work from Frederiksen and Balgovind (1994) and Frederiksen and Frederiksen (1996) demonstrated that the SST gradients in the tropical Indian Ocean favoured the development of NWCB with an influx of tropical warm and moist air into northwest Australia. Further studies (e.g. Risbey *et al.* 2009a, 2009b; Ummenhofer *et al.* 2011; Frederiksen *et al.* 2014) showed that during the negative phase of the Indian Ocean Dipole (IOD) (warm over the eastern part of the tropical Indian Ocean and cooler over its western part), a region of above average rainfall tends to occur on the Australian continent from the northwest to the southeast, which is supported by enhanced moisture transport from the warm Indian Ocean into the Australian continent. All these suggest a potential role of ARs in the formation of NWCB.

To illustrate the linkage between moisture transport and rainfall variations in Australia, Fig. 6 shows correlation vectors of the monthly mean IVT with the area-averaged monthly rainfall in north-western and south-eastern parts of the region for June, July and August. For the north-western part, one can clearly see that rainfall variation is significantly linked to the enhanced moisture transport from the eastern part of the tropical Indian Ocean and nearby warm waters close to Indonesia. The elongated IVT patterns are of high similarity to moisture transport associated with NWCB.



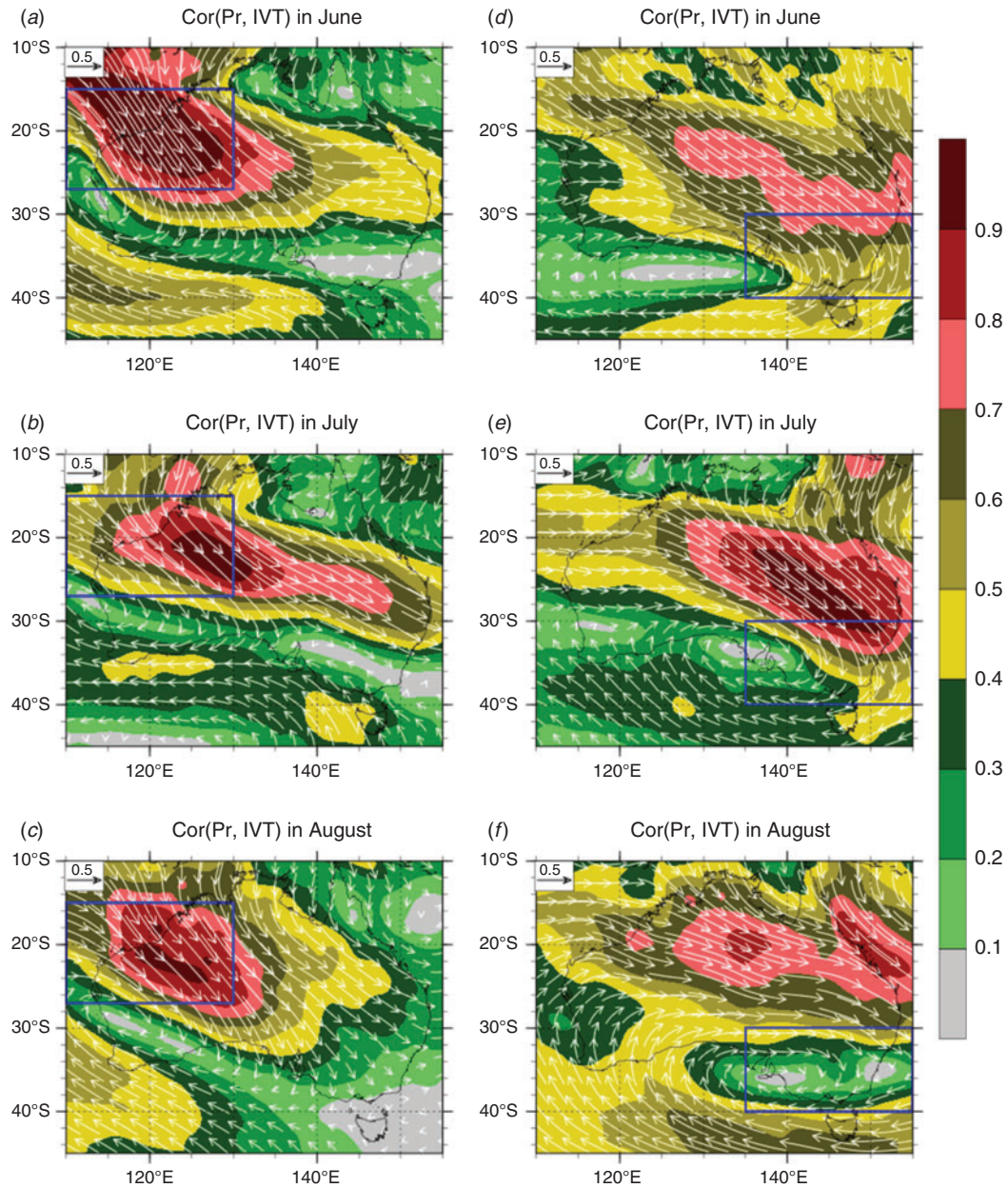
**Fig. 5.** (a) Satellite cloud image at 05:30 pm AEST on 29 August 2016. (b) Observed rainfall on 30 August 2016.

Another feature in Fig. 6a–c is that the northwest–southeast extension of enhanced moisture transport becomes more evident in the late austral winter month (August) when midlatitude cyclonic systems penetrate more equatorward and their interactions with the subtropical anticyclonic system over the north-eastern part of the continent become much stronger. This is similar to the synoptic patterns associated with NWCB as discussed in Wright (1997). For the rainfall in the southeast, patterns in Fig. 6d–f tend to suggest that there is limited moisture transport directly from the northwest but the contribution of tropical moisture from the northeast increases. Indeed, instead of using moisture transport, Cai *et al.* (2011) used a wave

propagation pathway to link the influence of IOD warming phases to the rainfall variations in southeast Australia. Therefore, the pathway of tropical-originated moisture affecting Australian rainfall is more variable compared to its East Asian counterpart. With these considerations in mind, in the Australian region, our project focused on:

- (v) Exploring the connections between ARs and NWCB. It is unclear if the long and narrow river-like NWCB is associated with an AR or the cloud band merely reflects the effect of midlatitude cyclonic dynamics, when such a system passes by. In this project, Chen *et al.* (2020) and Wu *et al.*





**Fig. 6.** (a)–(c) Correlation vectors of the monthly mean IVT vectors with the monthly precipitation averaged over northwest Australia (110°E–130°E and 15°S–27°S, as marked by blue lines) in June, July and August. (d)–(f) The same as in (a)–(c) but with the monthly precipitation averaged over southeast Australia (135°E–155°E and 30°S–40°S). The vector magnitudes, which range from 0 to  $2^{1/2}$ , are colour-shaded.

(2020) have used backward trajectory analysis to explore the moisture source of ARs and found the moisture originating from the tropical Indian Ocean is indeed very important for NWCB rainfall generation in the interior of Australia. For rainfall in southeast Australia, the moisture sources from both the midlatitudes and the tropical waters in the northeast are important.

- (vi) Exploring whether AR analysis can help us to better understand the NWCB-rainfall connections, including

the moisture source for NWCB formation and whether a NWCB supported by an AR is more likely to produce heavy rainfall or not. Analyses from [Chen et al. \(2020\)](#) and [Wu et al. \(2020\)](#) clearly demonstrated that when NWCB is supported by an AR, it is more likely to produce heavy rainfall.

Another important question we addressed in this project is why the occurrence of NWCBs and ARs in the Australian region

tend to peak in the austral winter at the same time as the AR events in the Asian monsoon season reach their peaks in the boreal summer. Are there any linkages between ARs in the two regions? The analysis of Xu *et al.* (2020a) showed potential connections between ARs in boreal summer in East Asia and ARs in the austral winter in Australia. They termed these ‘AR bifurcation’, with one branch of the warm and moist air over the tropical Indian Ocean and western Pacific Ocean being transported into the East Asian region and another branch penetrating into the Australian continent. Furthermore, they have analysed bifurcated AR events in the past two decades and found that they are more likely to occur in the boreal summer months. Most of the bifurcations occurred in the boreal summer following the decaying phase of an El Niño in its preceding winter. They have attributed this to delayed ENSO influence on the WPSH and subtropical high in the Australian region.

As ARs are influenced by how much tropical warm and moist air can be transported by large-scale circulations into the extratropics, their activities can be modulated by two conditions: (i) how warm the tropical oceans are; and (ii) how strong the large-scale tropical circulations are. Therefore, ARs are more directly linked to SST conditions in the tropical oceans than the rainfall in the extratropics. One may expect some higher predictability of ARs occurring in the A-A monsoon region at subseasonal to seasonal time scales. In fact, recent studies by DeFlorio *et al.* (2018) and Nardi *et al.* (2018) have documented some forecast skills of ARs from several operational systems. Accordingly, assessing the potential seasonal forecast application of ARs was another important component in this collaborative project; some preliminary results are shown in Liang *et al.* (2020). How AR activities in the A-A region are influenced by dominant SST patterns in the tropics associated with El-Niño Southern Oscillation and IOD are documented in Wu *et al.* (2020).

Finally, several recent studies (e.g. Ramos *et al.* 2016; Espinoza *et al.* 2018) have discussed the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report model-simulated ARs and their potential changes in a globally warming climate. This topic is important to the study of ARs in the monsoon region because there are competing effects of global warming on ARs: warmed tropical oceans against changes in monsoon circulation. It is widely accepted that global SST warming provides more abundant tropical moisture sources through enhanced oceanic evaporation. Nevertheless, the responses of monsoon circulation to global warming can be very complex, with some models predicting weakened monsoon whereas others predict an enhanced one. Indeed, our studies by Dong *et al.* (2016) and Zhang *et al.* (2016) showed that different SST warming patterns and different monsoon circulation responses to the global warming are the key factors leading to large uncertainty in these model-projected changes in monsoon development. ARs are the combined effect of these two processes. Therefore, in this project we also explored potential changes in ARs in the monsoon region and how these changes can be linked to model-projected rainfall changes. As a first attempt, Xu (2018) documented the changes in extreme rainfall in the A-A monsoon region, simulated by a series of IPCC Coupled Model Intercomparison Project Phase 5 (CMIP5)

models and their connections to tropical SST warming and changes in monsoon circulations and moisture transport. In this project, Xu *et al.* (2020b) further conducted an analysis of ARs simulated by a suite of CMIP5 models and this will be pursued in future analyses of newly released CMIP6 model results.

#### 4 Concluding remarks

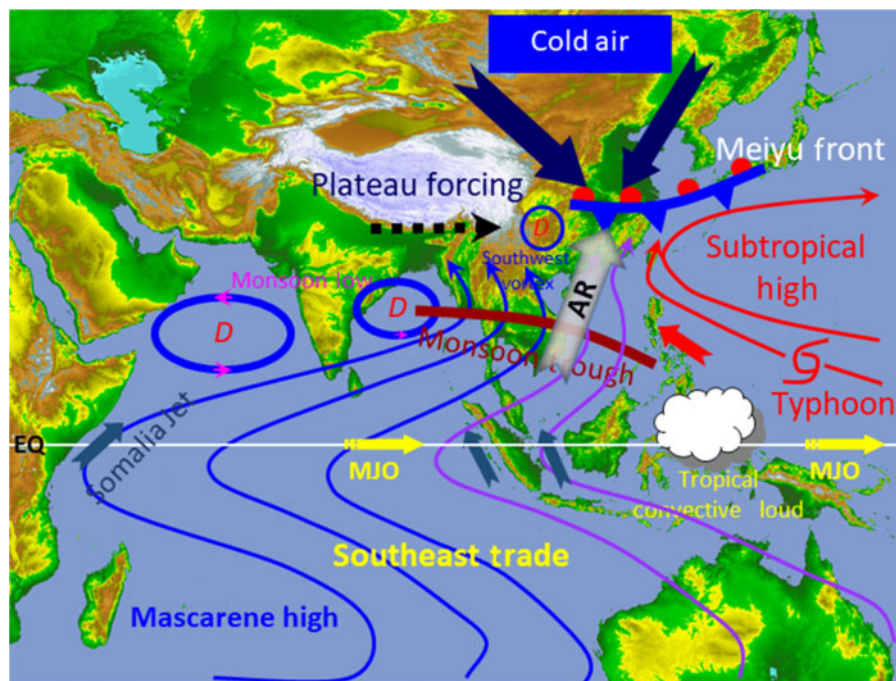
In this paper, we have reviewed the scientific background of AR diagnosis and its current applications in understanding regional weather and climate. We have documented why AR analysis is important for the study of the A-A monsoon climate, what are the new features in our BoM-CMA collaborative AR research, and finally, what are the key scientific questions we wanted to address in this project. We have pointed out that there are several key features in this collaborative project that make our studies different from existing AR analyses (Ralph *et al.* 2004, 2005, 2006; Neiman *et al.* 2008a, 2008b; Roberge *et al.* 2009; Lavers *et al.* 2011, 2012; Newman *et al.* 2012; Lavers and Villarini 2013; Guan and Waliser 2015; Mahoney *et al.* 2016; Ralph *et al.* 2017; Waliser and Guan 2017; Mo *et al.* 2019).

One key feature is that our AR analysis focused on the tropical–subtropical interactions within a monsoon climate, in which ARs can be generally wider and less filamentary, as compared to the ARs in extratropical areas (Waliser and Guan 2017). This is illustrated in a schematic diagram in Fig. 7, which shows ARs in the Asian monsoon context. Firstly, in the Asian monsoon system, the Iranian and Tibetan plateaus act as a dynamical blocking of the low-level Somali jet stream (Boos and Kuang 2010). At the same time, the surface elevated heating favours the formation of large-scale monsoon vortex and cyclonic flows surrounding the Tibetan Plateau (Wu and Liu 2016). Both factors contribute to the establishment of south-westerly monsoon flow, which penetrates from the tropical South Asia into the subtropical East Asia.

Another dominant process influencing the East Asian summer monsoon and its moisture transport is the WPSH. ARs in the Asian monsoon system act as carriers for moisture along the preferred channels in the Asian monsoon background. Within these channels, there are pulses of ARs supplying tropical warm and moist air to the extratropical monsoon region. This is different from AR studies in other regions, which focused on how moisture from the tropics is transported into the midlatitude cyclonic systems to produce heavy rainfall events over mountainous coastal areas (e.g. Ralph *et al.* 2006; Dettinger *et al.* 2011; Lavers *et al.* 2012; Mahoney *et al.* 2016; Zhang *et al.* 2019; Mo *et al.* 2019). A recent case study by Mo and Lin (2019) showed a similar influence of the subtropical high in the western Atlantic on a winter AR across central and eastern North America.

Furthermore, our AR analysis in the Australian region focused on documenting what the role of AR is in the formation of the NWCB, a key synoptic feature influencing Australian rainfall variations (Tapp and Barrell 1984; Wright 1997). In this project, we explored the connections between ARs and NWCBs and used backward trajectory analysis to explore the moisture source of ARs and found that moisture originating from the tropical Indian Ocean is very important for rainfall generation in the interior of the Australian continent associated with NWCBs (Chen *et al.* 2020; Wu *et al.* 2020). Furthermore, the analysis by





**Fig. 7.** Schematic diagram illustrating ARs (shown as the grey arrow) in the context of the East Asian monsoon system. The monsoon diagram was provided by Dr. Ping Liang of Shanghai Regional Climate Center based on a figure produced by Dr. Zuqiang Zhang (pers. comm. August 2019). MJO = Madden-Julian Oscillation. Black dotted arrow represents an eastward movement of Tibetan Plateau vortex.

Wu *et al.* (2020) has shown that when NWCBS is supported by an AR, it is more likely to produce heavy rainfall. This explains why NWCBS do not always produce heavy rainfall during their passages, as some of the cloud bands are associated with the condensation of midlatitude air masses rather than the warm and moist air transported by ARs from the tropics (which is more rainfall efficient).

Our analysis also proposed a potential linkage between ARs occurring almost simultaneously in the East Asian summer monsoon in Australia (austral winter). Xu *et al.* (2020a) termed these as ‘AR bifurcation’, with one branch of the warm and moist air over the tropical oceans being transported into the East Asian region through an AR embedded within the summer Asian monsoon and another branch penetrating into the Australian continent. They found that most of the AR bifurcations occurred during the boreal summer following the decaying phase of an El Niño in its preceding winter, and they attributed such connections to the influence of tropical SSTs on modulating the positions and intensities of WPSH and SPCZ. Nevertheless, much more research is needed to further consolidate the results from this project and uncover the underlying reasons.

Overall, results from this collaborative project have demonstrated the scientific benefits of applying AR analysis in the A-A region to achieve better rainfall forecasts at NWP, subseasonal and seasonal time scales. There are many important aspects of the ARs occurring in the A-A region that warrant further detailed studies. Although Dong (2018) and Liang *et al.* (2020) discussed the application of ARs in supporting seasonal and subseasonal precipitation forecasts in the Asian monsoon

region, more analyses are needed to assess such potential using operational coupled seasonal forecasting products, such as in the work by DeFlorio *et al.* (2018) and Nardi *et al.* (2018). Based on the dataset produced by manual AR detection, we also plan to develop or select automatic AR detection algorithms applicable in the A-A region. This will allow us to conduct AR-based diagnoses to support operational rainfall forecasts based on the NWP guidance and/or other seasonal forecasting models.

Finally, we will further expand our AR analysis in some climate change projection studies (e.g. Ramos *et al.* 2016; Espinoza *et al.* 2018). This is a very important research topic in the A-A region because there are competing effects of global warming on ARs: warmed tropical oceans against changes in monsoon circulation. While global SST warming provides more abundant tropical moisture sources through enhanced oceanic evaporation, the monsoon circulation responses to global warming can be very complex (Zhang *et al.* 2012, 2013, 2016; Dong *et al.* 2016; Zhao and Zhang 2016). Following the work by Xu *et al.* (2020b), more detailed AR analysis will help to understand and narrow down uncertainty in regional climate change projections in the A-A region, and the BoM-CMA collaboration will continue to make contributions in this regard.

### Conflicts of interest

The authors declare no conflicts of interest.

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