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RESEARCH ARTICLE

2018 International Atmospheric Rivers Conference: Multi-disciplinary studies and high-impact applications of atmospheric rivers

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Abstract
Atmospheric rivers (ARs) play a vital role in shaping the hydroclimate of many regions globally, and can substantially impact water resource management, emergency response planning, and other socioeconomic entities. The second International Atmospheric Rivers Conference took place at the Scripps Institution of Oceanography, University of California, San Diego, during 25–28 June, 2018, in La Jolla, California, USA. It was sponsored by the Center for Western Weather and Water Extremes (CW3E). A total of 120 people attended the Conference with 94 abstracts submitted and 30 participating students. In addition to the conference, the Student Forecasting Workshop was organised in the same week. During this workshop, students were exposed to AR forecasting tools, and learned examples of how these tools could be used to make decisions for various applications. The main goals of this conference were to bring together experts from across the fields of hydrology, atmospheric, oceanic, and polar sciences, as well as water management, civil engineering, and ecology to advance the state of AR science and to explore

the future directions for the field. The conference was organised into traditional oral and poster presentations, along with panel discussions and Breakout Groups. This format allowed enhanced interaction between participants, driving progress within the scientific community and the enhanced communication of societal needs by various stakeholders. Several emerging topics of research were highlighted, including subseasonal-to-seasonal (S2S) prediction of ARs and an overview of the AR Reconnaissance campaign. In addition to providing a forum to disseminate and debate new results from scientific talks and posters, the conference was equally effective and useful in linking scientists to users and decision-makers that require improved knowledge on ARs to manage resources and prepare for hazards.
The third International Atmospheric Rivers Conference will be held in Chile in 2020, and hosted by the University of Chile, Santiago.

KEYWORDS
atmospheric Rivers, International Atmospheric Rivers Conference, meeting report

1 | BACKGROUND

Regions around the globe face challenges in water management due to droughts and/or floods (IPCC, 2018). Since the seminal work of Newell *et al*. (1992) and Zhu and Newell (1998), research on atmospheric rivers (ARs) has emerged as an interdisciplinary convergence of hydrologists and atmospheric scientists on the transport mechanisms and impacts of precipitation extremes and other significant impacts caused by AR landfall (e.g., Ralph *et al*., 2004; Lavers and Villarini, 2013; Gorodetskaya *et al*., 2014; Paltan *et al*., 2017; Chen *et al*., 2018; Nash *et al*., 2018; Neff, 2018; Ramos *et al*., 2018). ARs are a focal point of research and operations within the Center for Western Weather and Water Extremes (CW3E; cw3e.ucsd.edu), as they project strongly onto interannual variations in precipitation over the western U.S. (Dettinger *et al*., 2011), but their hydrometeorological impacts are substantial in other regions of the globe (Ralph *et al*., 2017a; Espinoza *et al*., 2018), including over western Europe (Lavers *et al*., 2011; Lavers and Villarini, 2013; Ramos *et al*., 2015; 2016), western South America (DeFlorio *et al*., 2018; Viale *et al*., 2018), polar regions (Gorodetskaya *et al*., 2014; Nash *et al*., 2018), and other regions. Emerging research topics in AR science include an intercomparison of AR detection methods (Shields *et al*., 2018), subseasonal-to-seasonal (S2S) AR prediction (Baggett *et al*., 2017; DeFlorio *et al*., 2018; Mundhenk *et al*., 2018; Nardi *et al*., 2018; DeFlorio *et al*., 2019a, 2019b) and the creation of an AR scale to characterise societal impacts (Ralph *et al*., 2019), among many others.

A large community of scientists coalesced to create a formal definition for ARs by participating in debates at scientific conferences, Town Halls at the American Meteorological Society and American Geophysical Union Annual Meetings, as well as a panel discussion at the first International Atmospheric Rivers Conference (IARC2016, Ralph *et al*., 2017a). After years of these discussions and deliberations, the definition of ARs was finally submitted and made available to the Glossary of Meteorology of the American Meteorological Society (Figure 1, Ralph *et al*., 2018a). The definition states that an AR is: “a long, narrow, and transient corridor of strong horizontal water vapour transport that is typically associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapour in ARs is supplied by tropical and/or extratropical moisture sources. ARs frequently lead to heavy precipitation where they are forced upward—for example, by mountains or by ascent in the warm conveyor belt. Horizontal water vapour transport in the mid-latitudes occurs primarily in ARs and is focused in the lower troposphere. ARs are the largest” “rivers of fresh water on Earth, transporting on average more than double the flow of the Amazon River.” IARC2016 catalysed the preparation of this definition via an energetic panel discussion, which was requested by the American Meteorological Society. In addition, attendees of the IARC2016 strongly supported the idea of holding another IARC at the Scripps Institution of Oceanography in the summer of 2018, which ultimately occurred in June.

2 | THE 2018 INTERNATIONAL ATMOSPHERIC RIVERS CONFERENCE

The 2018 International Atmospheric Rivers Conference (IARC2018, http://cw3e.ucsd.edu/IARC2018/) took place at the Seaside Forum of the Scripps Institution of Oceanography,

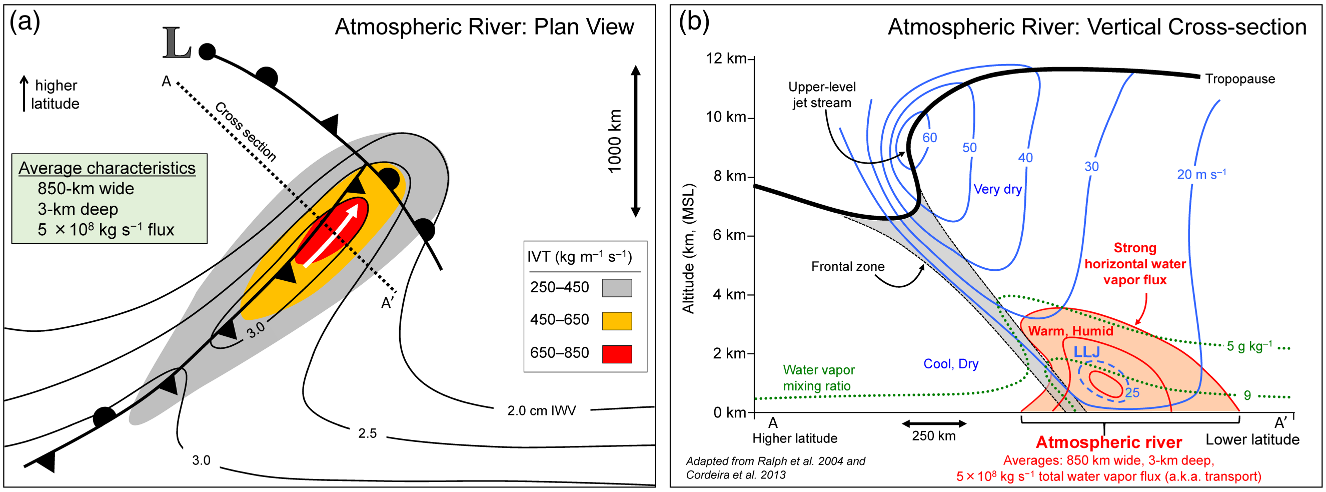

FIGURE 1 Schematic summary of the structure and strength of an atmospheric river based on dropsonde measurements deployed from research aircraft across many atmospheric rivers and on corresponding reanalyses that provide the plan-view context. Magnitudes of variables represent an average mid-latitude atmospheric river. Average width is based on atmospheric river boundaries defined by vertically integrated water vapour transport (IVT; from surface to 300 hPa) lateral boundary threshold of 250 kg m^{-1} s^{-1}. Depth corresponds to the altitude below which 75% of IVT occurs. The total water vapour transport (a.k.a. flux) corresponds to the transport along an atmospheric river, bounded laterally by the positions of IVT = 250 kg m^{-1} s^{-1} and vertically by the surface and 300 hPa. (a) Plan view including parent low pressure system and associated cold, warm, and warm-occluded surface fronts. IVT is shown by colour fill (magnitude; kg m^{-1} s^{-1}) and direction in the core (white arrow). Vertically integrated water vapour (IWV; cm) is contoured. A representative length scale is shown. The position of the cross-section shown in (b) is denoted by the dashed line A–A′. (b) Vertical cross-section perspective, including the core of the water vapour transport in the atmospheric river (orange contours and colour fill) and the pre-cold-frontal low-level jet (LLJ), in the context of the jet-front system and tropopause. Water vapour mixing ratio (green dotted lines; g kg^{-1}) and cross-section-normal isotachs (blue contours; m s − 1) are shown. (source: Ralph *et al*., 2017b; 2018a, http://glossary.ametsoc.org/wiki/Atmospheric_river)

25–28 June, in La Jolla, California, USA. It was hosted and sponsored by CW3E. A total of 120 people attended the IARC2018, in which 94 abstracts were submitted, corresponding to an increase in both the number of attendees and of abstracts when compared with the IARC2016 (105 and 78, respectively, Ralph *et al*., 2017a). A total of 30 students participated in the IARC2018, 15 of whom received a student scholarship waiving their registration fee.

The main goal of this conference was to bring together experts across the fields of atmospheric, hydrologic, oceanic, and polar sciences, as well as water management, civil engineering, and ecology, to advance the state of the AR science and to explore new directions, improved means of disseminating AR forecast information, and upgrades to existing monitoring techniques.

In pursuit of this goal, the conference was organised with oral presentations (61), poster presentations (33), panel discussions (2), and Breakout Groups (2). The topic of the two-panel discussions was "Advances in AR Research for Water Management," and "AR Definition and New Directions." Moreover, the two Breakout Groups allowed a thorough discussion on the topics of: "AR Reconnaissance and Data Assimilation" and "Subseasonal to Seasonal (S2S) Challenges and Ways Forward." The full agenda can be downloaded at the conference webpage: http://cw3e.ucsd.edu/IARC2018/.

2.1 | Sessions summary

The oral presentations, after two introductory talks (one on recent advances on ARs and the other focusing on AR impacts on the Atlantic Ocean), were organised in 12 sessions. These sessions stressed the importance of bringing together climate scientists, engineers, social scientists, impact modellers, and decision-makers to paint a full portrait of complex events. Due to the exceptional U.S. West Coast *Winter of 2016–2017*, a dedicated session was organised, where the large-scale dynamics of extreme precipitation was analysed in terms of atmospheric and oceanic forcing, which led to persistent ARs. The *Applications and Communications* session weighed in on strategic engagement as scientists-communicators in water management, media, and the general population. In addition, the *ARs and Hydrologic Impacts* session's focus was on the role of ARs in not only extreme precipitation and consequently floods, but also the lack of precipitation, with emphasis on the social-economic impacts of these types of events, for example, the influence on reservoir storage.

The *Airborne Observations of ARs* session discussed the role of dropsondes in AR predictability, and the advantages of airborne Global Navigation Satellite System—Radio Occultation observations data assimilation on numerical forecast weather models. Considering the ARs short-range impacts on extreme precipitation and floods, a session was devoted to the *Weather Forecasting of ARs*, where the skill of different numerical weather forecast models, mainly WRF and the ECMWF forecast systems, was quantified for case studies in California and the Iberian Peninsula. In terms of long-term forecast, the *Subseasonal to Seasonal (S2S) Forecasting of ARs* session showed the importance of seasonal forecasting in water management decisions. Several presentations were dedicated to hindcast analysis and experimental real-time forecasting efforts on the prediction skill of ARs at a global and regional scale using different forecasting models.

The ongoing Atmospheric River Tracking Method Intercomparison Project's (ARTMIP) main goal is to understand and quantify uncertainties in AR science based on the choice of the detection/tracking methodology. The climatological characteristics of ARs, such as AR frequency, duration, intensity, and seasonality, are all strongly dependent on the method used to identify ARs (Shields *et al*., 2018; Ralph *et al*., 2018b). Taking this into account, a session dedicated to AR Tracking was included in the IARC2018, where the latest results of the ARTMIP project were presented. The remaining presentations focused on novel AR detection schemes made by object-based algorithms and machine learning techniques.

ARs are a global phenomenon, and their frequency is highest in the mid-latitude storm track region during a given hemisphere's winter (Guan and Waliser, 2015, Ramos *et al*., 2016, DeFlorio *et al*., 2018, 2019a, Viale *et al*., 2018). In the Regional Perspectives on ARs session, the presentations discussed the importance of ARs in polar regions, as well as extreme precipitation events on the west coast of South America and South Africa, and non-coastal regions of the USA such as Texas or the southern Appalachian Mountains. The *AR Dynamics* session showed the importance of large-scale synoptic dynamics (e.g., Rossby wave breaking or extra-tropical cyclones) to the genesis and evolution of ARs.

The *ARs and Climate Variability: Past*, *Present*, *and Future* session focused on paleoclimate trends from model output (Paleoclimate Modelling Intercomparison Project Phase III, PMIP3), and on geological observations. Present variability was also analysed with a focus on the western USA. Finally, several presentations addressed ARs and future climate scenarios from CMIP5 and high-resolution future climate model simulations, not only at a global scale but also at the regional level.

In the AR Microphysics, Aerosols, and Chemistry and Emerging Directions sessions, several presentations focused on the role of local vs long-range transport of aerosols in precipitation formation within an AR. Furthermore, several presentations showed the utility of stable isotope analysis from precipitation or water vapour in determining the major moisture sources of ARs (local evaporation vs long-range moisture transport). In addition to these topics, another presentation focused on floods following wildfires and showed the relationship between ARs and debris flows in Southern California. This type of event is a clear example of a "compound event" (Zscheischler *et al*., 2018), where the processes that cause debris flows result from the interaction of two separate extreme events that are spatially and temporally dependent.

2.2 | Breakout groups and panel discussions

In the "Atmospheric River Reconnaissance and Data Assimilation" group, an update was provided on plans for upcoming seasons. The major conclusions from the breakout group were the following: (a) there is an excellent system in place for flight planning and data generation following the 2016 and 2018 missions; (b) an interagency team of experts has formed to guide work on modelling and data assimilation efforts in ARs with reconnaissance observations; and (c) appropriate time and resources are essential to follow through on the first two items. In the second case, an increase in the storm sample size is necessary. For the last case, additional research is needed to choose metrics and data assimilation methods, tested with a variety of models (Reynolds *et al*., 2019).

The "Subseasonal to Seasonal (S2S) Challenges and Ways Forward" breakout group started the discussion by defining an S2S forecast as a prediction of a variable in the climate system at lead times ranging from 2 weeks to 2 months (Vitart *et al*., 2017). The major conclusions from this breakout group were:) (a) there is high demand and high potential value to stakeholders and the applications community for skilful S2S forecasts of weather and climate variables (e.g., ARs and their associated precipitation); (b) S2S forecasts typically involve an exchange of spatio-temporal forecast precision for potential increased forecast skill at longer lead times; and (c) significant progress has been made in the research community in developing S2S forecast systems and identifying key physical processes (e.g., climate mode teleconnections and atmospheric ridging) that may provide conditional increases in longer-lead S2S forecast skill.

The first-panel discussion entitled "AR Research for Water Managers" was moderated by Mike Anderson and panellists included Ben Hatchett, Jeanine Jones, Nina

Oakley, and Jonathan Rutz. They discussed ongoing projects in California such as Forecast Informed Reservoir Operations (FIRO), and various projects in water-limited areas of the desert southwest, where ARs can have a large impact on water resources, but present challenges for management due to inconsistency in the number of annual ARs.

The second-panel discussion was focused on the recently established official AR Definition for the American Meteorological Society (AMS), as well as New Directions for AR science. The panel was moderated by Duane Waliser and panellists included Lance Bosart, Mike Dettinger, Rene Garreaud, F. Martin Ralph, Alexandre Ramos, and Natalia Tilinina. A wide array of new directions for AR science were discussed, including: (a) other types of extreme events in AR dominated areas, like floods following wild fires illustrating the relationship between ARs and debris flows, (b) the use of high temporal and spatial resolution new reanalysis datasets like ERA-5 from ECMWF which can enable the study of physical processes between ARs and the ocean surface and (c) studies using isotope analysis during ARs to analyse their sources and the transport of water vapour, which can validate studies that use Lagrangian models to investigate water vapour transport (e.g., Ramos *et al*., 2016). The discussion then shifted to a more dynamically based one where it was noted that IVT as a detection method has several limitations and that new detection methods should also include the AR in relationship to large-scale features such as cyclonic activity or linkage with the associated frontal zone (e.g., Viale *et al*., 2018).

2.3 | AR forecasting workshop

A Student Forecasting Workshop sponsored by the CW3E was organised directly following the IARC2018 on 29–30, 2018. The workshop brought a smaller group of students (12 out of 30 students) that participated in the IARC2018 together with AR scientists and forecasters to gain hands-on experience with predictions focused on practical and scientific applications. The expected outcomes for participants included improved understanding of modern AR prediction tools and methods, and how AR forecasting supports selected examples of decision-making.

Students participated in two separate interactive lectures and hands-on sessions. The first was on AR predictions and was led by the National Weather Service (Reno and San Diego offices), the San Diego Swift Water Rescue Team, and CW3E. In this session, students learned about forecasting AR impacts as well as how to appropriately communicate various risks to local stakeholders. Students developed their own plans to help decision-makers mitigate dangers associated with the forecasted AR event. In the second section, students used CW3E's AR forecasting tools to plan an AR Reconnaissance mission. This section of the workshop gave students an operational perspective on the many challenges and opportunities associated with organising a large-scale field campaign.

In addition, the Student Forecasting Workshop included a visit to the National Weather Service in San Diego, with a tour given by the Warning Coordination Meteorologist, and a Radiosonde launch from the Scripps pier, where the students participated in preparing and releasing the balloon.

3 | OUTLOOK

Overarching conference outcomes include informing the planning of future conferences and colloquia that will best serve the community in terms of ensuring participation from various disciplines that are impacted by the development of AR science, tools, and applications; cementing collaborative relationships in this new and fast-growing community; and linking scientists to users and decision-makers that can incorporate improved knowledge on ARs to manage resources and prepare for hazards.

3.1 | Planning future conferences and colloquium

The large increase in scientific publications that discuss ARs (Ralph *et al*., 2017a) and the success of the IARC2018 led to a decision to continue holding the IARC conference on biennial basis, with plans for IARC2020 to be hosted at the Universidad de Chile in Santiago, Chile.

Students who participated in the Student Forecasting Workshop were invited by the organising committee (Chris Smallcomb, Alexandre M. Ramos, Meredith Fish, Anna Wilson, and Irina Gorodetskaya) to provide feedback that could be applied to the upcoming AR Colloquium Summer School at CW3E. The overarching goal of the Atmospheric Rivers Colloquium Summer School 2019 is to provide the next generation of atmospheric, hydrology, and other climate-related scientists with an in-depth look at the cutting-edge techniques in understanding, monitoring, and predicting ARs and their associated high-impact weather. Input from the students was essential to development of the Colloquium framework. Outcomes for participants will include improved understanding of (a) the fundamental dynamics and physics associated with ARs, including their role in the water cycle and impacts on different regions across the globe; (b) the techniques to detect, observe, model, and forecast ARs at all relevant time scales, including in future climate scenarios; and (c) applications of AR science to water management, engineering, and hazard resilience. Fifteen expert instructors, including four from institutions outside of the U.S., will give lectures and lead hands-on exercises. Thirty students are registered from institutions in 11 countries.

3.2 | Cementing collaborations

The AR Monograph entitled "Atmospheric Rivers," which has been developed and written over the past several years, is to be published by Springer International and will be released in 2019. The book is co-edited by: F. Martin Ralph (Chief Editor), Michael D. Dettinger, Jonathan J. Rutz, and Duane Waliser, with the contribution of international experts on AR research as chapter authors. This Monograph also forms the basic framework of topics covered at the AR Colloquium.

There are many examples of collaborative efforts begun within this community. Multiple side meetings were held with participants in these joint efforts. These include side meetings on Atmospheric River Reconnaissance efforts (in addition to the breakout group), the Atmospheric River Tracking Method Intercomparison Project (ARTMIP), and others. Since IARC2016 these groups have released publications together (Lavers *et al*., 2018; Shields *et al*., 2018; Ralph *et al*., 2018b; Reynolds *et al*., 2019) and more are in process. These are just a small sample of the collaborative activities fostered by the continued engagement with and dedication to group efforts by members of the AR community.

3.3 | Linking scientists to users and decision-makers

Improved understanding, modelling, and prediction of ARs is critical to support emergency and water management decisions in the many locations around the globe where they are associated with a majority of the precipitation accumulated on a yearly scale in just a few events (Dettinger *et al*., 2011; Blamey *et al*., 2018; Viale *et al*., 2018). In particular, on the U.S. West Coast significant investment has recently been made aimed at improving prediction of ARs for water resource benefits at time scales ranging from shorter (0–3 day) to subseasonal to seasonal, where the latter would allow for much more robust decision-making around resource allocation. At the shorter time scales, if forecasts can be shown to have enough skill, there has been interest in exploring the potential to use them to inform reservoir operations (FIRO, 2017). Given this interest from the applications community, as in IARC2016, several sessions and panels were dedicated to using scientific advances as bases for decision-making, developing decision support tools, and supporting sound data-driven policy. In 2018, these included, among others, the AR Research for Water Managers panel and Applications and Communications session. The AR Colloquium Summer School has several planned sessions on these topics, given by meteorologists and engineers from the US Army Corps of Engineers and CA Department of Water Resources, who were specifically invited to communicate with students about their needs and the importance of advances in research topics such as S2S scale forecasting. Having this sector integrated into each IARC benefits both the scientists and the stakeholders, as this fortifies lines of communication, builds trust and relationships, and allows for the coproduction of ideas (Vano *et al*., 2017).

In short, the international community focusing on the topic of ARs continues to grow more vibrant and connected, and we look forward to being involved in its continued development and maturation.

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