Advancing atmospheric river science and inspiring future development of the Atmospheric River Reconnaissance Program

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Atmospheric River Reconnaissance Workshop 2023

*What:* Forty collaborators from research, operational, and academic centers came together to discuss the latest research findings from Atmospheric River Reconnaissance, and to coordinate and inspire future work on data collection, data assimilation, metric development and impact assessment.

*When:* 27-29 June 2023

*Where:* ECMWF, Reading, UK
Overview of Atmospheric River Reconnaissance

Over the last two decades, the important role of atmospheric rivers (ARs, defined in the Glossary of Meteorology; Ralph et al., 2018) in many extreme precipitation and flood episodes in western North America (e.g., Ralph et al., 2006; Neiman et al., 2011; Corringham et al., 2019; Fish et al., 2019; Moore et al., 2020), the western Pacific (Park et al., 2021; Yong et al., 2023), Europe (e.g., Lavers et al., 2011; Lavers and Villarini, 2013; Ramos et al., 2015), New Zealand (Kingston et al., 2016), and South America (Viale and Nunez, 2011) has become clear. These long and narrow features—typically around 2000 km in length and 800 km in width—are often located ahead of the cold front within an extratropical cyclone and are characterised by strong horizontal water vapour flux (Zhu and Newell, 1998; Ralph et al., 2018; Ralph et al., 2020). In fact, the moisture transported by ARs can be the equivalent of greater than two times the freshwater flux of the Amazon River (Zhu and Newell, 1998; Ralph et al., 2017). Furthermore, the precipitation associated with ARs is essential for many precipitation-sensitive mid-latitude regions, where, for example, it can provide up to 50% of the annual precipitation in California (Dettinger et al., 2011), in Europe (Lavers and Villarini, 2015), and in Chile (Viale et al., 2018), and supply beneficial snowpack, which makes ARs crucial for water resources and supply.

As ARs can be responsible for extreme precipitation, flooding, and water supply in mid-latitude regions, the ability to forecast ARs accurately using numerical weather prediction (NWP) systems to provide warnings and awareness is important. In 2015, a Research and Operations Partnership (RAOP; Ralph et al., 2020) called Forecast Informed Reservoir Operations (FIRO) was launched to address the specific needs of water supply resilience and flood hazard mitigation in the western United States. The FIRO RAOP is engaged in several viability assessments at key watersheds with significant precipitation inputs from ARs, and through these assessments have determined that FIRO requires improved NWP forecasts of ARs to maximize its success. The cornerstone of producing accurate NWP forecasts is the Global Observing System, which is the network of observations from the surface, aircraft, and space from which an estimate of the observed state of the atmosphere and ocean can be ascertained. There are, however, gaps in the Global Observing System, for example, across remote ocean areas and importantly within ARs where conventional observations (e.g.,
radiosondes) are sparse and inadequate and where satellite radiances have less usable information content because of the presence of clouds and precipitation (Zheng et al., 2021).

Motivated by FIRO and the need to support water and emergency management in the western United States, an observational campaign called Atmospheric River Reconnaissance (AR Recon; Ralph et al., 2020) has been developed to fill the void in observations across the northeast Pacific and in turn improve forecasts of landfalling ARs and their impacts. AR Recon has been built as an RAOP, separate from FIRO though synergistic with it, and is led by the Center for Western Weather and Water Extremes (CW3E at Scripps Institution of Oceanography) and the US National Weather Service (NWS) / National Centers for Environmental Prediction (NCEP). Its partners include the US Naval Research Laboratory (NRL), the US Air Force (USAF), the National Center for Atmospheric Research (NCAR), the European Centre for Medium-Range Weather Forecasts (ECMWF), and multiple academic institutions. Building on earlier successes, AR Recon was formally incorporated into the US National Winter Season Operations Plan (ICAMS, 2022) since winter 2019/20. The plan indicates that resources shall be made available to support data collection within impactful ARs annually from November to March.

The AR Recon program represents an umbrella effort to advance methods and tools for observations, data assimilation, verification, and physical process studies integrated together to achieve better forecasts of ARs and their impacts. These advances support forecast improvements in both (1) real time and (2) over the long term through model upgrades and insights on physical process understanding. In real time, AR Recon deploys extensive unique and new observations that are assimilated via transfer to the Global Telecommunications System (e.g., dropsondes deployed by aircraft, extra radiosonde launches, drifting ocean buoys with barometers). These observations are usually targeted in places (e.g., within the AR) where there is a paucity of observations and in regions that are forecast to have an impact on west coast United States precipitation in the 1-to-3-day forecast horizon using fundamental knowledge of essential atmospheric structures (Wilson et al., 2022), complemented by both adjoint and ensemble methods (Ralph et al., 2020; Wilson et al., 2022). Over the long term, AR Recon explores/demonstrates new and emerging observing strategies that could in the future be integrated into real-time data assimilation (e.g., Airborne Radio Occultation (ARO) and Windborne long-duration balloons). Furthermore, the collection of observations has provided opportunities for diagnostic studies to be undertaken, which have helped to identify
model issues (Lavers et al., 2018, 2020a, 2023; Stone et al., 2020; Reynolds et al., 2023) and potential ways to correct them.

AR Recon has grown since its first flights in winter 2016, as shown in Figure 1, and most of these observations were assimilated into global NWP systems. There have also been 3,467 ARO profiles taken and 101 Windborne long-duration balloons launched in the 2021 and 2022 seasons (Todd Hutchinson, personal communication), but these were not assimilated; and AR Recon also leverages the hydrometeorological observing network across the western United States (White et al., 2013; Hatchett et al., 2020). The current observing systems that are enabled by AR Recon are presented in Figure 2. With the expansion of AR Recon, the plethora of observations now gathered, and the substantial ongoing research activities, the fourth AR Recon Workshop was held at ECMWF, Reading, UK from 27-29th June 2023 to share the latest research findings and discuss the next steps in this program. This paper summarises the workshop and the latest research and outlines the science questions raised and future campaign plans.

Fig. 1. A bar chart of the number of observations in each AR Recon season since 2016. The figure includes the number of dropsondes (black), radiosondes (blue), drifting buoys (green), flights (red), and ARO profiles (purple).
Fig. 2. A schematic showing the observing platforms currently used in the AR Recon program. This is an updated schematic that was first published in Zheng et al. (2021).

**AR Recon Workshop Summary**

The overarching goal of the annual AR Recon Workshop is to bring together AR Recon operational and research-focused participants, along with interested experts, to share results, to coordinate and inspire future work on data collection, data assimilation, metric development and impact assessment, and to discuss the RAOP approach pioneered by AR Recon. This year, forty collaborators from research, operational, and academic centers around the globe gathered at ECMWF for a range of invited presentations (both in-person and virtual), posters, and
discussions split into eight sessions. The agenda and recordings and slides of the presentations are available (https://ecmwfevents.com/i/180a172f-c106-4dde-9d1a-37539f3752a2/public/agenda). These were grouped under the following titles: (1) AR Recon in water year 2023; (2) Modeling, data assimilation, and impact studies; (3) Scientific advances in physical process understanding; and (4) the future of AR Recon. The AR Recon Workshop was followed by a 1-day meeting on the proposed observational campaign named North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign (NAWDIC); further details are available here.

Keynote talks were given by Dr Cary Talbot (US Army Corps of Engineers) on the “Importance of AR Recon Observations to Water Management” and by Rear Admiral Nancy Hann (NOAA Office of Marine and Aviation Operations) on “NOAA Aircraft AR support: now and future.”, which highlighted how AR Recon fits into the goals of their organizations. FIRO, and water management information needs in general, are evolving along with growing populations, climate change, and other stressors. This is a major application of AR Recon-enabled forecast improvements. The conveners consider it critical for those who are doing the science – including those developing and providing the forecasts, undertaking model diagnostics and physical process studies, and conducting data impact studies – to be closely connected with the operational communities that depend on their work. This is part of the ethos of the RAOP. Similarly, having participation from officials like Rear Admiral Hann is critical for the AR Recon community to proceed with a full understanding of expected observational resource upgrades, and to provide requested input on those upgrades. The goal, on both sides, is to produce the maximum societal benefit with revitalized aircraft capability.

The major themes this year were chosen to provide opportunities for reflection on the most salient points of AR Recon 2022–2023. First, water year 2023 was a record-breaking year in many parts of the West – especially in California (DeFlorio et al. submitted) – and was also the first year that AR Recon missions were tasked and flown in November and December. The temporal expansion of the campaign and the ARs sampled this year were the topics of multiple presentations, and mentioned in many more, including two dedicated sessions during the first day of the Workshop. Each year, a crucial component of the Workshop is to discuss advances in modeling and hear updates from each of the Steering Committee institutions (CW3E, NOAA NCEP, ECMWF, NCAR, NRL, and the University of Colorado at Boulder), along with many other partners, on assessments of the impact of data collected up to this point by AR Recon. The research undertaken is used to diagnose model deficiencies, inform model experiments to
test for potential improvements, and to refine our targeting strategies as we continue to learn how to maximize improvement in U.S. West Coast precipitation forecasts. Additionally, the Workshop presents an opportunity to cover advances in our physical understanding of ARs and their evolution and impacts, based on the operational data collected by our partners. Finally, there was time devoted to discussing the future development of AR Recon, and this is reported in the next Section of this summary.

This was the first time that the AR Recon Workshop was hosted outside of Scripps Institution of Oceanography. Co-chairs of the Workshop Steering Committee remained AR Recon PI and CW3E Director F. Martin Ralph and AR Recon Co-PI and NOAA Senior Scientist Vijay Tallapragada, with the addition this time of ECMWF Deputy Director-General and AR Recon Steering Committee member Florian Pappenberger. The benefits of holding the Workshop at ECMWF were the (1) greater participation from the European community including ECMWF, the University of Reading, and other institutions; and (2) connection with the NAWDIC science community and the associated 1-day NAWDIC workshop, which was fitting given the proposed AR Recon expansions.

The organizers feel that holding this Workshop on a yearly basis along with other elements of the AR Recon RAOP is critical for its success, allowing for participants to reflect upon accomplishments thus far, provide a holistic view on the current state and future of the Partnership, and to plan with colleagues for future developments. This year was no exception and provided opportunities to discuss AR Recon with currently involved parties in North America and Europe, with the inclusion this year for the first time of participants from Asia and South America.

**Workshop Recommendations and Future Plans**

The wide range of presentations and time set aside for discussion raised interesting science questions and generated many ideas for the future development and growth of AR Recon; and this section covers these topics in turn.

During the workshop, the following science questions were raised and suggested for further study:
(1) Although the essential atmospheric structures that are targeted with the adjoint and ensemble sensitivity tools are generally focused on days 1-2, why are some of the largest impacts in the forecast systems seen on forecast day 3?

(2) Are the varying impacts seen in the different modeling systems (e.g., ECMWF vs NCEP) a result of model differences or due to inconsistent assessment methodologies employed at the different centers?

(3) How will the forecast impacts change or improve if the forecast sensitivity is assessed based on other user-relevant variables, such as river basin precipitation or based on forecast sensitivities at longer lead times?

(4) How can new observation platforms – such as the NOAA G550 aircraft – that are coming online in the next few years be best used in AR Recon?

(5) Could different sampling strategies, such as deploying dropsondes in different temporal or spatial patterns, or expanding the AR Recon observing domain to the west Pacific, provide larger forecast impacts or improved process understanding of essential atmospheric structures?

To address these questions, the idea of working groups was proposed, with one in particular focused on ensuring that a consistent evaluation approach is applied across studies. A second working group could study the potential impacts of deploying dropsondes far upstream of the current AR Recon domain.

Several concrete recommendations came out of the Workshop in addition to the formation of working groups. First, the primary recommendation focused on the expansion in the spatial extent of observations. Results to date suggest that the growth of the AR Recon domain to include the northwest Pacific Ocean, the Gulf of Mexico, and North Atlantic Ocean may lead to increased short- (1-3 days) and medium-range (3-14 days) forecast skill not just across the western United States, but also across the whole of the United States and potentially the northern hemisphere. This expansion would build on previous flights over the Gulf of Mexico and supplemental radiosonde launches at NWS sites in the eastern United States that supported storm forecasts in the eastern region, and on ocean buoy deployments in the northwest Pacific and North Atlantic Oceans (Lavers et al., 2021) in 2022 and 2021, respectively. The adjoint and ensemble targeting tools will need to be advanced to provide expanded guidance both spatially and temporally. For the second time, ocean buoys will be released in the northwest Pacific Ocean in the winter of 2023/24. It is hypothesized that the pressure observations from
these buoys will provide a more accurate picture of the synoptic-scale atmospheric circulation and thus reduce uncertainty in the systems travelling towards North America. Furthermore, the USAF are planning reconnaissance flights out of Guam to sample systems in the northwestern Pacific in the boreal winter of 2023/24 or 2024/25. These expansion plans may also link in with campaign ideas of collaborators in Europe and Asia, which is in line with a perspective piece by Lavers et al. (2020b). In addition, efforts will be made via workshops or other forums, to engage with groups who could be potential collaborators on sampling in these different regions. Developing East Asian partnerships to enable effective upstream sampling in the northwest Pacific will be a near-term focus.

Second, this expansion would be supported by more aircraft resources coming online and more effective use of the increased quantity and diversity of observations. In particular, the new G550 aircraft described by Rear-Admiral Hann has an expected delivery in 2025. Four USAF C-130s were equipped with ARO by the end of the missions, and the entire fleet of 10 will be equipped by the 2023-2024 season. Assimilation of HDOBS and high-resolution radiosondes have been achieved and the ARO forward operator has been developed to enable effective data assimilation. Advances in data communications from the aircraft have moved ARO datasets closer to being used in real-time in global NWP systems (providing they are made available on the Global Telecommunications System), which will benefit the modeling of ARs across the northeast Pacific. Third, the exchange of visiting scientists between institutions, beginning with CW3E and ECMWF, is being discussed, which will allow for the exchange of ideas and further development of the program.

The next AR Recon campaign season will begin in November 2023 and the next AR Recon Workshop will be held at Scripps Institution of Oceanography in the fall of 2024.

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