BAMS Meeting Summary

Atmospheric River Reconnaissance Workshop Promotes Research and Operations Partnership

Anna M. Wilson, Alison Cobb, F. Martin Ralph, Vijay Tallapragada, Chris Davis, James Doyle, Luca Delle Monache, Florian Pappenberger, Carolyn Reynolds, Aneesh Subramanian, Forest Cannon, Jason Cordeira, Jennifer Haase, Chad Hecht, David Lavers, Jonathan J. Rutz, and Minghua Zheng

Atmospheric River Reconnaissance (AR Recon) Workshop 2021

What: Eighty attendees from 23 institutions and agencies representing the AR Recon team met to highlight both accomplishments and lessons learned from the prior reconnaissance season and discuss the future of AR Recon.

When: 28 June–1 July 2021

Where: Virtual

KEYWORDS: Aircraft observations; Sampling; Forecasting; Numerical weather prediction/forecasting; Decision making

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Corresponding author: Anna Wilson, amw061@ucsd.edu
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AFFILIATIONS: Wilson, Cobb, Ralph, Delle Monache, Cannon, Hecht, and Zheng—Center for Western Weather and Water Extremes, Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California; **Tallapragada**—NOAA/NWS/NCEP/Environmental Modeling Center, College Park, Maryland; **Davis**—National Center for Atmospheric Research, Boulder, Colorado; **Doyle and Reynolds**—U.S. Naval Research Laboratory, Monterey, California; **Pappenberger and Lavers**—European Centre for Medium-Range Weather Forecasts, Reading, United Kingdom; **Subramanian**—University of Colorado Boulder, Boulder, Colorado; **Cordeira**—Plymouth State University, Plymouth, New Hampshire; **Haase**—Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California; **Rutz**—NOAA/NWS/Western Region Headquarters, Salt Lake City, Utah

Atmospheric rivers (ARs) are the source of a large fraction of precipitation along the U.S. West Coast and the cause of the majority of major floods in this region. The goal of Atmospheric River Reconnaissance (AR Recon) is to support water management decisions and flood forecasting by using targeted airborne and buoy observations over the northeast Pacific to improve analysis and forecasts of landfalling ARs and their impacts on the U.S. West Coast at lead times of 0–5 days. Innovations in targeting methods, data assimilation, and regional forecast skill improvements are pursued through collaborative, cross-disciplinary, science-based strategies. To that end, AR Recon activities, conducted at Scripps Institution of Oceanography's Center for Western Weather and Water Extremes (CW3E), are guided by an international steering committee of senior experts from leading operational global numerical weather prediction (NWP) centers and research institutions. Successful observational campaigns have been run out of CW3E for several years, with the CalWater program from 2014 to 2016 (Ralph et al. 2016) and AR Recon in 2016–21, excluding 2017. This program was developed as a Research and Operations Partnership (RAOP), a framework that quickly demonstrated value. AR Recon grew from a concept to a field demonstration and an operational requirement and mission, called for in the National Winter Season Operations Plan (NWSOP) beginning in summer 2019 (Office of the Federal Coordinator for Meteorology 2019, 2020; Ralph et al. 2020).

AR Recon observations, which include targeted dropsonde data, drifting buoys that measure surface pressure and sea surface temperature, and innovative observing platforms such as airborne radio occultation (ARO; Haase et al. 2021), fill documented gaps in the traditional observation system (Zheng et al. 2021a). These gaps occur within and around ARs due to their associated deep clouds and represent some of the leading sources of uncertainty for the prediction of extreme events over the western United States (Lavers et al. 2018; Reynolds et al. 2019; Demirdjian et al. 2020a; Lavers et al. 2020a). Dropsonde and buoy observations are transmitted in real time to the Global Telecommunications System (GTS) to be assimilated in operational NWP systems. That capacity is currently being built up for ARO. Studies using AR Recon data have already shown the positive impact on forecasts (e.g., Stone et al. 2020; Zheng et al. 2021b). Furthermore, AR Recon data have enabled advances in the understanding of physical processes that modulate AR characteristics such as intensity (Hatchett et al. 2020; Cannon et al. 2020; Norris et al. 2020; Demirdjian et al. 2020b; Cobb et al. 2021).

Thus far, AR Recon has focused on improving forecast accuracy for the U.S. West Coast thanks to groundbreaking research programs like the U.S. Army Corps of Engineers' Forecast Informed Reservoir Operations (FIRO; Delaney et al. 2020; Jasperse et al. 2020) and the

California Department of Water Resources' AR Program (Ralph et al. 2020). However, ARs are a global weather phenomenon that transport most of the moisture across the midlatitudes, and what we learn in this program could be applicable to other areas of the globe (Lavers et al. 2020b).

Workshop overview

Following a successful virtual AR Recon workshop in 2020, and a highly productive AR Recon 2021 season with a record number (29) of intensive observation periods (IOPs), the workshop was held virtually again in summer 2021 over 4 consecutive days. The purpose of the AR Recon 2021 workshop was to document AR Recon data impacts and envision the evolution of AR Recon for the next 5 years and beyond. The workshop was cochaired by the PI and co-PI of AR Recon (F. Martin Ralph and Vijay Tallapragada) and chaired by the AR Recon Modeling and Data Assimilation Steering Committee. It created a specific opportunity for the team to take time to highlight both accomplishments and lessons learned from the prior season, prepare for the next season, share key results from data impact studies, and develop coordinated case study approaches. The workshop also enabled discussions about the future, the exploration of collaborative opportunities to learn more about the physical processes, and refinements in targeting strategies aimed at improving the representation of atmospheric initial conditions in operational NWP models. This year, the workshop welcomed 80 attendees from 23 different institutions and agencies over the 4-day period.

Workshop goals

The AR Recon 2021 Workshop goals were defined as follows:

- To share results from studies involving AR Recon data
- To coordinate and inspire future work on data collection, data assimilation, metric development, and impact assessment
- To strengthen the RAOP approach being developed in AR Recon

The workshop program was designed by the Steering Committee to meet these goals and stimulate engaging and effective discussion among all participants.

Presentations and discussion

The AR Recon workshop featured collaborators from research and operational centers in the United States and around the globe, including the National Centers for Environmental Prediction (NCEP), National Weather Service (NWS), U.S. Naval Research Laboratory (NRL), National Center for Atmospheric Research (NCAR), European Centre for Medium-Range Weather Forecasts (ECMWF), Plymouth State University (PSU), University of Colorado Boulder (CU Boulder), Northern Illinois University, and University at Albany, State University of New York. The invited presentations and discussions made up five sessions as listed below:

- Session I: AR Recon: RAOP
- Session II: AR Recon sampling strategy: Essential atmospheric structures
- Session III: AR Recon sampling strategy: Sensitivity tools
- Session IV: Data assimilation and impact studies
- Session V: AR Recon vision

The meeting began with opening remarks from workshop cochairs (F. Martin Ralph and Vijay Tallapragada), who gave an overview of AR Recon, and presented goals of the meeting. The first day's schedule focused on the RAOP, a key constituent of the AR Recon campaign, as described in Ralph et al. (2020). The concept of an "AR Recon sequence" was discussed,

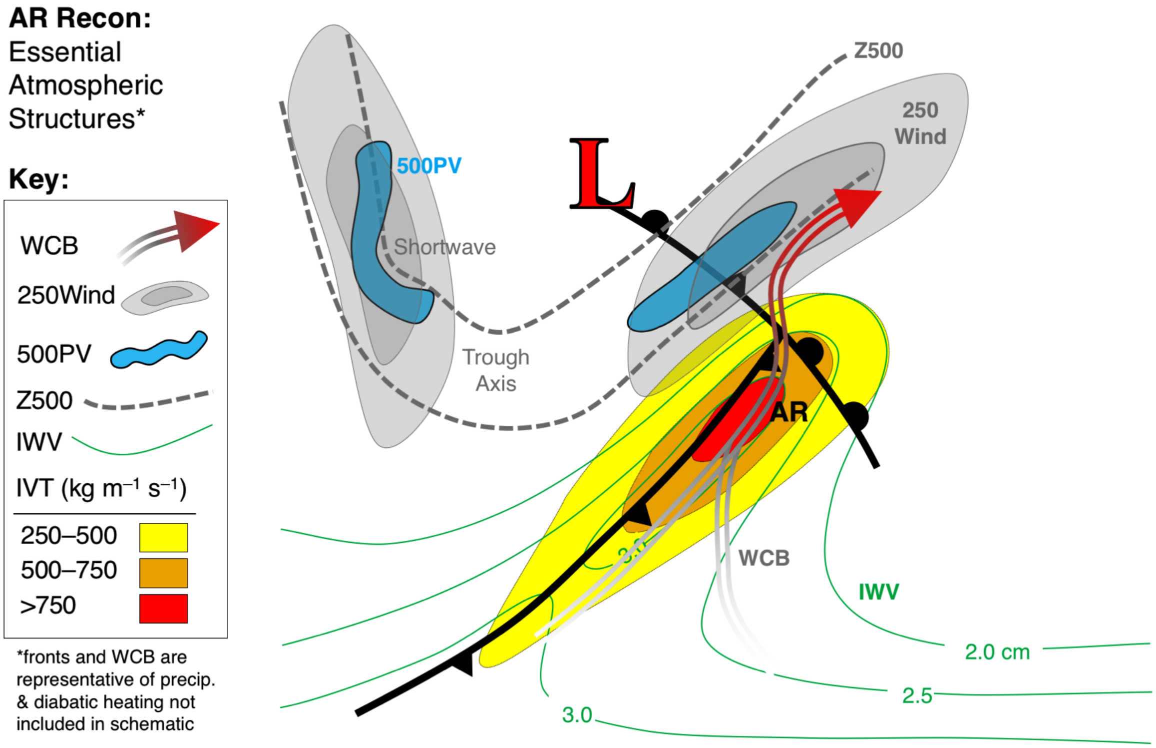

Fig. 1. Schematic of physical targets for AR Recon.

in which the same storm system is sampled over several IOPs. We then heard from Lt. Col. Ryan Rickert of the Air Force 53rd Weather Research Squadron "Hurricane Hunters" and NOAA Aircraft Operations Center Jack Parrish on the operational aspects of the 2021 season and looking toward AR Recon 2022 and beyond. We concluded this first day with a detailed examination of the vast number of observations that were collected as part of the 45 flights in AR Recon 2021, presented by Alison Cobb, Anna Wilson, and Jennifer Haase. These included profiles from 1,142 dropsondes, the deployment of 30 additional drifting buoys, and ARO profiles. Radiosondes at additional times (2100, 0000, and 0300 UTC) at locations in Northern and Southern California were also released in conjunction with the AR Recon flights, when it was appropriate given the AR location. This session not only highlighted how the observations collected far surpassed previous seasons, but also provided an opportunity to discuss logistical opportunities and constraints with NOAA and the Air Force.

The second day focused on AR Recon sampling strategy, as determined by AR Recon PI F. Martin Ralph. Jay Cordeira (Plymouth State University) and Jon Rutz (NWS) both served as mission directors during the AR Recon 2021 season, and shared perspectives on decision making using this guidance in real-time operations, with sampling essential atmospheric structures, notably ARs, as the primary target (Fig. 1). Lead AR Recon forecaster Chad Hecht (CW3E) closed this session with a detailed examination of the forecast tools available to create a forecast briefing, during which IOP selection and planning took place. This session included a discussion focused on potential future tools that could be used or developed for the forecast briefings and gave the opportunity for those external to the forecast team to see the complexities that are involved in collating a 30-min briefing each day during the AR Recon 2021 season.

Following this session on essential atmospheric structures, we heard how various initial condition sensitivity tools complement the foundational physical questions addressed by the AR Recon sampling strategy, as they provide information on optimal locations where additional observations could be most useful to minimize forecast errors or uncertainties. Forest Cannon and Minghua Zheng (CW3E) provided details on how these tools are used in flight planning on the Google Earth platform. In AR Recon 2021, we utilized three sensitivity products developed by different collaborating centers. Jim Doyle (NRL) discussed the COAMPS adjoint forecast sensitivity, Ryan Torn (U. Albany) presented on ECMWF ensemble-based sensitivity, and finally, Xingren Wu (NCEP) closed with a summary of NCEP ensemble sensitivity tools, which also make use of the Canadian ensemble forecasts. Having leading experts on these sensitivity tools allowed for lively discussion on both technical developments and applications of these important tools.

On the third day we discussed research examining the data assimilation and impacts of AR Recon data on forecasts, with an introduction by Luca Delle Monache (CW3E). Exciting results were shared by all modeling centers partnering in the AR Recon Modeling and Data Assimilation Steering Committee. Vijay Tallapragada presented an evaluation of 2021 AR Recon data impact on the performance of NCEP operational Global Forecasting System (GFS). Minghua Zheng shared results showing an improved forecast skill in CW3E's in-house Weather Research and Forecasting (WRF) Model tailored for forecasts in the western United States (West-WRF; Martin et al. 2018), through the assimilation of AR Recon dropsonde observations. Carolyn Reynolds (NRL) shared an analysis of AR Recon buoy and dropsonde impacts, and David Lavers (ECMWF) presented jet stream diagnostics using AR Recon observations. The final presentations of this session were by Bill Kuo (NCAR), who introduced Constellation Observing System for Meteorology, Ionosphere and Climate (COSMIC)-2 and the application of Global Navigation Satellite Systems (GNSS) Radio Occultation data to AR analysis and prediction, and Aneesh Subramanian (CU Boulder), who provided a summary of buoy data impact on forecasts with the ECMWF Integrated Forecasting System model. This session showcased the utility of all these data streams, both in their impact when assimilated in real time into NWP, and how the observations provide critical information about the underlying physical processes. This session also highlighted the need for evaluating AR Recon data impacts on localized precipitation forecasts over the regions where they matter the most. Several different techniques were shared for data analysis, sparking suggestions for further studies and collaborations.

On the final day of the workshop there were facilitated discussions, with excellent participation from partners and collaborators. We discussed sampling strategies for 2022 and beyond, including lessons learned from AR Recon 2021 and opportunities for future developments (moderated by Alison Cobb, CW3E). One notable development is the possibility of expanding AR Recon sampling strategies for winter storms in the Gulf of Mexico and northeast Atlantic, which is planned for execution by the AR Recon team for 2022 winter season to support NCEP Weather Prediction Center (WPC) operations. We also discussed collaborations with European colleagues to develop AR Recon in the Atlantic, leveraging plans for the North Atlantic Waveguide, Dry Intrusion, and Downstream Impact Campaign (NAWDIC) effort [a follow-on campaign to North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX)] (moderated by David Lavers, ECMWF), with presentations from Julian Quinting (Karlsruhe Institute of Technology), F. Martin Ralph (CW3E), and Steven Cavallo (University of Oklahoma). Significant progress was made during these discussions and follow-up activities are planned on all topics.

Outcomes and future plans

During AR Recon 2021, there were significantly more targeted observations of all types gathered than previous years, despite challenges including the global pandemic. A growing number of collaborators were involved this year, including a number of students. This meant that the number of attendees for the workshop increased, with an additional day in the program this year compared to the 2020 workshop. The organizing committee hopes that next year the workshop can be held in person.

The AR Recon workshop provided a valuable opportunity to discuss both operational logistics and research findings and the important relationship between the two. For example, the group discussed the locations of the Air Force and NOAA aircraft in future missions from the perspectives of both agencies. Discussions also covered plans to deploy innovative equipment from all aircraft, and logistical constraints and opportunities regarding the transmission of full vertical profile dropsonde BUFR data to the GTS from the Air Force aircraft. Following this workshop, the ARO working group is exploring the feasibility of real-time assimilation of these data in future years and collaborating with the COSMIC-2 team in joint research studies. Plans are already in place for AR Recon 2022, where a similar number of flight hours and IOPs are anticipated between January and March 2022. Information will be provided on CW3E's AR Recon website: https://cw3e.ucsd.edu/arrecon_overview/.

This workshop facilitated a transfer of knowledge between scientists of various stages of their careers and between different institutions. Attendees discussed future opportunities for collaborative research and potential avenues for advanced research, ending with a decision to conduct a comprehensive case study. Joint efforts will be focused on evaluation of data impacts from a sequence of IOPs, with common research questions and complementary analyses currently being undertaken. The sequence to be studied, which consisted of six IOPs over 23–28 January 2021, sampled an AR critical for California water supply that also caused damaging debris flows in the central and southern parts of the state.

The key framework under which AR Recon operates is a RAOP, and in fact AR Recon is a successful prototype of this framework. One important outcome of this workshop is its strengthening of existing partnerships developed throughout the years and new partnerships from the latest seasons. The ongoing partnership with NAWDIC was strengthened, working toward a collaborative mission in the future (detailed in the AR Recon section in the NAWDIC Science Plan). Sharing successful targeting procedures used in AR Recon 2021 during this workshop enabled other observational campaigns to consider adopting the approach used in this campaign. Even in operational missions called for in other national plans, there has been discussion and planning around moving away from fixed tracks to design tracks that respond to the particular challenges of a given forecast. This will be tested as early as 2021/22 for Atlantic and Gulf of Mexico winter storms. In 2022, AR Recon will continue to operate as a RAOP, and the AR Recon Modeling and Data Assimilation Steering Committee will continue to utilize this framework to maximize the benefits of AR Recon both to operations and to deepening the basic physical and dynamical understanding of these important phenomena. Expanding the AR Recon from the current partial cool-season deployment (10 weeks) to full season (20 weeks), and to increase the area covered to include the northwest Pacific, have huge potential for increasing forecast skill at longer lead times out to 5–8 days, which can address the emerging and growing needs for improved water management and prediction of water cycle extremes.

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