ATMOSPHERIC RIVERS EMERGE AS A GLOBAL SCIENCE AND APPLICATIONS FOCUS

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Recent advances in atmospheric sciences and hydrology have identified the key role of atmospheric rivers (ARs) in determining the distribution of strong precipitation events in the midlatitudes. The growth of the subject is evident in the increase in scientific publications that discuss ARs (Fig. 1a). Combined with related phenomena, that is, warm conveyor belts (WCBs) and tropical moisture exports (TMEs), the frequency, position, and strength of ARs determine the occurrence of floods, droughts, and water resources in many parts of the world. A conference at the Scripps Institution of Oceanography in La Jolla, California, recently gathered over 100 experts in atmospheric, hydrologic, oceanic, and polar science; ecology; water management; and civil engineering to assess the state of AR science and to explore the need for new information. This first International Atmospheric Rivers Conference (IARC) allowed for much needed introductions and interactions across fields and regions, for example, participants came from five continents, and studies covered ARs in six continents and Greenland (Fig. 1b). IARC also fostered discussions of the status and future of AR science, and attendees strongly supported the idea of holding another IARC at the Scripps Institution of Oceanography in the summer of 2018.

The concept of atmospheric rivers emerged in the 1990s (e.g., Zhu and Newell 1998) and at first received significant criticisms. However, with the advent of new satellite measurements of integrated water vapor (IWV) over the oceans and a set of field experiments during which research aircraft probed these features (Ralph et al. 2016), interest in the subject has grown.

INTERNATIONAL ATMOSPHERIC RIVERS CONFERENCE

What: The first conference dedicated to the subject of atmospheric rivers was held with over 100 attendees from across the globe discussing the science, impacts, and applications of atmospheric rivers including dynamics, observations, predictions, climate projections, and water decisions.
When: 8–11 August 2016
Where: La Jolla, California

This growth is highlighted by the increase in publications using the term from fewer than 10 articles before 2004, when a publication by Ralph et al. (2004) combined research aircraft data, Special Sensor Microwave Imager (SSM/I) satellite IWV measurements, and the AR concept, to over 600 since then. Nonetheless, debate over the relationship between AR, WCB, and TME continues. It has been expressed by some that ARs, WCBs, and TMEs are the same thing, though the many papers, numerous funded proposals, doctoral dissertations and master's theses, and emerging applications of these various features of the midlatitude atmosphere indicate otherwise.

The 2016 IARC built upon an AR workshop in 2015 that had brought together about 30 scientists to help resolve the lingering questions about the relationship between AR, WCB, and TME. The 2015 workshop was organized by the new Center for Western Weather and Water Extremes (http://cw3e.ucsd.edu/) at the Scripps Institution of Oceanography at the University of California, San Diego. A brief workshop synopsis summarizing the discussions is available (Dettinger et al. 2015; http://cw3e.ucsd.edu/?p=2870). From independent analyses using differing methods, leaders on ARs, WCBs, and TMEs came to essentially the same conclusion, that is, that these phenomena are related but distinct. Two main activities emerged: 1) It was time to develop a comprehensive monograph on ARs, and 2) an open AR-focused conference was needed.

As a follow on to the IARC, which included the attendance of roughly 15 graduate students, it was decided to begin organizing a 3-week colloquium at the Scripps Institution of Oceanography in the future. It is intended to bring together the lead authors of the AR Monograph book chapters and graduate students from around the world for lectures, cross-disciplinary exchange, and mentored mini research efforts. IARC brought together most of the AR Monograph chapter authors at a point in the writing where new ideas garnered during the conference can be incorporated into the monograph.

IARC GOALS. The goals of the 2016 IARC were to

- evaluate the current state and applications of the science of the midlatitude atmospheric water cycle, with an emphasis on ARs and associated processes (e.g., WCB and TME);
- discuss differing regional perspectives;
- assess current forecasting capabilities; and
- plan for future scientific and practical challenges.

IARC received 78 abstracts on ARs, their impacts, and applications of AR information to decision-making. Submissions represent work on six continents plus Greenland. The conference was attended by 105 people, which included invited presentations, oral sessions, a poster session, and panels on applications to decision-making, definitions of atmospheric river, and future directions. Breakout sessions discussed AR forecasting, AR Monograph chapters, and ARs in future climates and subseasonal to seasonal prediction.

Sessions were organized around the following themes, which represent AR Monograph sections:

- history of AR science;
- AR applications;
- global and regional perspectives;
- observing and detecting ARs;
- impacts of ARs;
- theory, structure, and processes; and
- modeling methodologies.

ATMOSPHERIC RIVER DEFINITION. One panel discussed the definition of atmospheric river. The moderator noted that the AR concept has brought greater focus on the horizontal transport component of the global water cycle and on our growing understanding of the roles that those transports play in extreme precipitation, water supplies, flooding, snow, drought, aqueous and terrestrial ecosystems, and geomorphology. However, AR science and definitions used in most studies today focus on midlatitudes, even though the concept of ARs is clearly reaching into, and called upon in, subtropical and polar regions as well. The following questions were posed to the panel and audience:

a) Should this definition be based on extratropical dynamics, or should it be broadened to represent areas of concentrated horizontal transport globally, with less of a requirement that it be associated with a particular set of dynamics?
b) The editor of the *Glossary of Meteorology* has been asked by members of the community for a definition of AR. What definition of an AR should we offer to the glossary? Or how should a formal definition be developed?

Attendees strongly favored maintaining the extratropical dynamics framework in the definition and supported holding town halls on the subject

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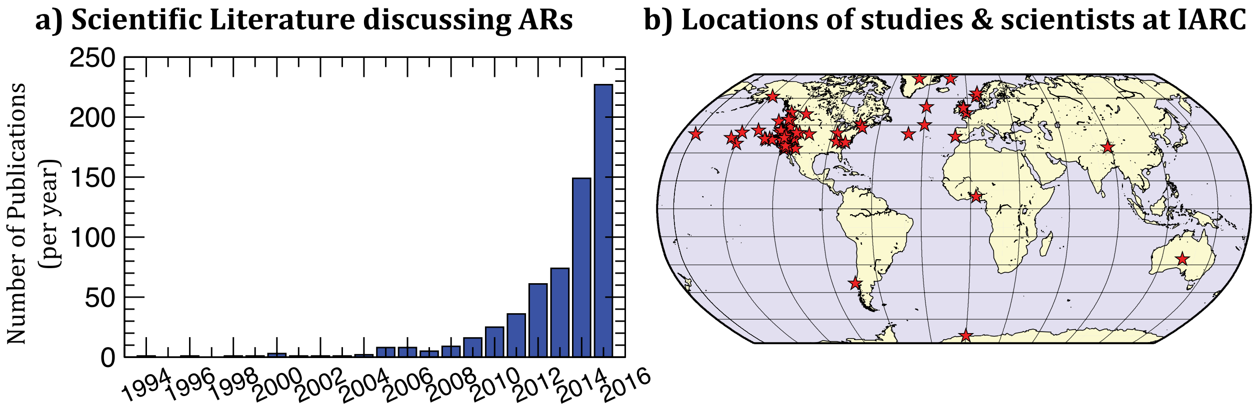

Fig. 1. (a) Numbers of references to ARs in the scientific literature per year based on a combination of Google Scholar citations (verified by downloading and searching each for the term atmospheric river) and a literature search by a librarian at the NASA Jet Propulsion Laboratory for years prior to 2014 and Google Scholar search since then (total of 630 through 2015). (b) Approximate locations of conference participants or study areas of research reports at the conference.

at both the 2017 American Meteorological Society (AMS) Annual Meeting and American Geophysical Union (AGU) 2016 Fall Meeting. The Town Halls were then planned and carried out by the cochairs of the AMS Mesoscale Committee (Tom Galarneau), Hydrology Committee (John Eylander), and AR specialists (F. Martin Ralph and M. Dettinger).

Atmospheric rivers: A discussion of a definition for the Glossary of Meteorology. The Town Halls included a combined 10 panelists and over 150 attendees, who had a chance to offer opinions on the draft AR definition provided below. The comments were considered in the process of finalizing the definition which has now appeared in the *Glossary of Meteorology*.

Atmospheric river draft definition. An atmospheric river is a long, narrow, and transient corridor of anomalously strong horizontal water vapor transport that is typically located in the lowest 3 km of the troposphere and associated with a low-level jet stream ahead of the cold front of an extratropical cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical moisture sources, and atmospheric rivers frequently lead to heavy precipitation where they intersect topographic or other lower-tropospheric boundaries or enter into the warm conveyor belt–related isentropic upward air motion. Atmospheric rivers conduct over 90% of all poleward water vapor transport in the extratropics in less than 10% of the zonal circumference of the globe.

SESSION SUMMARIES. *AR observations.* Satellite-based microwave radiometric measurements of integrated water vapor in ARs have been the foundation of AR monitoring over the oceans (Ralph et al. 2004; Wick et al. 2013). However, the microwave technique fails over land and ice surfaces because of their high and varying emissivities, and satellite methods cannot measure winds within ARs offshore, even though winds strongly control the water vapor transport and orographic precipitation enhancement upon AR landfall. However, two key methods are available now to measure horizontal water vapor transport in ARs: 1) atmospheric river observatories, which are an integrated system of ground-based remote sensing and in situ instruments that detect the forcings and impacts of ARs at a particular location (White et al. 2013), are now operating on the U.S. West Coast at seven locations; and 2) dropsondes released from aircraft offshore for example, during the multiyear CalWater program of field studies (Ralph et al. 2016).

AR dynamics. The IARC included two sessions related to theory, structure, and processes that govern the formation and intensity of ARs and their contained spatial and vertical distributions of water vapor and water vapor transport. The invited talk in the session investigated the interrelation of ARs in the life cycles of midlatitude cyclones and demonstrated the spatial overlap of ARs with TMEs (e.g., Knippertz and Wernli 2010) and the WCB (e.g., Carlson 1980). For example, large portions (50%) of regions encompassed by ARs globally have a TME origin, whereas smaller portions (25%) are related to a WCB or neither. These findings shed light on the processes that may form or maintain some ARs (TMEs) and lead to the dissipation of others (WCBs).

AR impacts. These two sessions discussed emerging studies of a broad range of effects of ARs on precipitation, floods, and other natural hazards and benefits, as well as strategies for communicating AR impacts. Strong ARs are increasingly known for yielding extreme orographic or warm conveyor belt precipitation that can cause major floods, effectively defining flood frequency regimes in many settings globally. The AR-related precipitation and floods have been widely addressed in the literature in terms of their significant impacts and costs; new studies are showing that ARs also trigger dangerous snow avalanches, landslides, debris flows, and damaging winds, often in the same uplands that yield the downstream floods. On the other hand, research highlights positive roles that ARs play in water resources, aquatic and terrestrial ecosystems and vegetation, seasonal snowpacks, and groundwater recharge. Finally, ARs critically affect the mass balances of the Antarctic and Greenland Ice Sheets, balances that will do much to define the extent and rate of sea level rise in centuries to come.

AR applications. The emerging understanding of ARs, from monitoring to dynamics and impacts, has led to a number of application areas, a few of which are highlighted here. A panel discussion focused on how AR information is affecting decision-making in water management and flood risk mitigation. These included perspectives from local, state, and federal water management experts who described how the development of AR science, monitoring, and forecasting tools offer opportunities to refine decision-making strategies related to reservoir operations. They also identified emerging areas of information needs, such as for subseasonal to seasonal predictions of precipitation in the western United States. Another major application area is evaluating climate change projections and documenting the key role of extreme events, especially those related to ARs, in determining annual precipitation. This included recognition of the risk of stronger ARs in future climate conditions where more water vapor is available due to warmer atmospheric conditions.

Student and early career perspectives. Roughly 20 graduate students and postdoctoral scholar attendees were invited to offer their personal perspectives on what has drawn them to the AR topic. The following motivations were described: i) AR research covers many scales of atmospheric motion and benefits from the study of pure atmospheric dynamics as well as applied research. This provides opportunities for people with a range of interests and talents. ii) Studying ARs offers opportunities for cross-disciplinary research, pairing meteorology with fields such as chemistry, geology, hydrology, climatology, civil engineering, and ecology. iii) ARs impact weather and climate in many areas, appealing to the student who observed their impacts while developing an interest in meteorology. iv) Finally, early-career researchers are motivated by a desire to make a difference through their work, and recognition that AR research presents a pathway for making scientific contributions that have a lasting impact on decision-making related to natural hazards, water resource management, and climate change has drawn them to the topic.

FUTURE DIRECTIONS IN AR SCIENCE AND APPLICATIONS. Directions of future research and applications were discussed, including development of an AR Monograph and summer colloquium, intercomparison of AR identification methods and criteria, quantification of water vapor sources and budgets through field campaigns, and assessments of ARs as key players in the global water cycle and heat and energy budgets.

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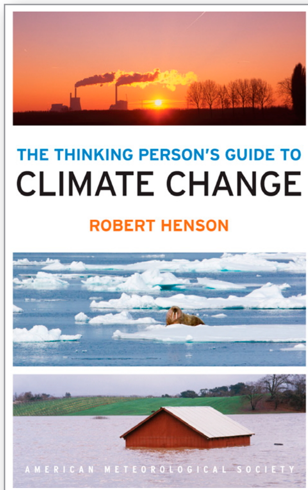

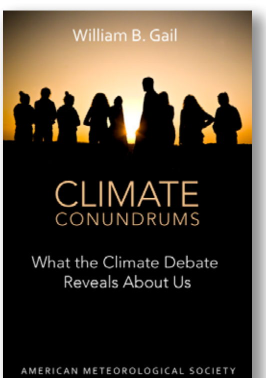

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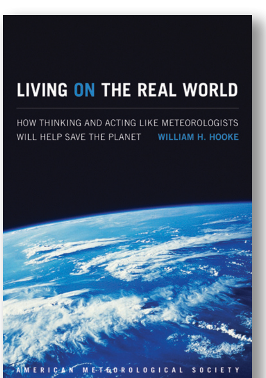

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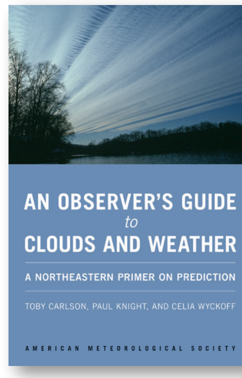

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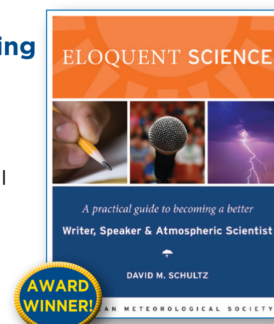

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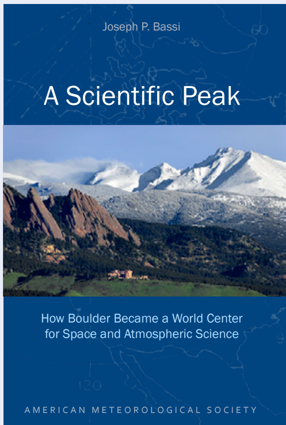

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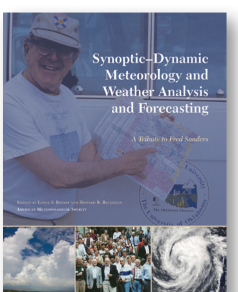

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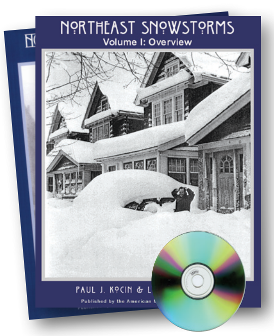

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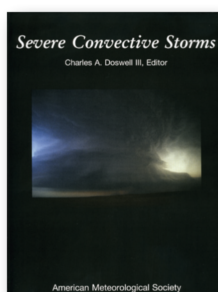

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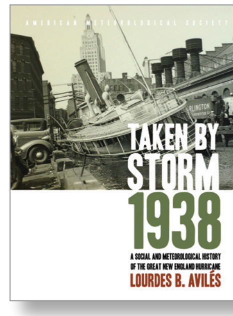

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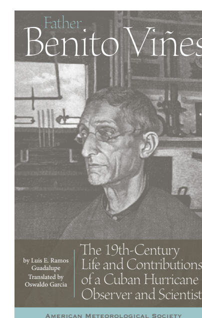

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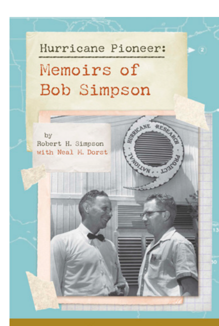

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