



1 **Atmospheric Rivers Emerge as a Global Science and Applications Focus**

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ABSTRACT

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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: Scripps Institution of Oceanography, La Jolla, California

1. Background

Recent advances in atmospheric sciences and hydrology have identified the key role of atmospheric rivers (AR) 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, i.e., warm conveyor belts (WCB) and tropical moisture exports (TME), the frequency, position and strength of ARs determines the occurrence of floods, droughts, and water resources in many parts of the world. A conference in La Jolla, CA, 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 needs for new information. This first International Conference on Atmospheric Rivers (IARC) allowed for much needed introductions and interactions across fields and regions, e.g., 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 Scripps Institution of Oceanography in the summer of 2018.

53 The concept of atmospheric rivers emerged in the 1990s (e.g., Zhu and Newell (1998)), and
54 at first received significant criticisms. However, with the advent of new satellite measurements
55 of integrated water vapor (IWV) over the oceans, and a set of field experiments during which
56 research aircraft probed these features (Ralph et al. 2016), interest in the subject has grown. This
57 growth is highlighted by the increase in publications using the term from less than 10 articles
58 before 2004, when a publication by Ralph et al. (2004) combined research aircraft data, SSM/I
59 satellite IWV measurements and the AR concept, to over 600 since then. Nonetheless, debate over
60 the relationship between AR, WCB and TME continues. It has been expressed by some that ARs,
61 warm conveyor belts (WCBs), and tropical moisture exports (TMEs) are the same thing, though
62 the many papers, numerous funded proposals, PhD dissertations and MS theses, and emerging
63 applications of these various features of the midlatitude atmosphere indicate otherwise.

64 The 2016 IARC built upon an “AR Workshop” in 2015 that had brought together about 30
65 scientists to help resolve the lingering questions about the relationship between AR, WCB and
66 TME. The 2015 Workshop was organized by the new Center for Western Weather and Water
67 Extremes (CW3E.ucsd.edu) at Scripps Institution of Oceanography at the University of California
68 San Diego. A brief workshop synopsis summarizing the discussions is available (Dettinger et al.
69 (2015); and at <http://cw3e.ucsd.edu/?p=2870>.) From independent analyses using differing
70 methods leaders on ARs, WCBs and TMEs came to essentially the same conclusion, i.e., that
71 these phenomena are related but distinct. Two main activities emerged: 1) it was time to develop
72 a comprehensive monograph on ARs, and 2) an open AR-focused conference was needed.

73 As a follow on to the IARC, which included attendance of roughly 15 graduate students, it was
74 decided to begin organizing a 3-week colloquium at Scripps Institution of Oceanography in the
75 future. It is intended to bring together the lead authors of the AR Monograph Book Chapters and
76 graduate students from around the world for lectures, cross-disciplinary exchange and mentored

77 mini-research efforts. IARC brought together most of the AR Monograph Chapter authors, at a
78 point in the writing where new ideas garnered during the conference can be incorporated into the
79 Monograph.

80 **2. IARC Goals**

81 The goals of the 2016 IARC were to:

- 82 ● Evaluate the current state and applications of the science of the mid-latitude atmospheric
83 water cycle, with an emphasis on ARs and associated processes (e.g., WCB and TME)
- 84 ● Discuss differing regional perspectives
- 85 ● Assess current forecasting capabilities
- 86 ● Plan for future scientific and practical challenges

87 IARC received 78 abstracts on ARs, their impacts and applications of AR information to deci-
88 sion making. Submissions represent work on 6 continents plus Greenland. 105 people attended
89 the conference, which included invited presentations, oral sessions, a poster session, and panels
90 on “applications to decision making,” “definitions of atmospheric river” and “future directions.”
91 Breakout sessions discussed “AR Forecasting,” “AR Monograph Chapters” and “ARs in future
92 climates and subseasonal to seasonal prediction.”

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

- 94 ● History of AR science
- 95 ● AR applications
- 96 ● Global and regional perspectives
- 97 ● Observing and detecting ARs

- 98 • Impacts of ARs
- 99 • Theory, structure and processes
- 100 • Modeling methodologies

101 **3. Atmospheric River definition**

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

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

115 Attendees strongly favored maintaining the extratropical dynamics framework in the definition,
116 and supported holding Town halls on the subject at both the 2017 AMS Annual meeting (1215
117 - 115 PM PT Monday 23 January) and AGU 2016 Fall Meeting (1230 - 130 PM Thursday 15
118 December). The AMS Town Hall is co-led by the co-chairs of the AMS Mesoscale Committee
119 (Tom Galarneau), Hydrology Committee (John Eylander) and an AR specialist (F. Martin Ralph).

120 **Atmospheric Rivers - A Discussion of a Definition for the Glossary of Meteorology**

121 The AMS Town Hall provides an opportunity for attendees of the 2017 AMS Annual Meeting
122 to weigh in on a definition of “atmospheric river” that is being developed for the Glossary of
123 Meteorology.

124 **Atmospheric river draft definition:** A long narrow and transient corridor of anomalously
125 strong horizontal water vapor transport that is typically located in the lowest 3 km of the tro-
126 posphere and associated with a low-level jet stream ahead of the cold front of an extratropi-
127 cal cyclone. The water vapor in atmospheric rivers is supplied by tropical and/or extratropical
128 moisture sources and atmospheric rivers frequently lead to heavy precipitation where they inter-
129 sect topographic or other lower-tropospheric boundaries, or enter into the warm-conveyor-belt-
130 relatedisentropic upward air motion. Atmospheric rivers conduct over 90 percent of all poleward
131 water vapor transport in the extratropics in less than 10 percent of the zonal circumference of the
132 globe.

133 **4. Session Summaries**

134 *a. AR Observations*

135 Satellite-based microwave radiometric measurements of integrated water vapor in ARs have
136 been the foundation of AR monitoring over the oceans (Ralph et al. 2004; Wick et al. 2013). How-
137 ever, the microwave technique fails over land and ice surfaces because of their high and varying
138 emissivities, and satellite methods cannot measure winds within ARs offshore, even though winds
139 strongly control the water vapor transport and orographic precipitation enhancement upon AR
140 landfall. However, two key methods are available now to measure horizontal water vapor trans-
141 port in ARs: 1) atmospheric river observatories, which are an integrated system of ground-based

142 remote sensing and in situ instruments that detect the forcings and impacts of ARs at a particular
143 location (White et al. 2013) are now operating on the U.S. West Coast at seven locations, and 2)
144 dropsondes released from aircraft offshore, e.g., during the multi-year CalWater program of field
145 studies (Ralph et al. 2016).

146 *b. AR Dynamics*

147 The IARC included two sessions related to theory, structure, and processes that govern the
148 formation and intensity of ARs and their contained spatial and vertical distributions of water vapor
149 and water vapor transport. The invited talk in the session investigated the interrelation of ARs in
150 the lifecycles of midlatitude cyclones, and demonstrated the spatial overlap of ARs with tropical
151 moisture exports (TMEs; e.g., Knippertz and Wernli (2010)) and the warm conveyor belt (WCB;
152 e.g., Carlson (1980)). For example, large portions (50%) of regions encompassed by ARs globally
153 have a TME origin, whereas smaller portions (25%) are related to a WCB, or neither. These
154 findings shed light on the processes that *may* form or maintain some ARs (TMEs) and lead to the
155 dissipation of others (WCBs).

156 *c. AR Impacts*

157 These two sessions discussed emerging studies of a broad range of effects of ARs on precipi-
158 tation, floods, and other natural hazards and benefits, as well as strategies of communicating AR
159 impacts. Strong ARs are increasingly known for yielding extreme orographic or warm-conveyor-
160 belt precipitation that can cause major floods, effectively defining flood-frequency regimes in many
161 settings globally. The AR-related precipitation and floods have been widely addressed in the lit-
162 erature in terms of their significant impacts and costs; new studies are showing that ARs also
163 trigger dangerous snow avalanches, landslides, debris flows, and damaging winds, often in the

164 same uplands that yield the downstream floods. On the other hand, research reported highlights
165 positive roles that ARs play in water resources, aquatic and terrestrial ecosystems and vegetation,
166 seasonal snowpacks, and groundwater recharge. Finally, ARs critically affect the mass balances
167 of the Antarctic and Greenland ice sheets, balances that will do much to define the extent and rate
168 of sea-level rise in centuries to come.

169 *d. AR Applications*

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

181 *e. Student and Early Career Perspectives*

182 The roughly 20 Graduate students and Postdoctoral Scholar attendees were invited to each of-
183 fer their personal perspectives on what has drawn them to the AR topic. The following moti-
184 vations were described: i) AR research covers many scales of atmospheric motion and benefits
185 from the study of pure atmospheric dynamics as well as applied research. This provides oppor-

186 tunities for people with a range of interests and talents; ii) studying ARs offers opportunities for
187 cross-disciplinary research, pairing meteorology with fields such as chemistry, geology, hydrology,
188 climatology, civil engineering, and ecology; iii) ARs impact weather and climate in many areas,
189 appealing to the student who observed their impacts while developing an interest in meteorology;
190 iv) a desire to make a difference through their work, and recognition that AR research presents a
191 pathway for making scientific contributions that have a lasting impact on decision-making related
192 to natural hazards, water resource management, and climate change.

193 **5. Future directions in AR Science and Applications**

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

198 *Acknowledgments.* The IARC Organizing Committee thanks the California Department of Water
199 Resources and Scripps Institution of Oceanography's Center for Western Weather and Water Ex-
200 tremes for support, as well as the proactive group of graduate students and Postdoctoral Scholars
201 who provided invaluable logistical support throughout the conference.

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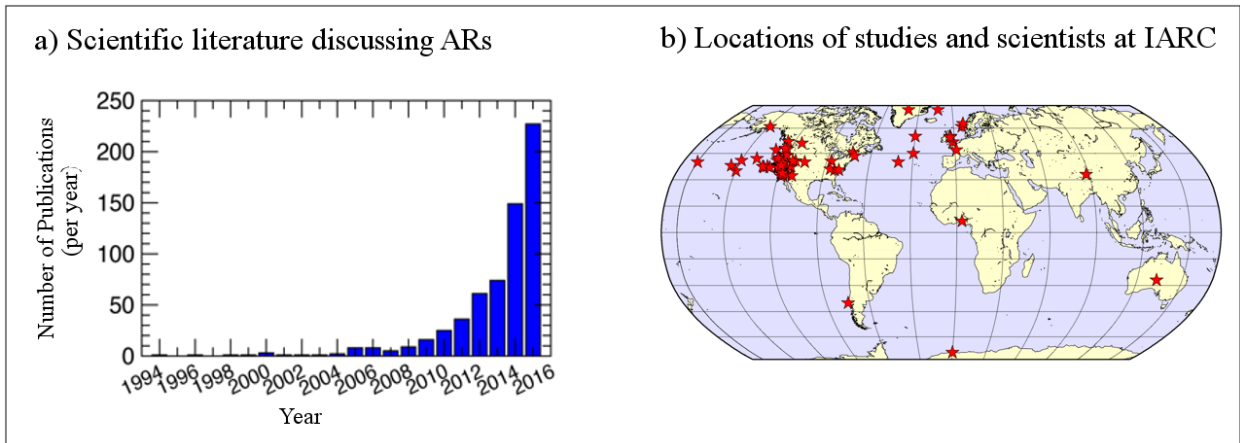
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226 **LIST OF FIGURES**

227 **Fig. 1.** a) Numbers of references to atmospheric rivers (AR) in the scientific literature per year,
228 based on a combination of Google Scholar citations (verified by downloading and searching
229 each for the term “atmospheric river”) and a literature search by a librarian at the NASA
230 Jet Propulsion Lab for years prior to 2014, and Google Scholar search since then (total of
231 630 through 2015). b) Approximate locations of conference participants or study areas of
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