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Improved forecasts of atmospheric rivers through systematic reconnaissance, better modelling, and insights on conversion of rain to flooding

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Atmospheric rivers lie behind many extreme precipitation and flood episodes in the mid-latitudes. Better forecasts of atmospheric rivers and their impacts could help with preparedness. Here we argue that a comprehensive and systematic observational campaign could help advance numerical weather prediction, and thereby provide a path towards much improved forecasts of atmospheric rivers. We envision an interdisciplinary European-American observational campaign in the North Atlantic to identify and address numerical weather prediction errors in atmospheric rivers, and the associated extratropical cyclones. Insights gained could be applied in other regions. With improved understanding of the physiography of river basins and insights into their flood response to extreme precipitation, the impacts of atmospheric rivers can also be forecast more reliably.

In early 2020, northern Europe experienced widespread flooding. The period had heightened cyclonic activity across the North Atlantic and was punctuated by two storms, Ciara and Dennis, on 9 and 16 February, respectively. Within these storms, it was the Atmospheric River (AR) component that was mostly behind the large precipitation totals and flooding. ARs are a global phenomenon linked to the extratropical storm tracks, and in early February 2020 just before the European storms, a different AR brought major flooding (and beneficial snow-pack) to the western United States. The socioeconomic effects are representative of the roles ARs play in hydroclimate, flooding, and water supply. The needs for better forecasts and the range of disciplines involved (meteorology, hydrology, and water resources management) provide the motivation for this perspective on the forecasting of ARs and their impacts.

This article describes ARs and their impacts, and presents recent advances in forecasting including modelling improvements, newly available AR forecast products, and the AR Reconnaissance observational campaign across the northeast Pacific. We follow this with a vision to improve forecasts of ARs and their impacts by (1) lengthening their skilful forecast horizon through better modelling and better observations to initialise the forecasts, (2) considering river basin properties, and (3) proposing an AR Reconnaissance campaign in the North Atlantic. The interdisciplinary approach required is also discussed.

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Atmospheric Rivers

The horizontal flux of water vapour across the mid-latitudes largely occurs within ARs^{1,2}. Typically around 2000 km in length and 800 km in width³, these long and narrow regions are located ahead of the cold front within an extratropical cyclone⁴ and are frequently connected to a low-altitude jet stream⁵. Their moisture can originate from both local mid-latitude sources over which the extratropical cyclones travel and from more remote, sometimes tropical, regions⁶, and strikingly ARs often contain larger freshwater fluxes than the Amazon River^{1,7}. There can also be an ascending airstream known as a warm conveyor belt (WCB)^{8–11} that feeds off the moisture in an AR. This WCB flow usually slopes along the warm front toward the upper troposphere forming the comma-shaped cloud feature of an extratropical cyclone. It is in this region that precipitation is produced and where the latent heat release due to the condensation of water vapour can affect the atmospheric circulation^{12–14}.

Interest in ARs has grown rapidly in recent years, as their key role in the global water cycle has become clearer. In particular, they have been found responsible for multiple hazards, most notably extreme precipitation and flooding in coastal mid-latitude zones in Europe^{15–17}, western North America^{18,19}, South America²⁰, and New Zealand²¹. Two AR events in February 2020 are presented herein to exemplify their features and hydrological impacts, one in the Pacific Northwest (Fig. 1a) and another, Storm Dennis, across northwest Europe (Fig. 1b). Each storm had typical Eulerian AR characteristics of large vertically integrated horizontal water vapour transport (integrated vapour transport, IVT) and a parent extratropical cyclone located away from the AR, which in the case of Dennis had extreme IVT exceeding 1200 $\text{kg m}^{-1} \text{s}^{-1}$ and a minimum surface pressure approaching 920 hPa, respectively. The important part played by the large-scale atmospheric circulation²² in steering these two ARs (and hence in determining the location of downstream precipitation) is illustrated by the mean sea-level pressure field in Fig. 1. In terms of impacts, the Cascades in Washington in the Pacific Northwest received over 250 mm of precipitation in the 7-day period around the AR, and western regions of Britain had over 150 mm recorded in <3 days²³; major flooding also followed. The insured damages across Europe associated with Dennis have been estimated at 286 million euros; these losses chiefly being in the UK, Germany, and

Belgium²⁴. In the western United States, more broadly, ARs are the major driver of flood damages, where over 90% of all flood damages are due to AR storms in major coastal areas, highlighting their important socioeconomic effects²⁵. Furthermore, ARs can occur concurrently with wind extremes²⁶ and high sea levels²⁷.

There are, however, benefits from the precipitation delivered by ARs to mid-latitude land masses. For example, in California they can provide up to 50% of the annual precipitation²⁸ and supply beneficial snowpack (as with the AR in Fig. 1a), which makes them crucial for water resources. Moreover, precipitation in California tends to occur in a few large winter storms and therefore the occurrence or non-occurrence of these few AR events can determine the amount of water available in the water year. Thus, the management of the water received during these storms is of great importance to public water supply and the way in which ARs cut across the meteorological, hydrological, and user communities illustrates how interdisciplinary efforts are needed when dealing with their effects.

Given the significant part ARs play in extreme precipitation, flooding, and water supply in mid-latitude regions, it is critical to be able to accurately forecast ARs and the large-scale atmospheric circulation using numerical weather prediction (NWP) systems to provide warnings and awareness of these events (at all relevant time scales, from days to seasons); and studies show that global NWP models do have useful skill in forecasting AR occurrence^{29–34}. A recent evaluation using the ensemble forecasts—multiple forecasts run to obtain a probability distribution of the future weather³⁵—from the European Centre for Medium-Range Weather Forecasts (ECMWF) Integrated Forecasting System found that the AR structure, as defined by IVT, was also forecast skilfully³⁶. As the forecast lead time increased, however, the uncertainty of forecasted IVT grew substantially which resulted in precipitation uncertainties over land. This uncertainty in the IVT, and hence the issues in determining the intensity and timing of AR conditions, as well as the locations to be affected (even at short lead times), can create substantial problems for the responders who are responsible for flood preparedness and water resources management. It is with these thoughts in mind that we are motivated to present this perspective on improving the forecasts of ARs and in turn their impacts.

Fig. 1 Two Atmospheric River events in February 2020. The vertically integrated horizontal water vapour transport (IVT; shaded contours) and mean sea-level pressure (black line contours) in the analysis of the European Centre for Medium-Range Weather Forecasts (ECMWF) control forecast at (a) 00UTC 5 February 2020 across the northeast Pacific Ocean and (b) 00UTC 16 February 2020 across the North Atlantic Ocean. The Atmospheric River (AR) in a was sampled as part of AR Recon and the black dots overlaying the thick black lines correspond to the dropsonde locations and the aircraft flight track out of Portland, Oregon, respectively.

Recent advances in forecasting

The AR properties of interest to forecast users are different at various lead times. First, at seasonal time scales, it is sufficient to know the AR frequency and the associated total precipitation within a season across a region (e.g., northeast Pacific). This may be obtained by the counting of AR events and accumulating the forecast precipitation following the application of an AR detection algorithm³⁷ to seasonal forecasts. Second, in the late medium-range and early extended-range forecast horizons (forecast week-2 and week-3), the approximate time period when an area (e.g., river basin) may experience extreme precipitation and flooding is desired; this awareness provides the opportunity for discussions to take place about appropriate event preparations. Finally, the most challenging questions for forecast users—the main foci of this perspective piece—are in the short and early medium-range (1–7 days), a time when it is essential to know the intensity, location, and timing of ARs (the improvement of the forecasts at these lead times will also affect the forecast skill at longer ranges). The uncertainties that can arise, for example from poor observation coverage within the storms over ocean areas or from low predictability atmospheric features, such as mesoscale frontal waves³⁸, present users with difficult decisions on which river basins may flood, and how to manage precious water resources. Recent forecasting advances that have made progress towards improving AR forecasts are now detailed in this section.

Global NWP centres regularly upgrade their forecast systems to include new earth-system process understanding, the latest observation sources (e.g., new satellite retrievals), and more efficient and powerful supercomputers. These updates have all led to a continuous improvement in NWP³⁹ and more skilful forecasts of extreme events, such as ARs. An important step to exploit these better forecasts is the development of products to visualise and extract the relevant forecast information. Two newly available AR forecast products are the Extreme Forecast Index (EFI) for water vapour flux^{31,32,40,41} and the AR Scale⁴². The EFI compares the probability distribution of the ECMWF

ensemble forecasts with its model climate; and the values range from -1 to 1 , where -1 indicates extremely low and 1 indicates extremely high values with respect to the model climate. The AR Scale uses two parameters, the maximum IVT and AR duration (i.e., the duration of at least minimal AR conditions, $IVT \geq 250 \text{ kg m}^{-1} \text{ s}^{-1}$) at a given geographic location and defines AR rankings from 1 to 5 .

Figure 2 illustrates the EFI and AR scale for Storm Dennis for the period 00UTC 14 February 2020 to 00UTC 17 February 2020 (during forecast days 7–9). First, a clear sign of the AR within Dennis is found in both products which elucidates the high water vapour flux and hence the atmospheric processes at play, thus improving understanding of the forecast event. This also suggests that although the two product formulations draw out and communicate different information, they are complementary in identifying the AR conditions. Second, in Fig. 2a visual inspection of the areas with EFI exceeding 0.5 shows that at these forecast lead times the EFI for IVT (yellow filled contour) is more skilful than the precipitation EFI (blue line contour) in discriminating the large observed precipitation totals in western Britain (black crosses). This highlights that the EFI for IVT can afford earlier awareness of the locations likely to be affected, which corroborates previous research³¹. Therefore, this AR product has made progress in realising improved precipitation forecasts during ARs.

A crucial advancement of late has been the development of an observational campaign called AR Reconnaissance (AR Recon) in the northeast Pacific⁴³. The aim of AR Recon is to improve the science and forecasts of landfalling ARs to help better inform decision-makers on water management and flooding in the western United States through improving NWP models. Unique observations are collected from dropsondes from up to three aircraft flying simultaneously, extra radiosonde launches, drifting ocean buoys, and airborne radio occultation (the positions of the dropsondes launched from one aircraft in an AR Recon intensive observing period on 5 February 2020 are shown in Fig. 1a). The locations to sample are largely determined using both adjoint and ensemble methods to estimate the forecast sensitivity of west

Fig. 2 Forecasting the Atmospheric River in storm Dennis. **a** Extreme Forecast Index (EFI) in the European Centre for Medium-Range Weather Forecasts (ECMWF) ensemble forecast for integrated vapour transport IVT (shaded contours and red dashed line) and total precipitation (blue contour; areas inside the contour denote EFI for precipitation > 0.5). **b** Atmospheric River (AR) Scale in the ECMWF control forecast. The forecasts were initialised at 00UTC 8 February 2020 and are valid for the period 00UTC 14 February 2020 to 00UTC 17 February 2020 (forecast days 7–9). The nine black crosses in each panel in western Britain indicate rain gauges in the synoptic network where the corresponding 3-day total exceeded 50 mm.

coast United States precipitation to moisture and wind conditions over the eastern Pacific before AR landfall⁴³. These regions can include the strong IVT filament in the AR and upper-level circulations seen as potential vorticity anomalies. With the gathered observations, it is then possible to (1) improve the next NWP forecast by assimilating these observations from the data-sparse northeast Pacific and (2) undertake diagnostic studies^{36,44,45} and model experiments to identify model biases and improve the data assimilation and modelling systems, respectively. AR Recon has been developed as a Research and Operations Partnership and is led by the Center for Western Weather and Water Extremes (at Scripps Institution of Oceanography) and the US National Weather Service/National Centers for Environmental Prediction, together with its core partners of the US Naval Research Laboratory, US Air Force, the National Center for Atmospheric Research, ECMWF, and multiple academic institutions. As of winter 2019/20, it has also been formally incorporated in the US National Winter Season Operations Plan⁴⁶. We furthermore note a complementary campaign over the North Atlantic Ocean in 2016, the North Atlantic Waveguide and Downstream Impact Experiment (NAWDEX)⁴⁷, which has aided our understanding (and so fed into improved modelling) of the large-scale flow, extratropical cyclones, and the WCB.

A path to improved forecasts and the interdisciplinary approach required

Following the advances in AR forecasting obtained by NWP improvements, AR forecast products, and observational campaigns, such as AR Recon, we now set out a vision on how to progress this further. A primary challenge is how to reduce the uncertainty of the intensity, location, and timing of ARs in the short and early medium-range (1–7 days), which will also influence the forecast skill of the WCB outflow and therefore the jet stream and large-scale atmospheric circulation (e.g., high-pressure ridges)^{13,48}. To this end, the first important requirement is the continued improvement in NWP, which will, in turn, lead to a lengthening of the skilful forecast horizon. This could be achieved via the better representation of physical processes (through, e.g., higher model resolution), the coupling of more physical processes via an efficient earth-system data assimilation approach, and by improved modelling of the connections between the low-level water vapour in ARs and WCBs, and the mid- and upper-level atmospheric flow. Another issue to address is the development of a stable boundary layer beneath the AR, as it advects warm air over cooler water. This condition can cause the ocean surface to become relatively decoupled from the strong winds in the AR aloft and represents a challenge for data assimilation systems to properly distribute ocean surface condition information vertically into the model. Furthermore, the procurement of temperature, water vapour content, and wind observations with the fidelity to capture the sharp gradients across extratropical cyclones, ARs, and the jet stream is vital. For example, the reduction of errors in the tropopause structure⁴⁹ may lead to better forecasting of the cyclone and AR development, and in turn at later forecast times, the large-scale circulation and weather regimes. The routine deployment of dropsondes (e.g., in AR Recon) and the launch of the AEOLUS wind lidar⁵⁰ mark progress in this area, but new observation platforms are needed over the generally data-sparse oceans where ARs form. Also, research into the way data assimilation systems use observations is needed to ensure that all of the available information is used. Finally, for AR applications at extended-range and seasonal forecast horizons, knowledge of the role of the large-scale circulation in modulating AR occurrence and the further

investigation and identification of sources of extended-range predictability and tropical–extratropical connections (e.g., the Madden-Julian Oscillation⁵¹) could be beneficial.

The hydrological impact of an AR event is to a large extent determined by the AR interaction with the land surface, and many aspects of the land surface physiography can play an important part in translating the water vapour within an AR into precipitation and river discharge. These include the river basin antecedent conditions (i.e., soil moisture), which dictate how much precipitation the basin can absorb; terrain characteristics of height and orientation, and in turn, the potential orographic enhancement of precipitation in certain areas and rain shadows in others¹⁹; underlying bedrock and soil type, where low permeability regions (e.g., granite) preclude infiltration and permeable regions (e.g., chalk) allow water to infiltrate deep into groundwater reservoirs; and land use, such as the presence of urban areas and lakes/reservoirs. Although the river basin properties that affect the river discharge and floods are mostly well known, it is the large heterogeneities and hence unique characteristics across regions that lead to a varying attenuation of the precipitation-to-discharge signal in different places^{19,52,53}. We suggest that the detailed investigation (possibly partly via increased instrumentation in basins) of the role of the land surface physiography in the translation of AR precipitation into river discharge in adjacent river basins would improve understanding of the flood response potentially resulting in better flood forecasting capabilities. This interdisciplinary activity, which may also include hydrological modelling, would be dependent on engaging meteorologists, hydrologists, and water managers, and this could be developed and tested following the example of the US Army Corps of Engineers' atmospheric-river-focused Forecast-Informed Reservoir Operations Program⁵⁴.

A key consideration we forward for improving forecasts of ARs and their impacts is the organisation of a combined European–American observational campaign in the North Atlantic, named herein 'AR Recon Atlantic'. This proposed campaign would build on the operating procedures and airborne weather reconnaissance strategies developed in AR Recon in the northeast Pacific and on the results from NAWDEX⁴⁷ over the North Atlantic, to probe ARs, the associated WCB, and mesoscale dynamical features (e.g., mesoscale frontal waves). The *esprit de corps* that could be fostered through the interdisciplinary and intercontinental collaboration of meteorologists, hydrologists, and instrument operators could lead to new discoveries that advance the better representation of the global water cycle in NWP; the ultimate result being the improved forecast skill of ARs and their impacts. A hypothetical set-up of three research aircraft sampling different features in an intensive observing period is shown in Fig. 3. For example, the opportunities to fly transects and deploy dropsondes across the strong air temperature and wind speed (jet stream) gradients off the east of North America could provide insight into the way NWP systems handle this critical region for extratropical cyclone development. Further diagnostic studies on how the IVT in ARs and mesoscale storm features are resolved in NWP forecasts would also elucidate any model biases or uncertainties, which following future tailored NWP improvements towards these issues, could improve forecasts. Moreover, a global simultaneous AR campaign in the western and eastern Pacific Ocean and North Atlantic Ocean is a possibility, which may lead to even greater insights and forecast gains via detailed concurrent observations of the large-scale atmospheric circulation and Rossby Wave patterns across the northern hemisphere. It is also envisaged that in the future this campaign strategy could then be applied in the southern hemisphere.

Fig. 3 A hypothetical intensive observing period in Atmospheric River Reconnaissance Atlantic. The integrated vapour transport (IVT; shaded contours), mean sea-level pressure (black line contours), and 250 hPa winds (thick blue line contours at 50 and 75 m s^{-1}) in the European Centre for Medium-Range Weather Forecasts control forecast at 36-h. lead time at 12UTC 12 February 2020 (this is a few days before the arrival of storm Dennis in Europe). The thick black solid lines are the possible flight tracks of three aircraft from Europe and the United States and the black dots overlaying the thick black lines correspond to potential dropsonde locations. Depending on aircraft availability, Atmospheric River Reconnaissance Atlantic could, e.g., have a total of 15 flights over a 6-week campaign period.

Conclusions

ARs were predominantly responsible for the large precipitation totals causing flooding in northern Europe and the Pacific Northwest of North America in early 2020. Following the associated major flooding and socioeconomic damages, this perspective piece is motivated by the needs for better forecasts of ARs and their impacts and the close interdisciplinary collaboration required (meteorology, hydrology, water resources management). In this article, we first define ARs, introduce the vital roles they play in hydroclimate, flooding, and water supply, and discuss their current forecast skill. Second, we outline the recent advances in AR forecasting from NWP improvements, newly available AR forecast products, and the AR Recon programme across the northeast Pacific.

The main focus of this perspective is then the outlining of a vision to improve forecasts of ARs and their impacts. We believe this may be achieved through three principal ways: (1) the continued improvement in NWP systems and thus the lengthening of the skilful forecast horizon, e.g., by better resolving the interaction between the water vapour and latent heat release in ARs and WCBs, and the mid- and upper-level atmospheric flow, as well as examining the stable boundary conditions characteristic of AR conditions; (2) the detailed investigation of how heterogeneities in the land surface physiography in sometimes adjacent river basins affect how AR precipitation is converted into river discharge; and (3) the proposal of an interdisciplinary European–American observational campaign in the North Atlantic, named herein ‘AR Recon Atlantic’. The vision of an intercontinental campaign would combine expertise and resources, thus providing ample opportunities to comprehensively sample extratropical cyclones, ARs, WCBs, and mesoscale atmospheric features to identify any forecast issues over the North Atlantic Ocean in our current NWP systems. Before improvements can be made in modelling the global water cycle, and in particular the AR transport mechanism and its impacts, we need to identify the current errors and uncertainties so that modelling efforts can be targeted correctly. It is then that a better representation of ARs, WCBs, and their impacts may be afforded leading to socioeconomic benefits. We call for the disciplines involved and required to come together to make such a vision a reality.

Data availability

The data used to create the figures are stored in the ECMWF archive (<https://www.ecmwf.int/en/forecasts/datasets/archive-datasets>).

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Author contributions

D.A.L. developed and led the writing of the perspective. D.A.L. produced the figures. D. A.L., F.M.R., D.S.R., and F.P. discussed and edited the article.

Competing interests

The authors declare no conflicts of interest.

Additional information

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