Rare Atmospheric River Caused Record Floods across the Middle East

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ABSTRACT: Atmospheric rivers (ARs) are responsible for some of the hydroclimatic extremes around the world. Their mechanisms and contribution to flooding in the Middle East are relatively poorly understood. This study shows that the record floods during March 2019 across the Middle East were caused by a powerful AR, originated from the North Atlantic Ocean. Iran, in particular, was substantially affected by the floods. The nearly 9,000-km-long AR propagated across North Africa and the Middle East, and was fed by additional moisture from several other sources on its pathway. Simultaneous presence of a midlatitude system and a subtropical jet facilitated the moisture supply. The AR, as passing over the Zagros Mountains, produced record rainfall induced by the orographic forcing. The resulting floods caused widespread damage to infrastructures and left a death toll of at least 76 in Iran.

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Record rainfall in late March 2019 led to unprecedented flooding across several Middle Eastern countries and caused enormous damages and casualties, particularly in Iran. The intense rains have made the 2018/19 rainy season (October–March) the wettest in the past four decades, a sharp contrast with the prior year, which was the driest over the same period. Thus, this event is an example of rapid dry-to-wet transitions and intensification of extremes, potentially resulting from the climate change. An atmospheric river (AR), originated from the tropical Atlantic Ocean, was found responsible for the heavy precipitation that initiated the floods. To easily distinguish it from similar large-magnitude events over the region, here this AR is named Dena, after the peak of the Zagros Mountains, which played a crucial role in precipitation formation. Moisture transport by AR Dena was equivalent to more than 150 times the aggregated flow of the four major rivers in the region, that is, Tigris, Euphrates, Karun, and Karkheh. An AR of this magnitude can be pretty rare for the Middle East. Specific synoptic weather conditions, including tropical–extratropical interactions of the atmospheric jets, and anomalously warm sea surface temperatures in all surrounding basins provided the necessary ingredients for formation of such a massive AR. Various features of AR Dena are schematically shown in Fig. 1, and will be discussed in the following sections.

Impacts of March 2019 floods

Some of the hydroclimatic extremes around the world are caused by the atmospheric rivers, defined as “long, narrow, and transient corridor of strong horizontal water vapor transport” from tropical or extratropical moisture sources (Ralph et al. 2018). While a large body of research has shown the impacts of the ARs on weather-related natural disasters over various regions like the western United States (Ralph et al. 2006; Guan et al. 2013; Lavers and Villarini 2015), little is known about their mechanisms and contribution to flooding in the Middle East (Krichak et al. 2012; de Vries et al. 2013; Tubi et al. 2017; de Vries et al. 2018; Akbary et al. 2019). In fact, these two regions bear some geographical similarities, including their latitudinal extent, presence of a southeast–northwest-oriented mountain range overlooking a fertile plain and the associated low-level barrier jets (Kingsmill et al. 2013; Dezfuli et al. 2017). Those

Fig. 1. Various features contributing to atmospheric river Dena. Extent of the AR (green arrow), low pressure (blue arrow) and high pressure (red arrow) areas associated with a midlatitude weather system, evaporation over seas and oceans (wavy white lines), and other geographical features that contribute to formation of the AR and precipitation are shown.

mountain ranges are Zagros in the Middle East and Sierra Nevada in the western United States and their adjacent plains of Fertile Crescent and Central Valley, respectively.

In recent decades, increasing frequency and intensity of climatic extremes such as droughts and floods has imposed dramatic consequences for humans and natural ecosystems in the Middle East (Zereini and Hötzl 2008; Masih et al. 2011; Gleick 2014). Most recently, heavy precipitation during 24–25 March 2019, initiated widespread flooding across several countries in the region, including Iran that was hit hardest. Time series of rainfall during the rainy season (October–March), averaged over southwestern Iran that was most affected by the floods, revealed that 2018/19 was the wettest year over the period 1980–2019 (Fig. 2a). By contrast, the prior year (2017/18) was the driest over the same period. The total seasonal rainfall in both years fell outside two standard deviations of the long-term mean, resulting in the largest year-to-year change in the past four decades. This event presented a compelling example of shifts from prolonged drought to frequent floods and potentially the notion of “extremes become more extreme” in the changing climate (Dettinger 2013; Swain et al. 2018). The precipitation events that occurred in March 2019 had a significant contribution to the total seasonal rainfall. The 2-day mean rainfall data from Integrated Multisatellite Retrievals for GPM (IMERG) “late run,” was 57 mm day^{-1} during 24–25 March 2019. This value exceeds the maximum value of historical observations that is $\sim 50 \text{ mm day}^{-1}$ (Fig. 2b). Some areas received $\sim 400 \text{ mm}$ rainfall during this AR. The IMERG regional mean was consistent with some gauge-based records in the area.

The unprecedented floods, affecting 26 out of 31 provinces in Iran, caused an estimated \$2.5 billion (U.S. dollars) worth of damage to infrastructures, homes and agriculture, killed 76 people, damaged one-third of the country’s roads, destroyed 700 bridges, and forced mass emergency evacuations (Bozorgmehr 2019). Millions of people are still wrestling with the aftermath of the crisis. The chance of flooding remained high several weeks after the event since major dams were brought to their maximum level and could not hold more water influx resulting from the snow melting in spring.

What caused the heavy rains?

Vertically integrated water vapor transport (IVT) is commonly used to identify ARs (Zhu and Newell 1998; Rutz et al. 2014). Daily IVT from NASA Modern-Era Retrospective Analysis for

Fig. 2. Rainfall variability and frequency. (a) Interannual variability of rainfall during the rainy season (October–March) over the region most affected by floods (green box). Monthly data from Global Precipitation Climatology Project (GPCP), version 2.3, has been used to calculate seasonal rainfall totals for each year over the period 1980–2019. The total values have been then standardized by removing the mean and dividing by the standard deviation. The driest (2017/18) and wettest (2018/19) years are marked with red and blue circles, respectively. (b) Histogram of 2-day mean rainfall rate over the same region using GPCP daily 1DD V1.2 data available over the period 1996–2015. Note that the y axis is in logarithmic scale. The 99th percentile (green dashed line) and the 2-day mean daily average rainfall associated with AR Dena (blue dashed line) are shown for comparison.

Research and Applications, version 2 (MERRA-2), data were evaluated, and that enables us to detect a strong nearly 9,000-km-long AR, propagating from the North Atlantic Ocean across the Middle East and North Africa (Fig. 3a). To incorporate the aggregated effects of the features contributing to AR Dena, the 2-day mean IVT and the associated synoptic conditions have been analyzed. Typically, regions with IVT greater than $250 \text{ kg m}^{-1} \text{ s}^{-1}$ are considered to define ARs (Ralph et al. 2018). In current study, a $200 \text{ kg m}^{-1} \text{ s}^{-1}$ threshold has been used to account for the lower air moisture in the Middle East (de Vries et al. 2018). The IVT magnitude of AR Dena ranged between 200 and $350 \text{ kg m}^{-1} \text{ s}^{-1}$ as it passed through the Sahel–Sahara zone in a southwesterly–westerly direction. Its IVT exceeded $350 \text{ kg m}^{-1} \text{ s}^{-1}$ over northeastern Africa and remained high as it continued propagating southwesterly toward Iran. NASA satellite observations detected the maximum rainfall over the western half of Iran, where AR Dena hit the Zagros Mountains (Fig. 3c). The moisture laden air cools as it flows upslope due to orographic forcing, and the associated microphysical growth processes produce or strengthen the clouds (Houze 2012). As a result of this uplift, the precipitation generation is enhanced mainly over the mountains and their windward side. A conservative estimate shows that the water transport by AR Dena, as approaching the Zagros Mountains, was more than 150 times the discharge of the Arvand-Rud (aka Shatt al-Arab) River. This is the biggest surface water flow in Mesopotamia, formed by the confluence of four major regional rivers, namely Tigris ($815 \text{ m}^3 \text{ s}^{-1}$), Euphrates ($550 \text{ m}^3 \text{ s}^{-1}$), Karkheh ($185 \text{ m}^3 \text{ s}^{-1}$), and Karun ($775 \text{ m}^3 \text{ s}^{-1}$) that subsequently merge before flowing into the Persian Gulf [United

Fig. 3. Atmospheric river Dena over the Middle East during 24–25 Mar 2019. (a) Two-day mean vertically integrated water vapor transport (IVT; shading) showing the spatial pattern of AR Dena and the associated horizontal winds (arrows) in the 700–400 mb layer. (b) Two-day mean vertical cross section of zonal moisture transport (uq), averaged over the longitudes (15°W–52°E) of the AR. The NASA's MERRA-2 data are used in (a) and (b). (c) Two-day mean rainfall rate over the Middle East, using Integrated Multisatellite Retrievals for GPM (IMERG) "late run." (d) Sea surface temperature anomaly in March 2019, using NOAA Optimum Interpolation (OI) SST V2 (shading) and the associated evaporation anomaly (contour lines), using MERRA-2 data.

Nations Economic and Social Commission for Western Asia (UN-ESCWA) and Bundesanstalt für Geowissenschaften und Rohstoffe (BGR); UN-ESCWA and BGR 2013]. This estimate is based on an IVT magnitude of $350 \text{ kg m}^{-1} \text{ s}^{-1}$ across a 1,000 km width of the AR's core, as observed for example over the Arabian Peninsula (Fig. 3a).

Synoptic diagnostics of AR Dena

The atmospheric and oceanic conditions in late March were favorable for genesis of such a powerful AR over the Middle East. On its long journey from the equatorial Atlantic to Iran, AR Dena was likely fed by additional moisture from several other sources that were located on the pathway of the low-level winds, blowing toward the AR. All of the marine basins contributing to AR Dena were warmer than normal in March, and that suggests potential enhancement in their moisture supply (Fig. 3d). Since evaporation is more directly related to water vapor budget, its spatial pattern over the same domain as sea surface temperature (SST) has been also examined. Similarly, the evaporation was anomalously positive over the contributing waters, particularly along the winds associated with the AR.

The zonal flux of water vapor, averaged over the entire extent of this AR, was maximum in the 700–500 mb layer (Fig. 3b; approximately 3,000–5,500 m) and primarily determined by presence of a subtropical jet coming from the Atlantic Ocean. The jet then encountered a midlatitude weather system and merged with it approximately over the Red Sea. The low pressure component of this system was centered over the Fertile Crescent and its adjacent high pressure area was centered over the Arabian Sea (Fig. 4). This configuration facilitated moisture transport from the Arabian Sea, Gulf of Aden, and Red Sea toward the AR (Fig. 5). The moisture contribution from the Mediterranean, the smallest amount of all basins, was also controlled by this system and confined to lower troposphere. The Persian Gulf supplied moisture through the southerly winds associated with the high pressure region and the Zagros barrier jet (ZBJ) that is in turn induced by the midlatitude system (Dezfuli et al. 2017). The ZBJ is a similar feature to the Sierra barrier jet (SBJ) that has been shown to interact with the landfalling ARs over California (Neiman et al. 2013). AR Dena can be characterized in the context of tropical–extratropical interactions as it owes its existence to the combined effects of the aforementioned two features before its final landfall. This event is an example of moisture transport from remote sources that initiates an AR, which is then maintained and even reinforced by additional horizontal aggregation of water vapor along the AR corridors as shown for other regions (Bosilovich and Schubert 2002; Knippertz 2007; Cordeira et al. 2013; Sodemann and Stohl 2013).

Future work

This brief note provides some insight into the mechanisms influencing ARs over the Middle East by examining an individual extreme event. However, a comprehensive analysis of all ARs in the region is beyond the scope of this study and is a part of our ongoing research. We plan to extend the findings presented here by investigating the interannual variability of the ARs over

Fig. 4. Location of L and H during AR Dena (24–25 Mar 2019). Map of the geopotential heights (GHT) in the lower troposphere (925–700 mb). Regions with surface pressure lower than 925 mb are shaded in white. For better detection of the systems, charts are contoured at 5- and 20-m intervals for high and low pressure areas, respectively.

Fig. 5. Contribution of various water basins to AR Dena. (a) As in Fig. 3a, but for winds in the 975–700 mb layer. (b)–(d) Vertical cross section of zonal moisture transport (uq), across the latitudes shown with blue lines in (a). (e)–(g) Vertical cross section of meridional moisture transport (vq), across the longitudes shown with purple lines in (a). Unit of moisture transport is $10^{-2} \text{ m s}^{-1} \text{ g kg}^{-1}$. Various water bodies contributing to the AR are shown as Atlantic Ocean (ATL), Mediterranean Sea (MED), Red Sea (RED), Arabian Sea (ARB), Persian Gulf (PER), and all the basins (ALL).

the Middle East, using the 40-yr MERRA-2 records. That would enable us to offer a more robust understanding of the processes controlling the ARs. Leveraging such knowledge, we then plan to use the subseasonal-to-seasonal (S2S) predictions provided by NASA Goddard Earth Observing System (GEOS) to offer potential improvement in seasonal predictions of the frequency of extreme precipitation events in the region, and thus help mitigating their adverse impacts.

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