RESEARCH ARTICLE

Cut-off low systems over Iraq: Contribution to annual precipitation and synoptic analysis of extreme events

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Abstract

We combine daily in situ precipitation data with meteorological reanalysis data in order to explore the contribution of cut-off low systems to the seasonal and inter-annual rainfall variations over Baghdad from 2005 to 2016. During these 12 years (average rainfall of 131 ± 67 mm/year), 38 rainy cut-off lows brought 43% of the total precipitation, with extreme inter-annual variations. Indeed, precipitation associated with autumn cut-off lows was the principal factor that turned an arid into a wet year: during the three most arid years cut-off lows contributed about 25% of the average rainfall (10 out of 40 mm/year) while during the three wettest years they contributed near 67% (171 out of 254 mm/year). The extreme-rain cut-off low systems displayed analogous synoptic characteristics: upper-atmosphere divergence, upwards vertical motions in the middle atmosphere, and lower-atmosphere winds into central Iraq at times when the surface Red Sea and Persian Gulf waters were warmer than the surface air. During those days previous to an extreme event, the surface waters cooled substantially and the amount of precipitable water increased largely, suggesting high latent heat transfer. In order to characterize those conditions that favour rainfall, we focus on the November 18–20, 2013 cut-off low system, which led to the largest flooding and wettest year in Baghdad between 2005 and 2016. The distribution of properties in the middle (500 hPa) and upper (250 hPa) troposphere shows that the region was affected by intense horizontal divergence and upwards motions, coinciding with a surface low over the Arabian Peninsula that caused intense northwards winds over the Persian Gulf and brought substantial moisture to central Iraq. The analysis of several stability indexes indicates that convective instability played a secondary role during the episode.

KEYWORDS

cut-off low, extreme precipitation, Middle East, moisture source, rainfall records, synoptic conditions

1 | INTRODUCTION

The Middle East and northern Africa countries represent a vast region—roughly between 15°N and 35°N and from the Atlantic to the Indian Oceans—of arid and semi-arid

conditions, with annual precipitation less than 200 mm (Terink *et al.*, 2013). These conditions have become more extreme during the last three decades because of severe droughts, with major negative effects on local and national economies (Ghulam *et al.*, 2008; Asakereh, 2017). Further,

climate projections for the coming years predict a continued decrease in precipitation and an increase in desertification (IAU, 2012).

The decline of mean precipitation in the Middle East, however, contrasts with the presence of extreme meteorological and flooding events with large economic impact (Easterling *et al.*, 2009). The precipitation in Iraq is characterized by high temporal and spatial variability (UN-Iraq, 2010; 2013), as it happens for the entire Mediterranean region (Reiser and Kutiel, 2011; Lionello, 2012). The country's mean annual precipitation is 154 mm (Al-Ansari and Knutsson, 2011) though rainfall changes largely with latitude and elevation, from less than 100 mm over about 60% of the country to some 1,200 mm to the northeast. Rainwater is almost entirely restricted to October through May when the Mediterranean depressions enter Iraq (Al-Ansari and Knutsson, 2011; Lionello, 2012). However, the amount of rain varies considerably at inter-annual and decadal scales, with relatively moist 1970s and considerably arid 1990s (Mohammed and Hadi, 2012; Al-Rijabo and Salih, 2013). An extreme drought took place in 2008—the most severe for the 1980–2010 period—followed by heavy rainfalls and short storms in the central and southern Iraq (Al-Timimi and Al-Jiboori, 2013).

Several studies on precipitation in Iraq have looked at the spatial and temporal distributions of rainfall, with emphasis on the monthly precipitation (Al-Mansory, 2005; Alghazali and Alawadi, 2014). Using monthly data from 36 stations during the 1981–2010 period, Al-Salihi *et al.* (2014) observed a negative annual-rainfall trend in 32 sites, with most of the decrease occurring in winter and spring. In contrast, there is a substantial lack of studies on daily precipitation and on the weather systems responsible for the high precipitation events that occasionally affect Iraq. Designers and decision makers need a proper knowledge of the spatial and temporal distribution of rainfall, including an improved short- and long-term forecast of trends and variability (Hussein *et al.*, 2005; Mohammed and Hadi, 2012; Al-Suhili and Khanbilvardi, 2014). In particular, the development of water resource facilities and farming capabilities in the Middle East has to consider that rainfall often occurs as extreme flooding. This requires identifying what is the contribution of the extreme flooding events and which are the atmospheric conditions leading to these situations.

Here we explore the extreme precipitation events between 2005 and 2016, a 12-year period, focusing on those cases that correspond to a cut-off low system. In particular, we carefully examine the November 19, 2013 episode, which led to the maximum rainfall for the entire period. We use different sources of information, including in situ and reanalysis data, in order to assess what were the dynamical conditions that promoted the anomalously high humidity during the episode.

The paper is organized as follows. Section 2 presents the data sets and methods, section 3 describes the temporal variability of the rainy events and section 4 identifies those extreme precipitation cases that responded to cut-off low atmospheric systems. In section 5 we examine the atmospheric forcing during the flash-floods of November 19, 2013 and in section 6 we explore the source of moisture to the lower atmosphere during the extreme-rain cut-off low episodes. We close summarizing the main factors leading to high precipitation during cut-off low and the relevance of this atmospheric system for Iraq's hydrological regime (section 7).

2 | DATA AND METHODS

Iraq is located in the heart of the Middle East, extending around 29.50°–37.22°N, 38.45°–48.45°E (Figure 1). It is found adjacent to the shallow Persian Gulf, with very saline year-long waters and very warm summer waters (Yao, 2008), and relatively close to the eastern Mediterranean and Red Seas. Following Köppen's classification, Iraq can be divided into three main climates: subtropical desert in the south and central regions, subtropical steppe in central-northern Iraq, and dry-summer subtropical in the northern mountainous regions (Pannell, 2002; Walker, 2005; Peel *et al.*, 2007). Here we will focus on the large central plains, where topographic variability is absent and long data records are available.

2.1 | In situ precipitation

Daily precipitation records for a period of 12 years—January 1, 2005 to December 31, 2016—come from the Baghdad meteorological station, run by the Iraqi Meteorological and Seismology Organization. This station is located in the large central plains (33.33°N, 44.43°E; 34 m elevation), where topographic variability is absent (Figure 1). The homogeneity of the annual precipitation series has been verified using the Von Neumann and Thom tests (Meseguer-Ruiz and Sarricolea, 2017).

Data from three other Iraqi meteorological stations (Basra, Mosul, and Rutba; Figure 1) are available for selected periods. These data are complemented with satellite images in the visible spectrum, downloaded from the National Aeronautics and Space Administration (NASA) web page (<https://earthdata.nasa.gov/worldview>).

2.2 | Radiosonde data

Daily radiosonde data from the Baghdad station is available for the days previous, during and after the November 2013 flooding (except for 18 November due to a balloon failure). These data can be used to draw skew-T log-P diagrams, as well as to calculate several atmospheric instability indices

FIGURE 1 Physical map of the Middle East coloured according to topography. It shows the borders of Iraq (black line)—with the location of the Baghdad (middle black triangle), Basra, Mosul, and Rutba (encircling triangles) meteorological stations—and the external borders of all countries in the eastern margin of the Mediterranean Sea [Colour figure can be viewed at wileyonlinelibrary.com]

associated with the positive buoyant air parcels. These are the Lifted (LI), Showalter (SI), Total Totals (TT), SWEAT, K, and CAPE indexes, as well as the precipitable water (PW) content. The definitions, common usages, and threshold values for these indexes are shown in Table S1, Supporting Information.

2.3 | Reanalysis fields

The temperature, humidity, geopotential height, horizontal and vertical velocity, horizontal divergence, relative vorticity (RV), and potential vorticity (PV) fields come from the ERA-Interim global atmospheric reanalysis, available four times a day on a $0.75 \times 0.75^\circ$ latitude–longitude grid from the European Centre for Medium-Range Weather Forecasts (ECMWF). These data have been downloaded for a domain extending around 0° – 60° E, 10° – 60° N. Other inferred variables are equivalent potential temperature (EPT), PW, moisture flux (MF), moisture flux convergence (MFC), Q-vector divergence, RV and PV advection, and the instability indexes; the divergence and advection values are calculated using centred finite differences.

The moisture flux is vertically integrated between 1,000 and 700 hPa (VIMF, with units of $\text{kg m}^{-1} \text{s}^{-1}$) and its horizontal convergence is then calculated (VIMFC, with units of

$\text{kg m}^{-2} \text{s}^{-1}$) (van Zomeren and van Delden, 2007; Krichak *et al.*, 2015)

$$\text{VIMF} = -\frac{1}{g} \int_{p_{1,000}}^{p_{700}} (q\vec{u}) dp,$$

$$\text{VIMFC} = -\frac{1}{g} \int_{p_{1,000}}^{p_{700}} \left[\frac{\partial(qu)}{\partial x} + \frac{\partial(qv)}{\partial y} \right] dp,$$

where $\vec{u} = (u, v)$ is the horizontal wind velocity vector with components in the west–east and south–north directions (x, y), p is air pressure, q is specific humidity, ρ is air density, and g is gravity acceleration; the integrals are calculated between the 1,000 and 700 hPa pressure levels, $p_{1,000}$ and p_{700} . Note that in these definitions VIMF is a vector while VIMFC is a scalar.

2.4 | Sea and air surface temperature

The foundation (free from daily variation) sea surface temperature (SST) is available since January 2007 from the Operational Sea Surface Temperature and Ice Analysis (OSTIA) system run by the UK Met Office (Donlon *et al.*, 2012). For our analysis we have examined the 0.05° resolution daily SST data in the central Persian Gulf (26° N, 52° E)

and northern Red Sea (25°N, 36°E). These marine regions represent potential sources for low-level humidity; the selected sites are representative for these regions and yet are located far enough from coastal areas that could be influenced by local upwelling. The data used corresponds to the week previous to seven cut-off low events that brought extreme flooding to the Baghdad area; a one-week period is adequate to assess the arrival of air masses from nearby marine regions to central Iraq.

Additionally, we use temperature data for Basra (from the Iraqi Meteorological and Seismology Organization) and climatological temperature data for Kuwait City (from the Kuwait Meteorological Service, <http://www.met.gov.kw/>) to estimate the monthly-mean air surface temperature (AST) for the northern Persian Gulf. The procedure consists in calculating the mean climatological temperature difference between the two stations (Kuwait City is cooler than Basra by 7.1°C) and using this difference to obtain the monthly-mean AST for the northern Persian Gulf since January 2007.

2.5 | Cut-off low detection

We use an index as defined by Scherrer *et al.* (2006) and Davini (2013), which is a bi-dimensional extension of the original method by Tibaldi and Molteni (1990), set to identify reversals in the sign of the geopotential-height latitudinal gradient at 500 hPa. The algorithm is applied to the 1200 UTC data in the region 0°–60°E, 10°–75°N, as extracted from the 6-hourly ERA-Interim reanalysis. The procedure works routinely to identify all instances with a cut-off low pattern, including isolated low-pressure centres as well as more complex Rex-block or omega type patterns. Once the pattern is detected, the geopotential distribution is visually inspected, first, to check if the cut-off low centre was situated near or over Iraq (inside the 35°–50°E and 25°–40°N square) and, second, to verify whether the situation corresponded to a precipitation event. Some examples of cut-off low systems detected by the algorithm, with and without precipitation, are shown in Figure S1.

2.6 | Archive air trajectories

We use the HYSPLIT trajectory model (Stein *et al.*, 2015; Rolph *et al.*, 2017) to compute and plot forwards and backwards trajectories for air masses arriving to central Iraq on November 19, 2013. HYSPLIT is run in ensemble mode (27 trajectories obtained by offsetting the starting position both in the horizontal and the vertical) using the NCEP/NCAR reanalysis (data from the National Centers for Environmental Prediction [NCEP] and the National Center

for Atmospheric Research [NCAR]), with the isentropic approximation to calculate the vertical motions.

3 | SEASONAL AND INTER-ANNUAL HYDROLOGICAL VARIATIONS

The daily-precipitation 12-year time series from the Baghdad station shows that rain occurred as isolated events, for a total of 204 incidences (Figure 2a,b and Table S2); these rainy events were nearly absent during summer, with one single instance of rain in 12 years. The annual precipitation rate for this 12-year period is 130.8 ± 67.1 mm/year. Rain fell for 421 days (9.6% of the days), with daily rainfall exceeding 1 mm only on 145 occasions (3.3%). We have gathered rainy days into events or episodes, with each individual event defined as a group of days when rain fell continuously, for a total of 204 instances. There were 20 extreme events, defined to equal or exceed the 90-percentile rainfall per event (20 mm), which accounted for 51.3% of the precipitation during the entire period (Figure 2b and Table S2).

The precipitation time series (Figure 2a) also illustrates the existence of substantial seasonal (Figure 3a) and intra-annual (Figure 3b) variability. Peak rain values occurred during November although moderate rain (above the mean monthly value of 10.9 mm/month) took place between October and April, in what constitutes the Mediterranean rainy season (Xoplaki *et al.*, 2004). Hence, for calculating the annual precipitation figures, we set natural years running from July to June and identify them through the year of the second semester, for example, natural year 2006 corresponds to the period between July 1, 2005 and June 30, 2006; this reduces the number of annual histograms to only 11 natural years (Figure 3b,d). The highest natural-annual precipitations occurred in 2013 (263.6 mm), 2014 (278.1 mm), and 2016 (219.4 mm), for a mean precipitation of 253.7 mm (Figure 3b), so we combine these 3 years to characterize the wet conditions. In contrast, the lowest natural-annual precipitations were in 2008 (37.6 mm), 2009 (52.2 mm), and 2012 (29.3 mm) for a mean precipitation of 39.7 mm (Figure 3b), so again we pool these 3 years to portray the arid-year conditions. Notice that this selection of three wet and three arid years is equivalent to thresholds of 25 (95.1 mm) and 75 (167.9 mm) percentiles.

The daily precipitation time series demonstrates the exceptionality of the November 19, 2013 event (Figure 2a,b and Table S2). This episode, the largest flood for the entire time series, took place as part of a series of events that began in autumn 2012, following a severe drought in Iraq that lasted for some 30 years (1980–2011) (Al-Timimi and Al-Jiboori, 2013). The precipitation during November 2013 (172.7 mm) represented 62.1% of the total annual precipitation for the natural 2014 year (and 58.2% of the calendar 2013 year)

FIGURE 2 Precipitation data (mm) over Baghdad for the 2005–2016 period: (a) time series with daily precipitation values; (b) sequence of precipitation events over Baghdad, colour-coded to differentiate between cut-off lows, extreme events (over the 90-percentile) other than cut-off lows, and all other non-extreme rainy events; (c) monthly values during 2013; and (d) daily values during November 2013 [Colour figure can be viewed at wileyonlinelibrary.com]

(Figure 2c). Further, more than half the November precipitation (89.1 mm) took place on November 19, representing 30.2% of Baghdad's rainfall during the 2014 natural year (Figure 2d).

The data illustrate how the extreme values recorded in Baghdad were also anomalously large as compared with other locations in the country. No rain was observed to the north of the country (Mosul station) and substantially smaller values were recorded to the west (20 mm in

Rutba, with peak precipitation also on November 19) and south (40 mm in Basra, with peak value on November 18) (Figure S2). These measurements confirm that the extreme precipitation was fairly localized, with maximum values in the eastern part of the country and lasting no more than 48 hr.

The localized rain observations somewhat contrast with widespread cloud coverage over the Middle East, which increased rapidly between November 17 and

FIGURE 3 Precipitation histograms for Baghdad during 2005–2016 (panels b and d correspond to natural-annual values, hence representing the period from July 1, 2005 to June 30, 2016). (a) Monthly and (b) annual precipitation values (mm), distinguishing the fraction associated to cut-off low events. Number of cut-off low events (c) per month and (d) per year, with and without precipitation. (e) Seasonal precipitation (mm), distinguishing the fraction associated to cut-off lows. (f) Number of cut-off lows per season, indicating those with and without precipitation [Colour figure can be viewed at wileyonlinelibrary.com]

November 19, 2013 (Figure S3). On November 19 the extension of the clouds was largest, covering portions of the southern Arabian Peninsula as well as all Iraq and part of Iran. On November 20 the cloud coverage was still large but had disappeared from most of the Arabian Peninsula and southern Iraq.

4 | CUT-OFF LOW CONTRIBUTION TO EXTREME EVENTS

The algorithm that detects the latitude reversals in geopotential height (section 2.5) allows investigating the frequency of cut-off low patterns and their contribution to rainfall (Figure 2b). The

algorithm automatically identified a total of 294 distinct cases with a cut-off low pattern in the (0° – 60° E, 10° – 75° N) region between 2005 and 2016; however, only 94 of these cut-off low systems affected Iraq, with 38 of them causing precipitation and 14 leading to extreme rainfall. The number of cut-off low events influencing Iraq ranged between 3 and 10 per natural year (Figure 3d). The number of cut-off low rainy events was less than doubled for the wet years as compared with the arid years:

either for the entire year (14 vs. 9 events) or the autumn months (9 vs. 5 episodes); however the amount of rain brought by these rainy events was 16 times more during the wet than during the arid years, 512.3 mm as compared with 31.3 mm.

The monthly frequency of all cut-off lows is bimodal, with the largest mode centred in May and June and a second mode in October and November; however, the cut-off low conditions associated with rain peaked in November (Figure 3c). If we

FIGURE 4 Precipitation histograms for Baghdad during (a, c, e) arid and (b, d, f) wet years; the number of rainy days (rainy events) was 98 (32) for the arid years and 185 (69) for the wet years. Frequency of (a, b) days and (c, d) events with precipitation, split into cut-off lows and all other types of events, colour-coded as noted. (e, f) Cumulative precipitation of rainy events; the lower line corresponds to cut-off lows and the upper line considers events of all types, colour-coded as noted [Colour figure can be viewed at wileyonlinelibrary.com]

group the cut-off lows per season (December–February, March–May, June–August, September–November), it turns out that the number of cut-off lows remains fairly constant among seasons (Figure 3f) though the amount of rain associated with these events is much larger during autumn (Figure 3e), with all the rain falling in October and November (Figure 3a).

Most cut-off lows lasted only 1–3 days, though some events persisted longer, up to 7 days (Figure S4). As a result, the 38 rainy cut-off low events over Baghdad led to 118 rainy days (21.6% of the total number of wet days), although these events brought 43.4% (681.9 mm) of the total precipitation. There were major differences between the arid and wet years. The total rain for the arid years was of 119.1 mm, with a contribution of 31.3 mm (26.3%) from cut-off lows. During 2008, the driest natural year of the time series, the contribution of cut-off lows to the annual precipitation was only 0.3 mm. In contrast, during the wet years the total rain was 761.1 mm, with an input of 512.3 mm (67.3%) from cut-off lows. In 2014, the wettest year of the time series, the rainfall associated with cut-off lows was 63.4% of the total (176.3 out of 278.1 mm); this fraction increased even more during 2016, with a cut-off low contribution of 80.9% (out of a total of 219.4 mm).

The daily- and event-precipitation histograms help quantify the differences between arid and wet years (in the event-precipitation histograms the abscissa corresponds to the total precipitation during an event, Figure 4). The shape of the arid- and wet-years daily-precipitation histograms is fairly similar for values less than 4 mm: during the arid years, 74% of the rainy days had precipitations ≤ 1 mm, 14% had precipitations between 1 and 4 mm, and 11% had precipitations between 4 and 14 mm; during the wet years these values were 61, 17, and 12%, respectively (Figure 4a,b). However, during the wet years there were 8% of days with rainfall over 14 mm (4% exceeding 30 mm) as compared with none during the arid years.

The relative impact of cut-off lows on total rainfall during arid and wet years shows up in the event-precipitation histograms that distinguish cut-off lows from all other rainy events (Figure 4c,d). The number of cut-off lows was 10 out of 32 rainy events during arid years (25%), and 15 out of 69 during wet years (22%). Despite the similar proportions, the influence of cut-off lows on rain was very disparate: during wet years, the cut-off lows add mostly to high-rain events (being the sole contribution to events over 20 mm) and instead have a residual contribution to low-rain events; in contrast, during arid years, the cut-off lows have a moderate contribution to events with less than 10 mm. Specifically, considering the 0–4, 4–14, and >14 mm intervals, the number of events during the arid years was 7, 2, and 1, while for the wet years they were 2, 1, and 12.

We may use these event-precipitation data to draw cumulative precipitation histograms for both arid and wet years (Figure 4e,f). We have drawn two curves for each histogram, one accounting for all rainfall and the other only including rain associated with cut-off lows: these events represent a relatively minor contribution to total rainfall except for the large increment resulting from extreme precipitation events (over 30 mm) during the wet years, when a 249 mm rainfall increase (from 512 to 761 mm) was entirely caused by cut off lows.

In Figure S5 we present the distribution of geopotential height at three different pressure levels (850, 500, and 250 hPa) for six cut-off low systems that recorded extreme precipitation: two in November 2012, October and November 2015, and March and December 2016 (all except the December 2016 event belong to the wet-years compiled in Figure 4d; a seventh event, in November 2013, is analysed in next section). These distributions (for the day that best displayed the cut-off low pattern) are shown together with the horizontal divergence at 250 and 850 hPa, and the pressure vertical velocity at 500 hPa. In all cases, the cut-off low was located on top of the Baghdad area, displaying divergence. This was accompanied by low-level air (and moisture, not shown) convergence and upwards vertical velocities at intermediate heights.

In order to best describe the cyclogenesis that led to rainy events caused by cut-off low systems, in the following section we focus on the November 2013 flood, presenting the daily synoptic situation for a period ranging from 2 days before the event to 1 day after the event, as calculated using the ERA-Interim reanalysis. The variables used are geopotential height, EPT, horizontal velocity, PV and PV-advection, and RV and RV-advection.

5 | CASE STUDY: THE NOVEMBER 2013 EVENT

5.1 | Synoptic situation

We begin presenting the daily fields of geopotential height for November 17–20, 2013, at high (250 hPa), middle (500 hPa), and low (850 hPa) levels, accompanied by the PV distribution at the upper level (1 PV unit = 1 PVU = $10^{-6} \text{ m}^2 \text{ s}^{-1} \text{ K kg}^{-1}$), the equivalent potential temperature at the middle level, and the wind fields in the lower level (Figure 5). Notice we have selected the 850 hPa level in order to minimize the influence of the orography on our maps, as the mountain ranges in the northern and eastern Iraq reach heights well above 3,000 m.

On November 17, the geopotential maps at 250 and 500 hPa show an omega block pattern, with high values over central Europe and low values on both ends of the Mediterranean Sea. The EPT and PV fields illustrate the penetration of high-PV cold streaks along both margins of the omega high (Figure 5a,e). The 850-hPa geopotential height

FIGURE 5 (top panels) PV (coloured with intervals of 1 PVU) and geopotential height (solid contours with intervals of 10 dam) at 250 hPa for November 17–20, 2013, 1200 UTC. (middle panels) EPT (coloured with intervals of 5 K) and geopotential height (solid contours with intervals of 4 dam) at 500 hPa. (bottom panels) Geopotential height (solid contours with intervals of 2 dam) and wind vectors solely for the Iraq region (arrows, units of m/s; the reference arrow denotes 1 m/s) at 850 hPa for November 17–20, 2013, 1200 UTC. The star indicates Baghdad's location [Colour figure can be viewed at wileyonlinelibrary.com]

indicates a low-level cyclonic circulation centred near (27°N, 39°E), causing southeasterlies that introduced air from the Red Sea and Persian Gulf into central Iraq (Figure 5i). In November 18, the geopotential and PV contours at 250 hPa show that the omega block pattern evolved towards a Rex block pattern with its high and low geopotential values oriented in the northwest–southeast direction. This was caused by a deepening of the eastern trough, as well as by a slight shift of the blocking anticyclone to the southwest. The 250 and 500-hPa geopotential maps illustrate the evolution of the eastern trough towards an isolated low, crafting the cut-off low system (Figure 5b,f). At this time, the 850 hPa cyclone deepened over the northern Arabian Peninsula, causing strong low-level winds from the Persian Gulf and Arabian Sea (Figure 5j); the penetration of this low-pressure wedge appears correlated with the deepening of the eastern trough at the mid and high levels.

On November 19, the cut-off low stretched southeast at the 250 and 500 hPa levels, into the Arabian Peninsula, becoming vertically aligned on top the 850 hPa low. This low-level cyclonic feature, together with the anticyclone between the Black and Caspian Seas, favoured the appearance of intense southeasterly winds, from the Persian Gulf into central Iraq (Figure 5c,g,k). Finally, on November 20, the cyclone remained vertically aligned over central Iraq despite the low-level winds from the Persian Gulf had weakened considerably (Figure 5l).

5.2 | Horizontal divergence and vertical flow

We want to identify those regions that underwent low-level horizontal divergence and vertical convection for November 18–20, 2013. For this purpose, we plot the distributions of PV (P) at 250 hPa and RV (ζ) at 500 hPa together with their

horizontal advection ($\vec{u} \cdot \nabla P$ and $\vec{u} \cdot \nabla \zeta$) (Figure 6). The cyclogenesis during the flood day is revealed by the peak PV and RV advection values on November 19 over central Iraq (Figure 6b,e).

The horizontal velocity divergence at 250 and 850 hPa helps identify the coupling between the upper and lower atmospheric levels (Figure 7, top and bottom panels). High absolute positive and negative values, respectively at 250 and 850 hPa, match over central and eastern Iraq on November 19 (Figure 7b,h). Such correspondence points at the existence of dynamical forcing from the upper to the lower levels, confirmed by intense upwards motions in the middle atmosphere (700 hPa) (Figure 7e). These high values remained on November 20 but centred over Iran (Figure 7c,f,i).

The existence of deep vertical motions in central Iraq during the November 2013 event is confirmed by the 700–400 hPa mean horizontal distributions of both vertical velocities and Q -vector divergence (Figure S6). Peak vertical velocities developed in regions of high RV and PV advection (Figure 6) and intense horizontal divergence (Figure 7). The Q -vector divergence was patchy (Figure S6e), yet high negative values (convergent regions) coincided with low-level/high-level convergence/divergence and upwards motions (negative pressure vertical velocities) (Figure 7), as expected to occur ahead of a cyclone (Sanders and Hoskins, 1990).

A vertical section along 44.5°E, crossing almost right over Baghdad, helps appreciate the vertical extension of the convective motions (Figure 8). Between 0000 UTC of November 19 and 0000 UTC of November 20 (Figure 8c–e) the velocities reached maximum upwards values, all the way from near the surface to the 250 hPa level, precisely over the Baghdad area.

5.3 | Convective instability

We complete the dynamic analysis by assessing whether the conditions over Iraq at the time of the November 2013 event had caused convective instability. For this purpose, we use radiosonde data from the Baghdad station and the ERA-Interim reanalysis to compute several atmospheric instability indexes for the period November 17–20, 2013 (section 2.2). The instability conditions are assessed through the K index and, even better, the CAPE index (Table 1). Other indexes may not be as adequate for our analysis but are included for the sake of completeness: TT is more relevant for elevated regions and LI, SWEAT, and SI are commonly used to discriminate the potential for severe events, such as tornados (Table 1 and Figure S7). We compare the calculated values with the Lorente *et al.* (2008) thresholds, which were developed for another Mediterranean region (Table S1).

FIGURE 6 (top panels) PV (coloured with intervals of 0.5 PVU), PV advection (blue contours with intervals of 10^{-5} PVU s^{-1}), and geopotential height (black contours with intervals of 5 dam) at 250 hPa for November 18–20, 2013, 1200 UTC. (bottom panels) Positive RV (coloured shaded with intervals of 10^{-5} s^{-1}), advection of positive RV (blue contours with intervals of 10^{-5} s^{-2}), and geopotential height (black contours with intervals of 5 dam) at 500 hPa. The star indicates Baghdad's location [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7 (top panels) Horizontal divergence (coloured with intervals of 10^{-5} s^{-1}) and geopotential height (black contours with intervals of 5 dam) at 250 hPa, for November 18–20, 2013, 1200 UTC. (middle panels) Pressure vertical velocity (coloured with intervals of 0.2 Pa/s) at 700 hPa and geopotential height (black contours with intervals of 4 dam) at 500 hPa, for November 18–20, 2013, 1200 UTC. (bottom panels) Horizontal divergence (coloured with intervals of $0.5 \times 10^{-5} \text{ s}^{-1}$) and geopotential height (black contours with intervals of 1 dam) at 850 hPa for November 18–20, 2013, 1200 UTC; note the change in the colour bar as compared with the top panels, with the reddish colours now representing negative convergent values. The star indicates Baghdad's location [Colour figure can be viewed at wileyonlinelibrary.com]

Figure 9 presents skew-T log-P diagrams for Baghdad at 1200 UTC for November 17, 2013, November 19, 2013, and November 20, 2013. The diagrams show stability for November 17 and weak (marginal conditional) vertical instability for November 19 (Figure 9). The soundings are characteristic of a relatively small region over Baghdad, so we also assess the conditions over central Iraq using the ERA-Interim reanalysis (Figures 10 and S7). The less stable conditions correspond to November 19, 2013, with the local sounding leading to a K index of 27.4°C and the ERA-Interim data accounting for almost 37°C , both values above the 25°C threshold proposed by Lorente *et al.* (2008); in contrast, the local CAPE index was only 62 J/kg, increasing to 777 J/kg with the ERA-Interim data, in both cases well below

the 1,000 J/kg instability threshold (Lorente *et al.*, 2008). These relatively small values indicate the existence of marginally unstable convection. It is worth pointing that similarly small values have been reported to occur during flooding events in other Mediterranean regions (Iturrioz *et al.*, 2007; Lorente *et al.*, 2008).

The maps for CAPE and K display the penetration of unstable conditions from the Red Sea and Persian Gulf on November 18–19 (Figure 10c,g). The patterns of the SWEAT distribution were alike those for CAPE, particularly on 18 November, while the peak LI values were more scattered (Figure S7). The SI, LI, and SWEAT values never exceeded the threshold values (Table 1 and Figure S7). In contrast, the TT index surpassed the 44°C threshold during

FIGURE 8 Relative humidity (values above 60% with intervals of 10%, solid line) and wind velocity (horizontal velocity in m/s and pressure vertical velocity in Pa/s, arrows) for (a, b) November 18, 2013 (c, d) November 19, 2013 and (e, f) November 20, 2013 at 0000 UTC (left panels) and 1200 UTC (right panels), respectively (the velocity scale is shown in panel f). The star indicates Baghdad's location [Colour figure can be viewed at wileyonlinelibrary.com]

the entire event (Lorente *et al.*, 2008); its largest value over Baghdad, however, took place on November 20 rather than November 19.

A relevant variable is PW, the amount of water between 1,000 and 700 hPa (Table 1) (Peixoto and Oort, 1992; Kassomenos and McGregor, 2006). This variable attained peak values on November 19 but never reached

the 45–50 mm threshold for high moisture content (NOAA, 2017). In this case, however, the values deduced from the local soundings (28 mm) were larger than the values inferred from the ERA-Interim data (22 mm). This humidity translated in the progressive appearance of clouds over the Middle East between November 17, and November 19, 2013 (Figure S3).

TABLE 1 Precipitable water and convective indices as deduced from the soundings at Baghdad station (33.33°N, 44.43°E; elevation 34 m) at 1200 UTC (1500 LST) between November 17 and November 20, 2013

Convective indices	Threshold values	November 17, 2013	November 18, 2013	November 19, 2013	November 20, 2013
Precipitable water (PW, mm)	45–50	15.4 (15)	(18)	28.1 (22)	23.8 (20)
K (KI, °C)	25	19.5 (20)	(26.8)	27.4 (36.8)	27.3 (24.2)
Convective available potential energy (CAPE, J/kg)	1,000	0 (139.1)	(21.9)	61.8 (777)	13.6 (300.2)
SWEAT	200	33.4 (45.9)	(135.4)	136 (253.4)	135.3 (178.1)
Lifted index (LI, °C)	0 (upper limit)	2.01 (−2.5)	(−1.0)	0.45 (−0.5)	0.34 (−3.2)
Showalter index (SI, °C)	4 (upper limit)	−0.21		1.4	0.17
Total totals (TT, °C)	44	48.6		47.6	50.6

Note. The CAPE, K, and SWEAT indexes from the ERA-Interim reanalysis data set are shown between brackets. The Lorente *et al.* (2008) threshold values for convective instability are included (these are lower-limit values except for the LI and SI indices).

FIGURE 9 Skew-T log-P diagrams for Baghdad station at 1200 UTC (1500 LST) for (a) November 17, 2013 (b) November 19, 2013 and (c) November 20, 2013. The blue thick line represents the temperature of the air parcel when lifted adiabatically from the surface, the black solid line represents the environmental temperature, and the black dashed line is the dew point temperature [Colour figure can be viewed at wileyonlinelibrary.com]

In summary, the convective instability indexes show that the atmosphere was only marginally unstable over Iraq during the November 2013 event. The amount of water in the 1,000–700 hPa vertical range reached maximum values on November 19 but the indexes did not exceed the thresholds for intense storm events. Hence, thermodynamic instability was a secondary player in the flooding, which would have assisted the intense upwards dynamical forcing.

6 | MOISTURE SOURCE

The establishment of the November 2013 upper-level cut-off low over Iraq led to the reinforcement of the lower-level

cyclonic circulation and the generation of southerly winds from the Red Sea and the Persian Gulf. Further, the cut-off low caused intense upwards dynamical forcing ahead of the cyclone, with low-level wind convergence and upwards motion. These factors favour rainfall yet require a source of moisture.

Krichak *et al.* (2015) carried out a detailed analysis of the tropical and subtropical sources of moisture for high precipitation events in the Mediterranean region. They found that over most of the Mediterranean the source was in the North Atlantic, except for the easternmost region where moisture was associated with the Red Sea Trough—a low-level centre linking the Red and eastern Mediterranean Seas (Krichak *et al.*, 1997)—with humid air arriving from the Arabian and

FIGURE 10 (top panels) K index (coloured, units of $^{\circ}\text{C}$) and (bottom panels) CAPE index (coloured, units of J/kg) for November 17–20, 2013, 1200 UTC. The star indicates Baghdad's location [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 11 (top panels) Mean vertically integrated moisture flux (VIMF) (arrows, units of $\text{kg m}^{-1} \text{s}^{-1}$; the reference arrow denotes $200 \text{ kg m}^{-1} \text{s}^{-1}$) and mean vertically integrated moisture flux convergence (VIMFC) (coloured with intervals of $10^{-4} \text{ kg m}^{-2} \text{s}^{-1}$) over the 1,000–700 hPa band for November 17–20, 2013, 1200 UTC. (bottom panels) Precipitable water (PW) (coloured with intervals of kg/m) integrated over the 1,000–700 hPa band for November 17–20, 2013, 1200 UTC. The star indicates Baghdad's location [Colour figure can be viewed at wileyonlinelibrary.com]

Red Seas. The arrival of these air masses often takes place as a relatively narrow plume converging vapour at mid-latitudes, what they named an atmospheric river, the sort of warm conveyor belt that ascends and saturates near a warm front (Carlson, 1980).

In this section we first explore the moisture conditions during the November 2013 episode, followed by an analysis of the source of humidity that led to extreme precipitation.

Two key variables to assess the occurrence of precipitation are the availability of water in the lower atmosphere (precipitable water, PW) and the horizontal source of this water (vertically integrated moisture flux convergence, VIMFC) (section 2.3). In particular, the VIMFC has often been used for predicting the initiation of convection (van Delden, 2001; Banacos and Schultz, 2005; van Zomeren and van Delden, 2007; Ukkonen, 2015). We may expect that heavy

FIGURE 12 Ensemble trajectories of air parcels released near 2,000 m: (a) 6-days backwards starting over Baghdad on November 19, 2013, 1200 UTC; (b) 4-days forwards originating in the northern Red Sea on November 15, 2013, 1200 UTC. Tick marks are every 12 hr. Below each panel, we show the time evolution of the parcel's height (z , in m) and relative humidity (RH, in %) [Colour figure can be viewed at wileyonlinelibrary.com]

precipitation will occur when and where these variables are high and accompanied by upwards air motions.

The horizontal distribution of VIMFC and PW over the Middle East prior and during the November 19, 2013 episode is illuminating (Figure 11). On November 17, there was relatively little PW over Iraq (less than 16 kg m^{-2}) (Figure 11e). At this time, the vertically integrated moisture flux (VIMF) was moderate and the corresponding horizontal convergence values (VIMFC) were generally less than $4 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ (Figure 11a); these values may be compared with figures reported by Krichak *et al.* (2015), whom noted that most intense rain events in Mediterranean regions take place when the VIMFC exceeds $5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$.

On November 18, coinciding with the formation of the cut-off low over Iraq, the situation changed drastically. The southeasterly winds intensified significantly, bringing wet air from the Persian Gulf and Arabian Sea into the region. This moisture converged over Iraq and led to much higher VIMFC values, in excess of $8 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ in the southern part of the country and near $5 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$ over Baghdad (Figure 11b). The result was a doubling of PW over southern Iraq as compared with the previous day (Figure 11f). This situation continued and increased on

November 19, with the VIMFC reaching peak values (above $10 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$) precisely over Baghdad and the high-PW area stretching from the Persian Gulf into central Iraq. Finally, on November 20, the winds and, consequently, the amount of moisture transported north, weakened considerably (Figure 11d). There was still a region of high VIMFC values, but this had moved north of Baghdad. The amount of PW over central Iraq also decreased, with maximum values in the southern portion of the Arabian Peninsula (Figure 11h).

The marine source of the air masses arriving to Baghdad on November 19, 2013 can be confirmed by means of the backwards and forwards trajectories calculated using the HYSPLIT model (section 2.6) (Figure 12). Air parcels released at 2,000 m over Baghdad, at 1200 UTC on November 19, 2013, are consistently traced back to the south and southeast, most of them originating in the Persian Gulf and the Arabian Sea. Remarkably, the relative humidity of the air parcels is high during most of their trajectory, but they experience a rapid decrease between 0000 and 1200 UTC of November 13, indicative of precipitation (Figure 12a). Further, about half of the air parcels released at 2,000 m in the northern portion of the Red Sea, at 1200 UTC on November 15, 2013, end up 4 days later much

FIGURE 13 Evolution of SST (a, b) in the central part of the Persian Gulf (26°N, 52°E) and (c, d) in the northern part of the Red Sea (25°N, 36°E) during the six days previous to all 12 cut-off-low extreme flooding events in the Baghdad area between January 2007 and December 2016. The left panels (a, c) show the episodes during October and November, and the right panels (b, d) correspond to events between December and March; the black lines show the mean (solid) and standard deviation (dashed) values. Time runs backwards, with day zero corresponding to the flooding time [Colour figure can be viewed at wileyonlinelibrary.com]

higher in the atmosphere of central Iraq; these air parcels progressively increase their relative humidity along their pathways (Figure 12b). This southern-marine trail is also consistent with the observation that intense rainfall began in southern Iraq 1 day before the Baghdad area (Figure S2).

The predominant synoptic conditions during most cut-off low extreme-rain events over central Iraq also point at a southern source of humidity (e.g., six cases in Figure S5). The analysis of all 14 cut-off low cases (not shown) shows that the low-level southerly winds arrive into central Iraq from the Red Sea and the Persian Gulf, typically with the Red Sea as the initial and main source of humidity and the Persian Gulf acting as a secondary source 2–3 days later, as it happened during the November 2013 event. In a few cases there is also an additional moisture source from the Mediterranean Sea (e.g., March 2016, Figure S5).

It is reasonable to assume that the moisture arriving to central Iraq is associated with the release of latent heat from

the ocean to the atmosphere, arising when the cool cyclonic winds blow over the Red Sea and the Persian Gulf. This heat release would cool these surface waters, which should show up in the SST evolution previous to rainfall over Baghdad. Considering the distances between the Persian Gulf and the Red Sea to the Baghdad area, we expect that the temperature of these surface waters would decrease a few days before the flooding, for example, using typical surface winds of 6 m/s the change in SST should anticipate the event by 1–2 days over the Persian Gulf and 3–5 days over the Red Sea.

We may use the SST data (available since January 2007) to explore if this is the case for all extreme-rain cut-off lows during 2007–2016 (12 out of the total 14 extreme cases) (Figure 13). Indeed, except the March 2016 event when the moisture arrived from the Mediterranean, the SST always changed by 1–2°C in a few days. For the November 2013 event, for example, the main SST decrease in the Red Sea took place 4 days before the event and the SST in the

FIGURE 14 Mean SST west of the Strait of Hormuz (56°E) (solid line, left ordinate), mean AST in the northern Red Sea (29°N, 48°E) (dashed line, left ordinate), and the difference between SST and AST (black dotted line, right ordinate). The arrows indicate the time of occurrence of all 12 extreme cut-off lows (precipitation over 20 mm) between January 2007 and December 2016 [Colour figure can be viewed at wileyonlinelibrary.com]

Persian Gulf decreased the entire week with a maximum daily change (0.9°C) 1 day before the event (Figure 13). This SST change in the Persian Gulf on November 18 matched with high VIMFC and PW values stretching from the Gulf into central Iraq (Figure 11b,f).

The essential requirement for latent heat (and hence moisture) transfer to the atmosphere is that the AST be less than the SST. This only happens during late fall and early winter, with maximum temperature differences ($9.8 \pm 2.2^{\circ}\text{C}$) precisely in November–December (Figure 14). If this requirement takes place at times of intense southeasterly surface winds, then water vapour is first incorporated to the lower atmosphere and later transported to central Iraq. This happened during the November 2013 event, as reflected by the rapid SST decrease in the Persian Gulf (Figure 13) and the advent of high northwards fluxes of PW (Figure 11), as well as in most cut-off lows that brought extreme rain to the Baghdad area (Figure S5).

7 | CONCLUDING REMARKS

We have analysed a 12-year time series of daily precipitation values over Baghdad in order to identify the seasonal and inter-annual changes in rainfall, and the relative contribution of cut-off lows to these changes. Summer had no rain and autumn and winter were the wettest seasons; the contribution of rainy cut-off low episodes was largest in autumn, followed by spring. The mean annual precipitation was 130.8 ± 67.1 mm/year, with minimum/maximum values of 59.1/296.7 mm for the calendar years of 2009/2014. Because of the lack of summer rain, the precipitation is integrated for natural years, which run from July 1 to June 30 (labelled by the final year, e.g., natural year 2006 runs from July 1, 2005 to June 30, 2006). This shows that there were 3 years (2008, 2009, and 2012) with extreme low precipitation (mean value of 39.7 mm) and 3 years (2013, 2014, and 2016) with precipitation much greater than the annual average (mean value of 253.7 mm); the minimum

and maximum corresponded to 2012 and 2014 with 29.3 and 278.1 mm, respectively.

We have identified a total of 94 cut-off low systems affecting Iraq, with 38 of them bringing rain over the Baghdad area and 14 leading to extreme precipitation (over 20 mm). The persistence of the cut-off low rainy conditions is very short, typically 1–3 days. These rainy events lasted only 118 days (21.6% of the total number of rainy days) but brought 43.4% of the total amount of rain.

Our data shows that cut-off low systems can take place all year long, more often in May–June and October–November, when the Red Sea Trough (a low-level cyclonic circulation) sets over the Middle East (Krichak *et al.*, 1997), and less frequently between July and September, when the Atlantic subtropical high-pressure system extends into the Arabian Peninsula and inhibits the generation of cyclones (e.g., Bitan and Sa'aroni, 1992). The amount of rain associated with cut-off lows between October and December—when the surface waters of the Red Sea and Persian Gulf remain warm and can release water vapour to the atmosphere—accounts for about one third of the total annual precipitation (41.0 out of 130.8 mm/year).

The contribution of cut-off low systems to the total precipitation also shows large inter-annual variations. The fraction of rain associated with cut-off lows did not change substantially between arid and wet years but the total amount of rain accompanying these events increased by a factor of 16, from 31.3 mm during the three arid years (26% of the total) to 512.3 mm during the three wet years (67% of the total, with nearly 400 mm corresponding to only six extreme cut-off lows, each discharging over 30 mm). This is because rainy cut-off lows bring little water (<10 mm) during arid years while they bring high rain (>14 mm) during wet years. These data confirm that extreme-rain cut-off lows are the principal reason turning an arid into a wet year.

The analysis of the dynamic conditions during the 14 extreme cut-off low rainy events shows fairly analogous conditions, characterized by the conjunction of horizontal

divergence and upwards vertical velocities in the middle and upper atmosphere, together with the penetration in the lower atmosphere of a relatively narrow plume of humid air masses from the Persian Gulf and/or the Red Sea, probably associated with the winter development of the Red Sea Trough. Our results suggest that the presence of a cut-off low in the upper levels may favour these conditions. The ascending branch of a cut-off low, usually located in its eastpolewards sector, is a zone with upper level divergence that forces ascension and favours low-level cyclogenesis below; this cyclogenesis can then generate and convey humid maritime air into central Iraq. The SST evolution in these water bodies indeed shows substantial surface cooling ($1\text{--}2^{\circ}\text{C}$) during those days previous to an event, confirming an extensive release of water to the low atmosphere in the form of latent heat flux.

We have carefully analysed the synoptic conditions of the cut-off low leading to the largest flood event, taking place November 18–20, 2013. The middle and upper atmospheric conditions arose from an initial omega block that rapidly evolved into a Rex block pattern, with substantial frontogenesis in the eastern portion of its cyclonic structure, and ended up as a cut-off low system. Central Iraq was experiencing horizontal divergence and the associated upwards motions extended all the way from 1,000 to 250 hPa. Simultaneously, the low-level atmosphere (1,000–700 hPa) became loaded with precipitable water, originated from the evaporation of the Red Sea surface waters and brought into central Iraq by the intense southerly winds.

The November 19, 2013 event is a remarkable case of vertical motions driven dynamically by a cut-off low pattern, at a time when the surface moisture arose because of the southerly cool winds blowing over the warm Red Sea. During the entire event the thermodynamic conditions were only marginally unstable, hence playing a relatively minor role. The conditions leading to this event developed very swiftly, in only 1–2 days, making very difficult a proper forecast. Our results, pointing at the harsh consequences from the interaction of high-latitude upper-level perturbations with local low-level forcing, shall help identify, and timely predict analogous future situations.

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SUPPORTING INFORMATION

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