On the analysis of a summertime convective event in a hyperarid environment

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Abstract
A summertime convective event that developed on 5 September 2017 over the United Arab Emirates (UAE) is investigated in this study. Atmospheric profiles from a ground-based microwave radiometer along with satellite observations and in situ data from three weather stations in the UAE were used. The event was simulated using the Weather Research and Forecasting (WRF) model, forced with four input datasets: Global Forecast System (GFS), Climate Forecast System Reanalysis (CFSR), and the European Centre for Medium-Range Weather Forecasts ERA-5 and ERA-Interim reanalyses. The afternoon and evening convection was triggered by the intrusion of a mid-level trough from midlatitudes and was favoured by the convergence over land of thermally forced maritime air masses. Near-surface observations at a weather station revealed a 7 °C drop in air temperature, a doubling of the wind speed to 9 m·s⁻¹ in 30 min, and a shift in wind direction from easterly, to southerly and then westerly in about 45 min, associated with the passage of the cold pool emanating from a Mesoscale Convective System (MCS). At the location where the microwave radiometer was deployed, the pre-squall low and wake low signatures are also captured, with a 5 m·s⁻¹ increase in the wind speed in just 5 min. The observed features of the studied MCS were found to compare with those reported for MCSs in the Tropics. The four experiments gave a similar performance, although the GFS simulation generally generated higher skill scores. The investigated MCS event was not captured by WRF, which was attributed to a misrepresentation of soil moisture in the model. This study highlights the difficulties regional models like WRF may have in reproducing MCSs over arid/hyperarid regions, which may result in a misrepresentation of their impacts in climate projection studies.

Keywords
hyperarid region, infrared brightness temperature, meso-high and wake low, mesoscale convective system, microwave radiometer, WRF model
INTRODUCTION

The United Arab Emirates (UAE), located in the eastern Arabian Peninsula in the Middle East, features hyper-arid conditions, with total annual precipitation ranging from 30 mm over the southern desert to 120 mm over the Al Hajar mountains, located in the northeastern part of the country, with a mean spatial rainfall of roughly 80 mm (Ouarda et al., 2014; Wehbe et al., 2017). Consistent with the larger Arabian Peninsula rainfall regime, the majority of the precipitation occurs during the cold season from December to March, associated with midlatitude weather disturbances (Wehbe et al., 2018). Nevertheless, rain accumulations during the summer season in excess of 100 mm at isolated spots are recorded, and are mainly associated with short-lived mesoscale convective systems (MCSs) over the Al Hajar mountains (Branch et al., 2020; Wehbe et al., 2020).

Despite their minimal contribution to the country’s annual rainfall average, an understanding of the processes that favour the development of MCSs and an assessment of the capability of numerical models in representing them is crucial, for example, for the planning of cloud seeding activities that are regularly conducted in the eastern half of the country (Al Mazroui and Farrah, 2017; Branch et al., 2020). Moreover, summer rain associated with MSCs helps to recharge the underground aquifers, an important water resource to augment the increasing agricultural activity (Murad et al., 2007; Wehbe et al., 2018). Hence, a better understanding of the processes associated with MSC development over this region constitutes a crucial step towards an accurate projection of the occurrence of MCSs and associated rainfall, which is particularly relevant as recent studies have shown that both the frequency and rain rates associated with MCSs over arid regions are projected to increase under future climate change (Taylor et al., 2017; Fitzpatrick et al., 2020).

For deep convection to develop in a hyperarid environment, a combination of concomitant factors is needed. In the western flat desert region, and as discussed in Steinhoff et al. (2018), this includes low-level convergence between the Arabian heat-low and the sea-breeze front, with the latter advecting the moist marine air inland, and preconditioning the environment for the occurrence of convection. At a larger scale, the development of the less frequent summertime convection over the southwestern UAE is found to be linked to active phases of the Indian summer monsoon (Steinhoff et al., 2018; Attada et al., 2019). Steinhoff et al. (2018) reported on a cyclonic circulation over the Arabian Gulf, which develops during morning hours over eastern UAE, and vanishes around midday, when convection starts in the boundary layer, in response to surface heating by the sun. This circulation results from the convergence of the sea-breeze flows from the Arabian Gulf and the Gulf of Oman and the circulation associated with the thermal low that develops inland, and then propagates westwards over the Arabian Gulf during night-time hours. It hinders the inflow of dry air from the desert, while the strong surface evaporation continues to moisten the boundary-layer air. The moist air is eventually advected inland, a process which is later reinforced by the sea-breeze circulation, and plays a role in the development of afternoon convection in the region. Over the mountainous areas in the UAE, on the other hand, deep convection is found to be primarily triggered by the convergence of three flows: mountain upslope flows, southerly winds associated with the deepening of the Arabian heat-low, and the daytime sea breezes from the Arabian Gulf and the Gulf of Oman (Schwitalla et al., 2020). The initiation of convection over mountainous areas in arid regions is further promoted by the presence of an upper or mid-level trough and a strong temperature gradient at the surface (Knippertz et al., 2009; Francis et al., 2019). Studies based on satellite images (Schwitalla et al., 2020) have shown that convection over the Al Hajar Mountains initiates close to the highest central peaks (mostly for elevations between 600 and 800 m) and on the ocean side of the mountains, in local early afternoon hours (0900–1100 UTC, 1300–1500 local time, LT (UTC + 4 hr)), extending northwards, southwards and westwards over time. This diurnal progression can be attributed to the (a) outflow from primary cells, leading to the development of secondary cells downstream, (b) local orographic geometry and associated differential surface heating, and (c) westward advection by the diurnal sea-breeze circulation.

While convective events normally start with individual cumulonimbus clouds, thunderstorm cells can organize themselves and form large convective storms, the largest of which are MCSs. MCSs are responsible for the majority of the tropical rainfall and exhibit a slanted vertical structure, with regions of deep convection preceding areas of mesoscale stratiform precipitation (e.g. Houze, 1989; 2004). At the surface, the passage of the convective precipitation region is typically accompanied by a strengthening of the horizontal wind and a sudden change in its direction, the “gust front”, with the nose of the cold pool supporting gravity-wave motions (Bou Karam et al., 2008). The surface pressure field also experiences significant variability in response to an MCS, comprising several characteristic meso- lows and meso-highs. The surface meso-low, which occurs in association with the adiabatic warming of the descending unsaturated air at the back edge of the stratiform precipitation region that exceeds the evaporative cooling at lower levels, is commonly known as a “wake low”. Below the convective region, a surface meso-high develops in association with the convective downdraughts (Fujita, 1955; Johnson and Nicholls, 1983). This meso-high
is linked with the cold pool occurring due to precipitation fallout in the convective region (e.g. Houze, 1989; 2004). Meso-lows are also seen ahead of the convective line at the surface, “pre-squall low”, resulting from warming due to subsidence in the upper troposphere and lower stratosphere (Hoxit et al., 1976; Maddox et al., 1981). Further details about the structure and characteristics of MCSs are given in Houze (1989; 2004) and Johnson (2001).

Given the impacts of MCSs at spatial and temporal scales surpassing those at which they occur, numerical simulations have also been conducted to better understand the underlying processes of convective events in the UAE and to account for their impacts. Schwitalla et al. (2020) tested different configurations of the Weather Research and Forecasting (WRF: Skamarock et al., 2008) model for a summertime convective episode that took place on 14 July 2015. The best results were obtained when the Thompson aerosol-aware cloud microphysics scheme (Thompson and Eidhammer, 2014) is combined with the Mellor-Yamada Nakanishi Niino (MYNN) level 2.5 Planetary Boundary Layer (PBL) scheme (Nakanishi and Niino, 2006; 2009). This experimental set-up is recommended for warm season precipitation events in the UAE. For an extreme rainfall event in March 2016, Wehbe et al. (2019) compared the performance of the standalone WRF with WRF-Hydro, a coupling between WRF and its hydrological modelling extension package. The latter was found to outperform the former, with higher skill scores for the rainfall, radiation and surface temperature forecasts. This highlights the important role of land–atmosphere interactions in the simulation of the weather conditions in arid/hyperarid regions. Steinhoff et al. (2018) ran the WRF model down to 1 km spatial resolution for 21 July and 30–31 August 2011 convective events in western UAE. The authors noted that the daytime sea breeze was slower in WRF than in observations, which impacted the simulation of clouds and precipitation. Despite the referred biases, however, the WRF model has been successfully used as a tool to investigate warm season convective events in the UAE, justifying its choice for this study.

In this work, the convective event that developed over the UAE Al Hajar mountains on 5 September 2017 is investigated, using a combination of numerical simulations and unique observational datasets including temperature profiles from a microwave radiometer (MWR: Temimi et al., 2020a) at high temporal and vertical resolution. The main goal of the study is to better understand the atmospheric conditions from synoptic- to local-scale during a summertime convective event in an arid/hyperarid region and to assess their representation in a regional model.

This article is structured as follows. Section 2 provides a description of the numerical model and observational datasets used in this work. In Section 3, an overview of the convective event is given. The emphasis is placed on the large-scale conditions and triggering mechanisms. The WRF predictions are discussed and evaluated against in situ measurements in Section 4, while the main conclusions are outlined in Section 5.

2 | MODEL SET-UP AND DATASETS

2.1 | Numerical modelling set-up

The numerical model used in this study is WRF version 3.7.1, forced with Global Forecast System (GFS, https://www.nco.ncep.noaa.gov/pmb/products/gfs/), Climate Forecast System Reanalysis (CFSR: Saha et al., 2010), and the European Centre for Medium-Range Weather Forecasts ERA-5 (Hersbach et al., 2020) and ERA-Interim (Dee et al., 2011) reanalysis data. Figure 1a shows the model domains considered. The outermost grid is at 22.5 km, comprising the vast majority of the Arabian Peninsula and neighbouring regions, while the 7.5 km grid encompasses the full Arabian Gulf and Gulf of Oman. The focus of the work is on the hourly predictions of the 2.5 km grid and the 5 min forecasts of the 0.833 km nest, highlighted in blue and orange, respectively, with the orography given in Figure 1b. The former extends from Bahrain to eastern Oman, including the full region where convection developed in the afternoon of 5 September 2017, whereas the latter is centred on the Al Hajar mountains, comprising the site where the MWR was deployed, an aerial view of which is given in Figure 1c. Two main mountain ranges are seen in Figure 1b: the Al Hajar mountains, which extend from northern Oman to eastern UAE, and the Zagros mountains over Iran. The presence of high terrain over the southern Iranian coast, and the northwest–southeast shape of the eastern Saudi Arabia coastline, produces a “wind funnel”-like effect, helping to strengthen the background north to northwestly “Shamal” winds in the region (Al Senafi and Anis, 2015; Bou Karam Francis et al., 2017).

The simulation is initialized on 4 September 2017 at 0000 UTC, with the model run for 48 hr and the first 24 hr discarded as spin-up. A similar spin-up period was selected in Fonseca et al. (2020), Temimi et al. (2020b) and Nelli et al. (2020b), where high-resolution simulations in arid/hyperarid regions were also conducted. In the vertical, 50 levels are considered, more closely spaced in the PBL, with the first vertical level at about 25 m above ground and the model top at 30 hPa. A comparable model top has been used in convective studies over West Africa (e.g. Klein et al., 2015), East Asia (e.g. Kim and Hong, 2010) and North America (e.g. Ethington and Santos, 2008). The physics schemes selected are...
given in Table 1. This configuration reflects the findings of Schwitalla et al. (2020), who tested different WRF set-ups for a summertime convective event in the UAE. While 2.5 km horizontal resolution is expected to be convection-permitting (Prein et al., 2015), a comparison of the simulations with the cumulus scheme switched on and off indicated that, in the former the WRF-predicted convection is more in line with that observed, as given by satellite-derived products (not shown). As a result, the cumulus scheme is activated in this nest. In the 0.8333 km grid, a shallow cumulus scheme is employed, the one developed by the University of Washington (UW) (Bretherton et al., 2004), as this spatial resolution is still too coarse to fully represent shallow clouds. In this nest, slope and shading effects on the surface solar radiation flux are also added. The Noah-MP scheme, a sophisticated land surface model (LSM) available in WRF and employed in this study, is configured following Weston et al. (2018). The
sea-surface temperature (SST) is read in from GFS every 6 hours, with a simple interactive prognostic scheme applied to the sea-surface skin temperature (SSKT). This scheme, based on Zeng and Beljaars (2005), takes into account the effects of the heat and radiative fluxes as well as molecular diffusion and turbulent mixing, allowing WRF to capture the diurnal variation of the SSKT and its feedback to the atmosphere. In addition, Rayleigh damping is applied to the wind components and potential temperature in the top 5 km on a time-scale of 5 s (Skamarock et al., 2008).

In addition to GFS, and to investigate the sensitivity of the WRF predictions to the forcing data, three reanalysis datasets ERA-5, ERA-Interim and CFSR are considered. A summary of the main features of the datasets is given in Table 2. The GFS is the operational dataset of the National Centers for Environmental Prediction (NCEP), used worldwide as input for higher-resolution regional and local weather forecasts, including in the UAE (e.g. Valappil et al., 2019). ERA-Interim and ERA-5 reanalyses are developed by the European Centre for Medium-Range Weather Forecasts. As summarized in Mahto and Mishra (2019), ERA-5 employs a higher horizontal (31 vs. 79 km) and vertical (137 vs. 60 levels) resolution compared to ERA-Interim, also with a higher model top (0.01 vs. 0.1 hPa). It makes use of an updated radiative transfer model, features an improved bias correction, and assimilates a significant larger amount of observational data. CFSR, on the other hand, is a product of NCEP, and is the first reanalysis to be generated from a coupled climate atmosphere–land–ocean model. Mahto and Mishra (2019) evaluated the performance of five reanalysis products, including the three considered in this study, for hydrological applications in India. The authors concluded that ERA-5 generally gives the best results. Tahir et al. (2020) also found that ERA-5 outperforms other reanalyses in the simulation of the surface solar radiation in western Pakistan. Tegtmeier et al. (2020) investigated how the tropical tropopause layer (TTL), defined as the layer between the well-mixed convective troposphere and the radiatively controlled stratosphere, is represented in reanalyses datasets including CFSR, ERA-5 and ERA-Interim. While all datasets give a realistic representation of the major characteristics of the temperature structure within the TTL, ERA-5 and CFSR are the best performing. However, Alghamdi (2020), and in a comparison between radiosonde measurements and reanalyses data over southwestern Asia, found that ERA-5 is the worst performing of the four considered, with ERA-Interim giving the best scores. In summary, while ERA-5 has been found to outperform the other reanalysis products for several meteorological applications, it may not necessarily be the best performing in the Middle East.

### Table 2: Main characteristics of the reanalysis datasets employed in this study

| Model horizontal resolution | GFS | ERA-Interim | CFSR | ERA-5 |
|----------------------------|-----|-------------|------|-------|
| T1534 (~13 km)             | T255 (~79 km) | T382 (~38 km) | T639 (~31 km) |
| Vertical levels            | 64  | 60          | 64   | 137   |
| Model top pressure         | 0.2 hPa | 0.1 hPa     | 0.266 hPa | 0.01 hPa |
| Time period                | 2015–Present | 1979–August 2019 | 1979–Present | 1950–Present |
| Assimilation algorithm     | N/A | 4D-Var     | 3D-Var | 4D-Var |
| Model vintage              | 2015 | 2006       | 2009  | 2016  |
| Source                     | National Center for Atmospheric Research: https://rda.ucar.edu/datasets/ds084.1/ | National Center for Atmospheric Research: https://rda.ucar.edu/datasets/ds627.2/ | National Center for Atmospheric Research: https://rda.ucar.edu/datasets/ds094.0/ | Climate Data Store: https://cds.climate.copernicus.eu |

2.2 Observational datasets

In this work, six observational datasets are used, listed in Table 3. The first four datasets described in Table 1 are satellite-derived products, at a spatial resolution between 4 and 6 km, and a temporal resolution of at least hourly. The characteristics of the Radiometer Physics Gesellschaft mit beschränkter Haftung (RPG)-Humidity And Temperature PROfile (HATPRO), RPG-HATPRO, passive MWR deployed on the mountains are given in Temimi et al. (2020a). When it was deployed at Masdar Institute, roughly 4 km from Abu Dhabi’s International Airport, its measurements were assessed against radiosonde observations collected at the airport. A comparison of the two...
sets of observations for a roughly two-year period revealed that the air temperature profiles are in close agreement, generally within 1 K. The humidity profiles, however, can differ by more than 6 g kg\(^{-1}\), possibly because of deficiencies in the retrieval algorithm. Given this, only the temperature profiles will be considered for analysis. \textit{In situ} meteorological measurements from three weather stations maintained by the UAE’s National Center of Meteorology (NCM), whose locations are given in Figure 1d, are also considered in this work.

### 2.3 Verification diagnostics

The verification diagnostics proposed by Koh \textit{et al.} (2012) are employed here. They comprise the model bias, correlation (\(\rho\)), variance similarity (\(\eta\)), and normalized error variance (\(\alpha\)), and are defined in Equations (1) to (5) below:

\[
D = F - O, \quad \text{(1)}
\]

\[
BIAS = < D > = < F > - < O >, \quad \text{(2)}
\]

\[
\rho = \frac{1}{\sigma_O \sigma_F} < (F - < F >) \cdot (O - < O >) >, -1 \leq \rho \leq 1, \quad \text{(3)}
\]

\[
\eta = \frac{\sigma_O \sigma_F}{\frac{1}{2} (\sigma_O^2 + \sigma_F^2)}, \quad 0 \leq \eta \leq 1, \quad \text{(4)}
\]

\[
\alpha = \frac{\sigma_D^2}{\sigma_O^2 + \sigma_F^2} \equiv 1 - \rho \eta, \quad 0 \leq \alpha \leq 2. \quad \text{(5)}
\]

The model bias, Equation (2), is the mean discrepancy \(D\) between the model forecast \(F\) and the observations \(O\), with \(< D >\), \(< F >\) and \(< O >\) denoting the mean of \(D\), \(F\) and \(O\), respectively. The correlation, \(\rho\), provides an indication of how well the phase of the modelled and observed variables agree, while the ability of WRF to capture the amplitude of the signal can be assessed with the variance similarity, \(\eta\). These two diagnostics are defined in Equations 3 and 4, respectively, with \(\sigma_F\) and \(\sigma_O\) being the standard deviation of \(F\) and \(O\), respectively. The last skill score considered is the normalised error variance, \(\alpha\), which accounts for both phase and amplitude errors. \(\sigma_D\) in Equation (5) denotes the standard deviation of the discrepancy between the model predictions and the observations. The optimal model performance corresponds to zero bias, \(\rho\) and \(\eta\) equal to one, with the latter two giving \(\alpha = 0\). For a random forecast, \(\rho = 0\) giving \(\alpha = 1\). Hence, for a model prediction to be considered useful, \(\alpha < 1\). Further details about the diagnostics can be found in Koh \textit{et al.} (2012).
3 | THE CONVECTION ON 5 SEPTEMBER 2017

In this section, an overview of the synoptic-scale environment, and the triggers of the convective clouds that developed over the Al Hajar mountains on 5 September 2017, is given, using a combination of observational and reanalysis data. Figures 2 and 3 show ERA-5 reanalysis fields on the day of the event, from local noon (0800 UTC, 1200 LT) to night-time hours (1800 UTC, 2200 LT). One feature that stands out is a trough in the 500 hPa geopotential height over the UAE, which appears to be an extension of the midlatitude trough located over Iran (Figure 2). This feature likely promoted the development of the afternoon and evening convection in the region that flared up on the lee side of the mountains. This is in line with published works, which suggest a link between the presence of a trough at this level and surface precipitation/cyclogenesis (Srinivas et al., 2018; Branch et al., 2020).

The low-level circulation is characterized by southwesterly winds over the eastern half of the UAE which persisted throughout the day and a weak cyclonic circulation to the east of Qatar mostly in the early- to mid-afternoon hours (Figure 2). Typically, in the afternoon the low-level wind blows from the northwest over the UAE, in line with the progression of the sea breeze (Eager et al., 2008; Nelli et al., 2020a). On this day, however, the referred mesoscale circulation was shallower over most of the UAE coastline, not being present at 850 hPa but seen at 10 m (Figure 2). Around 1000 UTC (1400 LT), the land–sea temperature gradient along the UAE coastline exceeded 10 °C in some places (Figure 3b). The resulting pressure gradient triggered the occurrence of a vigorous sea-breeze circulation, which led to an increase in the water vapour mixing ratio from 8–10 g kg⁻¹ in the early afternoon (Figure 3h) to 22–24 g kg⁻¹ in particular coastal locations in the evening hours (Figure 3k,l). A further inspection of Figure 3 reveals that the moist marine air from the Arabian Gulf converges with that from the Arabian Sea and the Gulf of Oman over the northeastern UAE, therefore preconditioning the environment for the development of convection. Over the mountains in Oman, on the other hand, the daytime thermally forced upslope flows, reinforced by the moisture-rich sea breezes from the Gulf of Oman to the north and the Arabian Sea to the southeast, converged over the higher elevations (Figure 3). This is the most dominant triggering mechanism for deep convection in the region (Fonseca et al., 2020), with this area being well known for the occurrence of summertime convective events, some of which extend westwards into the UAE (Branch et al., 2020; Schwitalla et al., 2020).

Figure 4 shows the infrared brightness temperatures (IRBRTs) from 1000 to 1500 UTC on the day of the event. According to Rao et al. (2012), clouds can be classified based on the IRBRT as follows: (a) highly convective (IRBRT < 210 K), (b) very deep convective (210 K < IRBRT < 235 K), (c) deep convective (235 K < IRBRT < 260 K), (d) mid-level (260 K < IRBRT < 270 K), and (e) cirrus or low-level (270 K < IRBRT < 280 K). IRBRT values in excess of 280 K are an indication of clear skies. A mesoscale convective system (MCS) is identified based on the IRBRT threshold of 240 K (Reddy and Rao, 2018), a contour highlighted in purple in Figure 4. This value is 10 K lower than that proposed by Branch et al. (2020) for the identification of deep moist convection in the region, and therefore more conservative. As can be seen, there is extensive convective activity along the Al Hajar Mountains, with an MCS located just to the north of Al Farfar (cross in the plots) between roughly 1200 and 1300 UTC. These convective cells first developed on the oceanic side of the mountains, in a region of low-level wind convergence and higher moisture content (Figures 2c and 3i) and initially propagated northwards, westwards and southwards. Figure 4 also shows a significant propagation of the mid-to upper-level cloud tops northeastwards into the Gulf of Oman, with some reaching the southern coast of Iran in the late-afternoon and evening hours. An inspection of the upper-level winds from ERA-5 reveals that strong west to southwesterly winds prevailed (not shown), which could have advected the clouds towards Iran. It is possible that the increased vertical shear hindered a further intensification of the convective cells, as it is known to disrupt the mesoscale circulations (Findell and Eltahir, 2003).

Deep convection also flared up over parts of southern Iran, possibly arising from the presence of the mid-level trough as well as from the convergence of the daytime sea breeze with the downslope winds from the Zagros mountains (Figure 2). Convective clouds are observed in central parts of UAE in the late afternoon (Figure 4). A possible trigger mechanism is the convergence of the southeasterlies turning southwesterlies blowing from Oman, with the northwesterly winds in association with the surface low to the east of Qatar (Figure 2). This genesis mechanism has been reported by Steinhoff et al. (2018). However, and according to the aforementioned cloud classification, these are mostly low to mid-level clouds and not deep convective clouds like those that developed over the mountains.

The convective cells mentioned above are clearly seen in Figure 5, where satellite images from Spinning Enhanced Visible and Infrared Imager (SEVIRI) are given every two hours from 0200 to 1800 UTC (0600–2200 LT). Early in the morning there was extensive cloud cover, mostly medium to high-level clouds, over Oman extending into parts of southeastern UAE, eastern Saudi Arabia and northern Yemen. These clouds thinned out during
F I G U R E 2  
Sea-level pressure (shading; hPa) and 10 m horizontal wind vectors (arrows; m s$^{-1}$) at (a) 0800 UTC, (b) 1000 UTC, (c) 1200 UTC, (d) 1400 UTC, (e) 1600 UTC and (f) 1800 UTC on 5 September 2017 from ERA-5 data. (g–l) As (a–f) but with geopotential height (m) at 500 hPa in shading, and the 850 hPa horizontal wind vectors in arrows. The cross highlights the approximate location of Al Farfar, where the MWR was deployed.
morning hours, lingering only over coastal Oman around local noon. It is apparent that there was an intrusion of water vapour from the Gulf of Oman into the region (Figure 3) in the early morning hours (0200–0600 UTC, 0600–1000 LT). This is consistent with the offshore winds seen in Figure 2, and aided in the development of convection later in the day. An analysis of the SSTs (Figure S1 in Appendix S1) reveals a gradient of 2–3 K between the Gulf of Oman and the Arabian Sea, which enhanced the moisture advection. The deep convective clouds that developed in the mid-to late-afternoon hours over the Al Hajar mountains are shaded in dark red, having reached their maximum intensity around 1200 UTC (1600 LT). The effects of the strong mid- to upper-level winds on the convective cells highlighted above is seen mostly from 1400 to 1800 UTC (1800 to 2200 LT).
An analysis of the NCM station data for this day revealed that precipitation was only recorded at three stations located in the northeastern part of the country: 0.2 mm at station no.1 (Hatta, Figure 1d; 305 m above sea level, ASL), 2 mm at station no.2 (Masafi; 525 m ASL), and 1.6 mm at station no.3 (Fujairah airport; 47 m ASL). The time-series of the weather variables at the location of these stations are given in Figure 6, with the last panel showing the 30 min IRBT. On 5 September 2017, the cold pool that emanated from an MCS reached Masafi (blue curve) around 1200 UTC (1600 LT). At this time, there is a sudden decrease in air temperature, by roughly 7 °C in 30 min; a shift in the wind direction, from an easterly to southerly and then westerly in roughly 45 min; and an increase in the wind speed from below 1 to about 9 m·s⁻¹ in roughly 1 hr (Figure 6). These features are commonly seen in the passage of a cold pool, which presents the characteristics of a gust front (Flamant et al., 2007; Bou Karam et al., 2008; Knippertz et al., 2009). The depressed short-wave radiation flux at the surface, dropping from about 930 to 175 W·m⁻² in just 15 min, is due to the presence of clouds, with variable amounts during the event. The surface pressure time-series features a roughly 4 hPa increase in about 30 min, the signature of a meso-high. This field exhibits a temporal evolution consistent with that expected during the passage of a cold pool (Johnson, 2001; Engerer et al., 2008). Roughly at the same time as when the wind speed reaches a peak and the air temperature a minimum, the IRBT drops from roughly 300 to 234 K in about 90 min, associated with the development of very deep convective clouds (Figure 6). The fact that the minimum in IRBT largely coincides with the minimum in the surface radiation flux (about 86 W·m⁻²) is consistent with the fact that deeper cumulonimbus clouds block a larger fraction of the incoming short-wave radiation. All these signatures, albeit present, have a much-reduced amplitude at Hatta (red curve), and cannot be seen at Fujairah, for which the temporal resolution of the NCM data is also lower (hourly vs. 15 min). The temporary increase in the air temperature at Hatta after 1200 UTC can be explained by a shift of the wind direction to westerly, and subsequent advection of the drier inland air into the site.

Unique observations from an MWR deployed at the Al Farfar site (cross in Figure 1b), provided high temporal measurements of the temperature vertical structure and near-surface fields. The black curve in the panels in Figure 7 shows the observed 5 min near-surface meteorological variables as measured by a weather station attached to the MWR. Figure 8a gives the observed temperature vertical profile in the lowest 5 km of the atmosphere, as measured by the MWR. All fields are given on 5 and 6 September, with the gaps in the observed data, shaded in white, being due to an electrical failure of the system.
As opposed to at Masafi, at Al Farfar the full signatures of an MCS in the surface pressure are observed: the “pre-squall low”, “meso-high” and “wake low” are identified in Figure 7c, with an overall change of \(\sim 4\) hPa. These fluctuations in surface pressure are superimposed on the semi-diurnal tide, with the expected minima at 0000 UTC (0400 LT) and 1200 UTC (1600 LT) and maxima at 0600 UTC (1000 LT) and 1800 UTC (2200 LT). In fact, in the observed 5 min data, two MCS events are captured, one on 5 September just after 1200 UTC, and another on 6 September after 0900 UTC, just before the measurements are interrupted. In both events, the changes in surface pressure are accompanied by a decrease in air temperature, by up to about 6 °C in 1 hr, and an increase in wind speed, by up to 5 m \(\cdot\) s\(^{-1}\) in just 5 min, which also exhibits large shifts in direction. On 5 September the relative humidity drops by about 40% during the event, while on 6 September, after the passage of the MCS, the mixing ratio increased rapidly, possibly due to the advection of moisture from the Gulf of Oman, as the wind shifted to a more easterly direction. Figure 8a shows the vertical temperature profile measured by the MWR. From about 0600 to 1200 UTC (1000 to 1600 LT) on 5 September, the near-surface atmosphere warms up rapidly as the sun heats up the ground, with a superadiabatic temperature profile. After 1200 UTC, and persisting until about 0300 UTC on 6 September, a warm anomaly centred at about 800 m AGL is seen in the MWR observations. This warm anomaly was associated with the
FRANCIS et al.

FIGURE 6  (a) Air temperature (°C), horizontal wind (b) direction (°) and (c) speed (m·s⁻¹), (d) sea-level pressure (hPa) and (e) surface downward short-wave radiation flux (W·m⁻²) at the location of Hatta (red; station no.1 in Figure 1d), Masafi (blue; station no.2), and Fujairah (green; station no.3), on 5 September 2017. The time frequency is 15 min for Hatta and Masafi, and hourly for Fujairah, for which the downward short-wave radiation flux is also not available. (f) The 30 min IRBT (K) at the closest grid-point to the location of the stations. The meso-high (MH) is identified in (d) presence of clouds (figure 5 of Chan and Lee, 2015) until around 1600 UTC. After that time, the skies were clear at the site in the local night-time into the morning hours on 6 September, suggesting that the referred-to low-level temperature inversion during night hours (Figure 8a) is linked with the nocturnal boundary layer. This is further confirmed by the fact that this feature is seen on other days in cloudless conditions (not shown). After roughly 0300 UTC on 6 September, the environment returns to the state observed early on 5 September, with a superadiabatic profile re-developing in the local morning hours (Figure 8a).

4 | NUMERICAL MODELLING ANALYSIS

In this section, an assessment of how well WRF simulates the 5 September 2017 convective event is conducted. The model predictions are evaluated against satellite observations and in situ measurements, in particular those taken at the NCM weather stations (Figure 1d), and by the MWR and attached weather station at Al Farfar, deployed at the site highlighted by a cross in Figure 1b.

4.1 | Convection and associated circulation

Figure 9 shows the outgoing long-wave radiation (OLR) from the 2.5 km grid (domain no.3), for the same time the satellite-derived IRBT is given in Figure 4, for the simulations initialized with GFS, CFSR, ERA-5 and ERA-Interim data.

While WRF largely captures the convection that occurred in the Al Hajar mountains in the afternoon of 5 September, a comparison with Figure 4 reveals that the convective clouds in the model generally developed further inland, almost reaching the UAE border around Al Ain by 1200 UTC, with weaker convection on the UAE side. The predictions of the GFS and ERA-5 runs are broadly similar, featuring larger-scale and more active convective cells over the region that extend into the UAE, even though here they are displaced to the west with respect to those observed. These simulations are the most realistic, with the convective clouds also advected into coastal Oman and farther into the Gulf of Oman later in the day as in Figure 4. On the other hand, in the ERA-Interim, and in particular in the CFSR, runs, the convective cells are more localized, and take longer to develop. In all simulations the convection over southern parts of Iran and central UAE is much reduced in the model, almost absent in the ERA-Interim run. The latter is more significant in the CFSR run, generally to the west of where it was observed.

The large-scale conditions are given in Figures 10 and 11. The first column shows the WRF output of the GFS simulation. A comparison with Figure 2 reveals that, by and large, the model successfully captures the major features: a trough in the 500 hPa geopotential height over
northeastern UAE, an extension of the midlatitude trough over Iran; a low-level cyclonic circulation to the east of Qatar, stronger in WRF; and low-level wind convergence over the Al Hajarm mountains, aiding the occurrence of convection over northeastern parts of the UAE, and potentially explaining the development of clouds in the region. As is the case with the OLR plots (Figure 9) there are considerable differences between the model runs. For example, in the ERA-Interim simulation, the low-level wind field is very different (please note that the reference arrow used for the wind vector difference is the same as that used for the actual wind in the GFS plots), with mostly westerly to northwesterly winds over the UAE. This arises from a much-increased land–sea temperature gradient (Figure 11) which leads to a more vigorous sea-breeze circulation in a northwest to southeast path, generally parallel to the Al Hajarm mountains. Over the central and western UAE coastline, on the other hand, the sea breeze is weaker, explaining the lack of convective clouds in central UAE (Figure 9). In the ERA-5 and ERA-Interim runs, the 500 hPa trough is deeper and extends further to the east, with lower height values over the majority of the domain. This would have supported enhanced convection in both simulations, which is not true in the ERA-Interim run: as seen in Figure 9, the convective cells have a smaller spatial extent in this run. This can be explained by the very different low-level wind flow, as discussed above, and highlights that just the presence of a trough at mid-levels does not guarantee the occurrence of convection. The fact that the air over the Gulf of Oman is colder in the ERA-5 run with respect to the ERA-Interim (and GFS) simulation (Figure 11), leads to a locally enhanced sea-breeze circulation which, together with the deeper mid-level trough, may explain the more active convection in the Al Hajarm mountains. The sea-breeze over the UAE in the CFSR simulation is more active than that in the GFS run over...
northern and western parts but not over central areas, which leads to enhanced low-level wind convergence over central UAE and may explain the more active convection in the region seen in Figure 9. An inspection of Figure 11 reveals that in the CFSR, ERA-5 and ERA-Interim runs, and with respect to the GFS one, the 2 m air temperature is generally lower over the Arabian Gulf, which can be attributed to the colder SSTs (not shown). The surface skin temperature over land is generally warmer in the CFSR and ERA-5 simulations, in the former mostly over Oman, while in the ERA-Interim simulation it is colder than that of the GFS except around Abu Dhabi (not shown). These results are in line with the soil moisture differences (Figure S2). As highlighted in Temimi et al. (2020b), a drier soil will have a lower thermal inertia, meaning that it will warm up more during daytime and cool down more at night, i.e. it will respond faster to the solar forcing. While some of the referred anomalies in surface skin temperature are seen in the 2 m temperature presented in Figure 11, others are not: for example, in the ERA-Interim simulation the air temperature is generally warmer than that of the GFS run except over parts of western UAE. This is not surprising as other factors are at play, such as the strong near-surface winds and subsequent role of advection compared to the other runs. The fact that the soil conditions have an appreciable impact on the sea-breeze circulation and occurrence of convection has been reported by several authors (Gantner and Kalthoff, 2010; Mao et al., 2016). Finally, it is interesting to note the sudden change in the sign of the 2 m differences, from positive to negative, with respect to the GFS simulation from 1200 to 1400 UTC, in particular in the CFSR and ERA-5 simulations (Figure 11)
Outgoing long-wave radiation (W·m$^{-2}$) on 5 September 2017 from 1000 to 1400 UTC every 2 hr from the 2.5 km WRF grid for the simulation forced with (a–c) GFS, (d–f) CFSR, (g–i) ERA-5, and (j–l) ERA-Interim data. The cross highlights the approximate location of Al Farfar, where the MWR was deployed.

and in southern and eastern parts of the UAE. This can be explained by (a) an increase in temperature in the GFS simulation, likely due to the advection of hot desert air by the southeasterly winds ahead of the daytime sea breeze (Figure 3), (b) a more moist soil in the CFSR and ERA-5 experiments (Figure S2), and (c) a drier near-surface atmosphere in comparison to the GFS simulation (not shown). In addition, the fact that the local sunset at this time of the year is around 1430 UTC (1830 LT), may also contribute to the referred-to temperature change.

4.2 | Model evaluation against in situ measurements

Figure 12 shows hourly near-surface fields at the three NCM stations discussed in Figure 6 on 5 September 2017. Shown are the observed and WRF-predicted fields for the four simulations, with the verification diagnostics given in Table 4.

Despite the fact that even at 0.8333 km resolution the complex topography of the Al Hajar mountains is not fully simulated, WRF generally captures the observed wind speed and relative humidity (RH) variability at Hatta, in particular the stronger winds around sunrise and in the afternoon, and the decrease in RH in the afternoon hours. However, it generally overestimates the short-wave radiation flux, a sign that it fails to simulate the observed cloud cover. This is in line with other WRF studies over the UAE (Wehbe et al., 2019; Fonseca et al., 2020), and may explain the colder night-time temperatures in all experiments. What is more, it takes longer for the near-surface atmosphere to warm up in the model during morning and early afternoon hours. This is particularly
true in the GFS and ERA-5 runs, which forecast more moist air over the region in particular early in the day, in line with a more onshore (easterly) wind direction, slowing down the rate of warming. In addition, the wind speeds around 0200–0300 UTC (0600–0700 LT), just after local sunrise, in these simulations are 5–6 m s\(^{-1}\) higher compared to the CFSR and ERA-Interim runs, with the associated increased vertical mixing making it harder for the atmosphere to warm up. The same is true in the ERA-Interim simulation at 0600 UTC, when the wind speed suddenly increases from 1 to 5 m s\(^{-1}\). WRF simulations over arid/hyperarid regions reported an underprediction of the night-time temperatures (Chaouch et al., 2017; Weston et al., 2018; Fekih and Mohamed, 2019; Fonseca et al., 2020; Schwitalla et al., 2020; Temimi et al., 2020b). This has been attributed to (a) deficiencies in the LSM and/or PBL scheme, and (b) an incorrect representation of surface properties, and atmospheric greenhouse and dust concentrations and cloud cover. The most notable bias at Masafi is the absence of the cold pool signatures discussed before (Figure 6): a sudden drop in air temperature and downward short-wave radiation flux, an increase in wind speed and sudden shift in its direction, and the MH in the pressure data. However, if the GFS simulation is repeated with a doubling of the soil moisture over all land points, the referred-to features are simulated by the model (Figure S3). As at Hatta, WRF has a tendency to overestimate the strength of the near-surface wind, but
the biases at this station are even more pronounced. The stronger winds in the model have been noted by Fonseca et al. (2020), Nelli et al. (2020b), Schwitalla et al. (2020), and Temimi et al. (2020b), and may be explained by a poor representation of its subgrid-scale fluctuations, likely more significant over complex terrain as is the case at the Al Hajar mountains, and/or of the surface drag parametrization. As at Hatta, WRF does not capture the observed cloud cover, is colder at night and takes longer to warm up in the morning, in particular in the GFS runs. In this simulation, the prevailing onshore (easterly) winds also lead to more moist air and slow down further the rate of warming. The last station shown is Fujairah, located on the east coast just off the Gulf of Oman, and for which the downward short-wave radiation is not available. The model forecasts at this station are more skilful than those at Hatta and Masafi, with temperature biases mostly within 2 °C, the observed and modelled RH generally within ±10 degC, and the wind speeds within ±2 m·s⁻¹. This is expected, as WRF is known to have a worse performance over the high terrain, as shown for example, in Fonseca et al. (2020) and Temimi et al. (2020b). The fact that Fujairah is a coastal station also explains the reduced diurnal variability in particular of air temperature, which is mostly in the range 30–35 °C. By and large, no WRF simulation clearly outperforms another. This can be seen in Table 4, where the verification diagnostics are given. Except for the horizontal wind vector and for the ERA-Interim run, α < 1, indicating that the model predictions can be considered useful. The temperature biases reflect the significant colder atmosphere mostly in the mountainous stations, whereas the overestimation of the strength of the wind is seen in all simulations, in line with Fonseca et al. (2020) and Nelli et al. (2020b). While the diurnal cycle of the downward short-wave radiation flux is well captured by WRF, as indicated by the rather high values of ρ and η.
and low values of $\alpha$, its magnitude is overestimated, as noted by Wehbe et al. (2019) and Fonseca et al. (2020), by roughly 65–70 W m$^{-2}$. Even though no configuration consistently gives the highest scores, the GFS simulation gives the lowest $\alpha$ scores for RH, horizontal wind and the radiation flux, and the second lowest for the pressure and air temperature fields. Using the output of the 2.5 km model grid for Hatta and Masafi would have led to similar results, that is, the higher spatial resolution (0.8333 km), and at least for the WRF configuration considered here, does not provide added value to the model forecasts (not shown).

Although WRF does not capture the observed convective system on 5 September at Al Farfar site, Figure 7, when forced with GFS data, it simulates a weaker one on 6 September at about 1200 UTC, roughly 3 hr later than in observations when the measurements are interrupted. If the soil moisture is doubled in this run, the MCS signatures on 6 September are even more pronounced (Figure S4), highlighting its important role in arid/semi-arid regions. The inability of the model to successfully simulate the observed MCSs is not unprecedented: for example, Kalinin et al. (2017) ran WRF at a convective-permitting resolution over the Urals targeting 23 MCSs, and concluded that in nine of the 23 cases the model either did not capture the feature or simulated it in a considerably different location. The authors attributed this to errors in the Climate Forecast System (CFS) reanalysis data used to drive the model. This finding is supported by the results presented in Figure 7. In addition, deficiencies in the physics parametrization schemes and/or a non-optimal representation of the local topography and surface properties, such
TABLE 4 Verification diagnostics (namely model bias, correlation, $\rho$, variance similarity, $\eta$, and normalized error variance, $\alpha$) for air temperature, relative humidity, sea-level pressure, horizontal wind vector, and surface downward short-wave radiation flux for a time-series of the stations Hatta (station no. 1 in Figure 1d), Masafi (station no. 2) and Fujairah (station no. 3), as given in Figure 12

| Variables                              | Diagnostics | GFS   | CFSR  | ERA-5  | ERA-Int |
|----------------------------------------|-------------|-------|-------|--------|---------|
| Air temperature                        | BIAS (K)    | −1.237| −3.005| −2.983 | −1.800  |
|                                        | $\rho$      | 0.599 | 0.615 | 0.488  | 0.575   |
|                                        | $\eta$      | 0.999 | 0.980 | 0.982  | 0.989   |
|                                        | $\alpha$    | 0.402 | 0.398 | 0.512  | 0.431   |
| Relative humidity                      | BIAS (%)    | −4.326| −9.086| 1.840  | −3.522  |
|                                        | $\rho$      | 0.471 | 0.366 | 0.406  | −0.019  |
|                                        | $\eta$      | 0.979 | 0.999 | 0.996  | ~1      |
|                                        | $\alpha$    | 0.539 | 0.634 | 0.596  | 1.019   |
| Sea-level pressure                     | BIAS (hPa)  | 0.895 | 1.173 | 0.840  | −0.083  |
|                                        | $\rho$      | 0.321 | 0.304 | 0.396  | 0.213   |
|                                        | $\eta$      | 0.993 | 0.978 | 0.994  | 0.958   |
|                                        | $\alpha$    | 0.682 | 0.703 | 0.606  | 0.796   |
| Horizontal wind vector                 | BIAS (speed; m·s$^{-1}$) | 0.538 | 0.528 | 1.812  | 0.816   |
|                                        | $\rho$      | 0.232 | 0.034 | 0.031  | −0.017  |
|                                        | $\eta$      | 0.347 | 0.367 | 0.344  | 0.325   |
|                                        | $\alpha$    | 0.919 | 0.987 | 0.989  | 1.006   |
| Surface downward short-wave radiation flux | BIAS (W·m$^{-2}$) | 66.414| 69.377| 66.801 | 70.988  |
|                                        | $\rho$      | 0.925 | 0.925 | 0.925  | 0.926   |
|                                        | $\eta$      | 0.992 | 0.991 | 0.992  | 0.990   |
|                                        | $\alpha$    | 0.082 | 0.084 | 0.083  | 0.083   |

as the soil moisture as noted in Figure S4, may also explain the poor WRF performance. This highlights the need to improve the model physics for present and future weather and climate simulations in arid/hyperarid regions.

Fog is predicted by WRF in the early hours of 5 September in the ERA-5 and GFS, and on 6 September in the ERA-5 and ERA-Interim runs. This is further confirmed by the vertical temperature profiles given in Figure 8, which show a persistent low-level temperature inversion. An inspection of the lapse rates just above the surface revealed magnitudes in excess of 30 K·km$^{-1}$, required for the development of fog in the region (Temimi et al., 2020a). The subsequent rapid warming and drying of the near-surface atmosphere suggests the absence of clouds, with the cooling that follows likely associated with increased vertical mixing (note the strengthening of the 10 m wind). The colder temperatures in ERA-Interim in the morning of 6 September can be attributed to the longer duration of the fog event and subsequent slower warm-up.

Despite not simulating the high-frequency variability of the horizontal wind vector on 5 September, the model-predicted wind is mostly easterly as in the observations, with the shift to southwesterlies on 6 September not forecasted by WRF. The persistent onshore winds from late on 5 September to 6 September are consistent with the higher amounts of water vapour mixing ratio in the model. What is more, WRF largely overestimates the strength of the near-surface wind for most of the 2-day period, as is found to be the case mostly at Massafi (Figure 12), a station also located on the Al Hajar mountains. This suggests that the stronger winds in the model are most probably due to an incorrect representation of the surface topography and associated roughness in this area (Nelli et al., 2020b; Temimi et al., 2020b).

As concluded in the analysis of the NCM station data, and as seen in Table 5, no WRF simulation clearly outperforms another, even though the GFS run has the edge as it generally gives the best scores according to all the diagnostics considered, except for air temperature. For this field and for the GFS run, a warm temperature bias is largely present from around 1500 UTC on 5 September to 0900 UTC on 6 September, and can be attributed to a drier environment, a more southerly (offshore) wind direction on 5 September, and weaker wind speeds on 6 September. The ERA-Interim simulation, on the other hand, yields the worst scores. What is more, the GFS run is the only simulation where the model predicts an MCS over the site on 6 September 2017, despite the fact that the timing does
not match that observed. If instead of the 0.8333 km model forecasts, the output of the 2.5 km grid was used for the evaluation in Figure 7, similar conclusions would have been reached (not shown). As noted in the previous subsection, and at least for the WRF set-up employed here, increasing the horizontal resolution to a 0.8333 km grid does not seem to have an impact on the performance of the model. By and large, the skill scores for Al Farfar are poorer than those obtained for the three NCM weather stations (Hatta, Masafi and Fujairah) given in Table 4, with $\alpha > 1$ for all runs for the air temperature and horizontal wind vector. A possible explanation is that this site is deeper into the Al Hajar mountains (Figure 1b), surrounded by very rough terrain (Figure 1c), which makes the simulation of the near-surface weather conditions more challenging. In addition, the fact that the temporal resolution of the data used here is 5 min and not hourly as in Figure 11 is also a factor, as the model will likely not be able to simulate the higher-frequency variability in the weather variables.

The observed and model-predicted temperature vertical profiles at the location of the MWR are given in Figure 8. The model bias is presented in Figure S5. The corresponding potential temperature profiles are provided in Figures S6 and S7. As is the case for the weather station data discussed in the previous paragraph, the gaps in the data coverage are due to electric-related problems.

The observed clouds, and the depth of the night-time temperature inversion are not captured by WRF, which predicts a surface-based inversion between 0000 and 0400–0600 UTC on 5 September in the GFS and ERA-5, and around 0000 UTC on 6 September in particular in the ERA-5 and ERA-Interim simulations. On 5 September in the ERA-Interim and on 6 September in the GFS runs, however, the aforementioned inversion did not last as long and was generally weaker, precluding the formation of fog.

As the atmosphere is clearer in the model the near-surface air will be hotter, with a generally warmer profile when compared to the MWR. This can be seen in the difference plots given in Figure S5. The positive model biases, in particular for heights above 3–4 km, may also be explained by the uncertainty in the observed measurements (Temimi et al., 2020a). There are two exceptions, however. One is on 5 September between 0600 and 1000 UTC, which can be explained by a more moist atmosphere in the GFS, ERA-5 and ERA-Interim simulations, with fog predicted during the early part of the period in the first two (Figure 7b) where the cold anomaly is also more pronounced. In the CFSR run, an increase in the strength of the low-level wind may explain the referred-to cold anomaly, which has a smaller amplitude. The other period is just before the observed data stops on 6 September. This is also seen in Figure 7, and has been attributed to the advection of more moist air from the Gulf of Oman, as it is accompanied by an increase in the water vapour mixing ratio and horizontal wind speed. The MCS predicted by the model in the GFS simulation around 1200 UTC occurs outside the window when observational data are available.

5 | DISCUSSION AND CONCLUSIONS

In this work, the atmospheric conditions from synoptic to local-scale that favoured the development of summer-time convection over the Al Hajar mountains are investigated using high-resolution model simulations, in situ and satellite-derived observational data, and ERA-5 reanalysis data. The occurrence of convection over this region has important implications for the much-needed water resources as well as for cloud-seeding activities that are regularly conducted in the area.

The convection over the mountains was triggered by the convergence of the moisture-rich daytime sea breeze from the Arabian Gulf and Gulf of Oman, driven by land–sea temperature gradients in some regions in excess of 10 °C, with southeasterly winds blowing from the Arabian Sea, which reinforced the local upslope circulations. Further promoting the event was the presence of a trough at 500 hPa over northeastern UAE, an extension of a mid-latitude trough over Iran. An analysis of 5 min data from a weather station located on the mountains revealed the main features of the passage of the cold pool emanating from an MCS: a rise (“meso-high”) in the surface pressure, by roughly 4 hPa; an increase in the strength of the wind, from below 1 m s$^{-1}$ to a maximum of 9 m s$^{-1}$ in about 1 hr; a shift in the wind direction from easterly to southerly and then to westerly in about 45 min; a drop in air temperature of 7 °C in just 15 min, from roughly 34 to 27 °C; and a significant reduction in the downward short-wave radiation at the surface, the largest drop of about 755 W m$^{-2}$ in just 15 min, with the minimum occurring at about the same time as the minimum in IRBT, which dropped below the 240 K threshold used to identify an MCS. At another site on the mountains, where an MWR was deployed for a field campaign, the 5 min surface pressure data exhibited the “pre-squall low” and “wake low” signatures of an MCS, in addition to the “meso-high”, not just on 5 September but also on 6 September. The overall 4 hPa fluctuation in the surface pressure in a 2 hr period is accompanied by a 5 °C drop in air temperature in 1 hr, a 40% drop in relative humidity in ~2 hr, and a 5 m s$^{-1}$ increase in the wind speed in 5 min. These signatures are consistent with those reported at other sites in the passage of an MCS (e.g. Cohuet et al., 2011), and the magnitudes are generally comparable to those seen in the Tropics and subtropics (Flamant et al., 2007; Engerer et al., 2008).
To further investigate the event, the WRF model was run in a four-nest configuration, with a 2.5 km grid comprising the region where convective clouds developed, and a 0.8333 km convective-permitting nest over the mountains. The model was set up following Schwitalla et al. (2020), who tested different configurations for a previous summertime convective event in the UAE. An analysis of the WRF predictions revealed that those given by the innermost grid were generally comparable to those generated by the 2.5 km nest, indicating that adding a fourth grid, and at least for the set-up considered here, did not add much value to the model forecasts. In order to investigate the sensitivity to the forcing data, four datasets were considered: GFS, CFSR, ERA-5 and ERA-Interim. WRF predicted widespread convection over the Al Hajar mountains in all simulations, even though in the model convection developed further inland than in observations, taking longer to flare up in the CFSR and ERA-Interim runs. Substantial differences were also noted in the synoptic-scale circulation. For example, and when compared to the GFS simulation, the near-surface air is generally cooler over the Arabian Gulf in the CFSR, ERA-5 and ERA-Interim runs, as a result of lower SSTs, while the land is warmer during daytime, possibly because of a drier soil. This will naturally lead to a more vigorous sea-breeze circulation, which will modulate the occurrence of convection. It highlights the need to properly represent the soil properties in arid/hyperarid regions for a correct simulation of the afternoon/evening convection. In the ERA-Interim run, on the other hand, the soil is generally more moist, but the near-surface wind field is very different, with a strong onshore flow over most of the UAE.

An evaluation against in situ measurements at individual weather stations revealed a tendency of WRF to underestimate the observed cloud cover. Consistent with the lack of clouds, the air temperature in the model at night is lower than the observed, likely arising from enhanced radiative cooling, as found to be the case by Fekih and Mohamed (2019) over Algeria, and by Weston et al. (2018) and Schwitalla et al. (2020) over the UAE. The near-surface wind speed is generally stronger in WRF, which can be attributed to a poor representation of its subgrid-scale

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**Table 5** Verification diagnostics (namely model bias, correlation, \(\rho\), variance similarity, \(\eta\), and normalized error variance, \(\alpha\)) for air temperature, relative humidity, surface pressure, water vapour mixing ratio and horizontal wind vector, for the Al Farfar station as given in Figure 7

| Variables                  | Diagnostics | GFS  | CFSR | ERA-5 | ERA-INT |
|----------------------------|-------------|------|------|-------|---------|
| Air temperature            | BIAS (K)    | 2.840| 1.170| 0.667 | 1.457   |
|                           | \(\rho\)    | -0.110| -0.105| -0.052| -0.187  |
|                           | \(\eta\)    | ~1   | 0.997| 0.991 | 0.954   |
|                           | \(\alpha\)  | 1.110| 1.104| 1.051 | 1.178   |
| Relative humidity          | BIAS (%)    | 4.906| -5.955| 10.718| 22.255  |
|                           | \(\rho\)    | 0.400| 0.135| 0.272 | -0.058  |
|                           | \(\eta\)    | 0.935| 0.967| 0.921 | 0.981   |
|                           | \(\alpha\)  | 0.626| 0.870| 0.750 | 1.057   |
| Surface pressure           | BIAS (hPa)  | -2.609| -2.511| -2.731| -3.438  |
|                           | \(\rho\)    | 0.925| 0.917| 0.908 | 0.920   |
|                           | \(\eta\)    | 0.994| 0.989| 0.982 | 0.963   |
|                           | \(\alpha\)  | 0.080| 0.093| 0.108 | 0.114   |
| Water vapour mixing ratio  | BIAS (g·kg\(^{-1}\)) | -1.515| -5.067| -1.489| 1.949   |
|                           | \(\rho\)    | 0.475| 0.225| 0.179 | -0.027  |
|                           | \(\eta\)    | 0.996| 0.864| 0.997 | 0.972   |
|                           | \(\alpha\)  | 0.527| 0.806| 0.822 | 1.026   |
| Horizontal wind vector     | BIAS (speed; m·s\(^{-1}\)) | 2.868| 3.351| 3.702 | 3.817   |
|                           | \(\rho\)    | -0.022| -0.118| -0.021| -0.141  |
|                           | \(\eta\)    | 0.288| 0.302| 0.270 | 0.294   |
|                           | \(\alpha\)  | 1.006| 1.036| 1.006 | 1.041   |
fluctuations and/or of the surface drag parametrization (e.g. Nelli et al., 2020b; Temimi et al., 2020b). Overall, no WRF simulation clearly outperformed another, at least for the model set-up considered here, even though the GFS run generally gave slightly higher scores. In addition to the weather stations, the model performance is also assessed against the 5 min near-surface observations and vertical temperature profiles given by an MWR deployed on the mountains for a field campaign. The measurements indicate the passage of two MCSs, one just after 1200 UTC on 5 September and another after 0900 UTC on 6 September. The MCS signatures seen here are in line with those reported earlier, and with the findings of Houze (1989; 2004). WRF does not capture the first event but, when forced with GFS data, simulates a weaker MCS on 6 September around 1200 UTC, roughly 3 hr later than in observations. If the soil moisture is doubled in the GFS run, the MCS signatures on 6 September are even more pronounced, further stressing its role in this arid region, as highlighted for example, by Kalinin et al. (2017) and Wehbe et al. (2019). As at the weather stations, WRF underestimates the observed cloud cover, with the sharper night-time surface-based inversions leading to the occurrence of fog in the early hours of 5 September in the GFS and ERA-5 simulations, and overnight on 6 September in the ERA-5 and ERA-Interim runs.

The fact that the MCS, and its impacts on the atmospheric state, are not accounted for in the simulations has important implications for the use of the current state-of-the-art models and physics parametrizations for climate projections in arid/hyperarid regions. The findings of this work help to better clarify the mechanisms behind the convective events, and understand the signatures of an MCS in particular on surface/near-surface weather variables. An extension of this study would include additional events in order to assess the robustness of the findings, as well as employing data assimilation, which may improve the model’s performance.

ACKNOWLEDGEMENTS
This work is supported by the National Center of Meteorology (NCM), Abu Dhabi, UAE, under the UAE Research Program for Rain Enhancement Science (UAEREP). The authors thank the NCM for providing the weather station observations, under an agreement with clauses for non-disclosure of data. Access to these data is restricted and readers should request them through contacting research@ncms.ae. We wish to acknowledge the contribution of Khalifa University’s high-performance computing and research computing facilities to the results of this research. We would also like to thank three anonymous reviewers for their detailed and insightful comments and suggestions that helped to significantly improve the quality of the article.

CONFLICT OF INTEREST
The authors declare that they have no competing interests.

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**How to cite this article:** Francis D, Temimi M, Fonseca R, et al. On the analysis of a summertime convective event in a hyperarid environment. *Q J R Meteorol Soc*. 2021;147:501–525. https://doi.org/10.1002/qj.3930