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Impact of Arabian Sea warming on trough dynamics and flooding intensification over the Dubai flood 2024

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सार – पूर्वानुमान क्षमताओं को बेहतर बनाने और जान-माल के जोखिम को कम करने के लिए अतिविषम जलवायु को समझना बेहद ज़रूरी है। 16 अप्रैल 2024 को, संयुक्त अरब अमीरात के शुष्क रेगिस्तानी शहर दुबई में 24 घंटों में लगभग 250 मिमी की अभूतपूर्व अत्यधिक वर्षा हुई। अचानक हुई इस अत्यधिक वर्षा से पूरे शहर में बाढ़ आ गई, जिससे बुनियादी ढाँचे, परिवहन, जल प्रणालियाँ और सामाजिक-आर्थिक गतिविधियाँ प्रभावित हुईं। इन व्यवधानों में, दुनिया के सबसे व्यस्त हवाई अड्डों में से एक, दुबई अंतर्राष्ट्रीय हवाई अड्डे पर अत्यधिक वर्षा के कारण काफ़ी देरी हुई और लगभग तीन दिनों तक उड़ानें बाधित रहीं। यह अध्ययन इस घटना के लिए ज़िम्मेदार वायुमंडलीय परिस्थितियों की जाँच करता है, और बड़े पैमाने पर और संक्षिप्त पैमाने पर, दोनों ही कारकों पर ध्यान केंद्रित करता है, साथ ही क्षेत्रीय महासागरीय परिस्थितियों, विशेष रूप से अरब सागर के शुष्क होने के प्रभाव पर भी। निष्कर्षों से पता चलता है कि यह संवहनीय घटना अरब सागर, लाल सागर और फारस की खाड़ी से आने वाले प्रबल निम्न-स्तरीय अभिसरण और असामान्य नमी परिवहन के कारण हुई थी। अरब सागर में समुद्र की सतह के तापमान में वृद्धि (सामान्य से 1.2 डिग्री सेल्सियस अधिक) ने निचले से मध्य वायुमंडलीय नमी को बढ़ाने में योगदान दिया है। निचले क्षोभमंडल में एक गंभीर चक्रवाती परिसंचरण विसंगति और 200 hPa पर भू-संभावित ऊँचाई से ऊपरी स्तर के प्रतिचक्रवाती और चक्रवाती पैटर्न द्वारा निर्मित एक उल्लेखनीय मध्य से ऊपरी स्तर के गर्त के कारण लंबे समय तक ऊर्ध्वाधर पवन कतरनी बनी रही। इन विशेषताओं ने, उन्नत ऊपरी-स्तरीय उपोष्णकटिबंधीय जेट धाराओं के साथ मिलकर, निरंतर संवहनी विकास के लिए गतिशील और ऊष्मागतिकीय दोनों तरह का समर्थन प्रदान किया। क्षोभमंडल में इन वायुमंडलीय प्रक्रियाओं का ऊर्ध्वाधर संरेखण गहरे बादलों के निर्माण और तीव्र वर्षा के लिए आधार तैयार करता है। कुल मिलाकर, यह अध्ययन अरब प्रायद्वीप पर प्रचण्ड मौसम की घटनाओं को प्रेरित करने में महासागर-वायुमंडलीय अंतःक्रियाओं, विशेष रूप से अरब सागर के शुष्क होने के संयुक्त प्रभाव पर प्रकाश डालता है।

ABSTRACT. Understanding climate extremes is vital for enhancing forecasting capabilities and minimizing the risk to lives and property. On 16 April 2024, the arid desert city Dubai in the United Arab Emirates witnessed an unprecedented extreme rainfall of ~250 mm of precipitation in 24hrs. The sudden downpour triggered extensive flooding throughout the city, impacting infrastructure, transportation, water systems, and socio-economic activities. Among the disruptions, Dubai International Airport, one of the world's busiest, experienced significant delays and flight operations persisted around the three-day period due to the heavy rainfall. This study investigates the atmospheric conditions responsible for this event, focusing on both large-scale and synoptic-scale drivers, as well as the influence of regional oceanic conditions, particularly the warming of the Arabian Sea. Findings reveal that the convective event was driven by strong low-level convergence and anomalous moisture transport from the Arabian Sea, Red Sea, and Persian Gulf. Warmer sea surface temperatures (>1.2 °C above normal) in the Arabian Sea have contributed to increasing lower-to-middle atmospheric moisture. Prolonged vertical wind shear was sustained by a severe cyclonic circulation anomaly in the lower troposphere and a notable mid to upper level troughs also created by the upper level anticyclonic and cyclonic patterns from the geopotential height at 200 hPa. These features, combined with enhanced upper-level subtropical jet streams, provided both dynamic and thermodynamic support for sustained convective development. The vertical alignment of these atmospheric processes throughout the troposphere sets the stage for deep cloud formation and intense rainfall. Overall, this study highlights the combined influence of ocean-atmosphere interactions, particularly Arabian Sea warming, in driving extreme weather events over the Arabian Peninsula.

Key words – Dubai flood, Extreme rainfall, Arabian Sea warming, Ocean-atmosphere interactions.

1. Introduction

In recent decades, the intensity, frequency, and spatial extent of climate extremes have increased globally, primarily due to anthropogenic climate change (IPCC, 2021, 2022; Kulkarni *et al.*, 2020; Vinodhkumar *et al.*, 2024, 2025). Floods, in particular, have emerged as one of the most destructive natural hazards, with profound impacts on infrastructure, economies, and livelihoods. Arid and hyper-arid regions, such as the United Arab Emirates (UAE), are particularly vulnerable to extreme precipitation events due to limited natural drainage, high impervious surface coverage from rapid urbanisation, and infrastructure designed for historically low rainfall levels (Chen *et al.*, 2015; Sharma *et al.*, 2024). In these environments, even moderate precipitation can lead to significant flooding, underscoring the critical need for robust early warning systems and accurate forecasting tools (Paul & Sharif, 2018; Taguchi *et al.*, 2022).

Southwest Asia (SWA; 20°- 40° N, 40°- 70° E) has experienced several high-impact extreme precipitation events that have severely disrupted daily life. For example, on 8 March 2016, an intense extreme weather event in the United Arab Emirates brought destructive winds reaching up to 67 m/s in Abu Dhabi and resulted in over 240 mm of rainfall in Dubai within a few hours (Wehbe *et al.*, 2019). Similarly, on 25 November 2009, the city of Jeddah faced catastrophic flooding triggered by a nearly stationary mesoscale convective system, which dumped more than 180 mm of rainfall in less than eight hours, causing widespread damage and loss of life (Haggag and El-Badry, 2013). Research by Nelli *et al*. (2021) and Rao *et al*. (2024) highlights an increasing trend in extreme rainfall events across the Arabian Peninsula under projected climate change scenarios. These events are anticipated to occur more frequently in the spring season, particularly in March and April, due to enhanced convective systems. Understanding the mechanisms behind such extreme events is essential for improving impact-based forecasting and developing effective adaptation strategies in this increasingly vulnerable region.

On 16 April 2024, Dubai experienced an unprecedented flood event following over 250 mm of rainfall in 24 hours more than twice its annual average precipitation (Aljazeera, 2024). The event followed similar past events, such as the March 2016 flood in the northern UAE, which also brought over 155 mm of rainfall in just a few hours (Wehbe *et al.*, 2019), indicating a potential rise in the frequency and intensity of such events in the region. Although speculation surrounded the role of cloud seeding, official sources confirmed no active missions during the April 2024 event and regional precipitation patterns suggest the dominance of large-scale synoptic processes (Farahat & Abuelgasim, 2022). Although historical records show that the Arabian Sea warmed by approximately 0.5 °C between 1904 and 1994 (Rupakumar *et al.*, 2002), its detailed response to global climate drivers remains inadequately understood. More recent studies, such as Roxy *et al*. (2014), have revealed that the western tropical Indian Ocean (WTIO), which includes the Arabian Sea, has been warming at a significantly faster rate than other parts of the tropical Indian Ocean in recent decades. This accelerated warming in the WTIO has emerged as a major contributor to the overall rise in global mean sea surface temperature (SST). The Arabian Sea, in particular, has exhibited a notable increase in SST, reinforcing regional warming patterns and exerting a considerable influence on broader ocean-atmosphere dynamics across the Indian Ocean basin.

Recent studies point toward significant warming of the Indian Ocean, particularly the Arabian Sea, as a critical factor in modulating regional atmospheric dynamics (Gulakaram *et al.*, 2023; Nekkali *et al.*, 2024). Since the 1990s, the Arabian Sea has warmed by more than 1 °C, with SSTs now exceeding 30 °C. This warming trend, amplified by mesoscale eddies and enhanced surface mixing, alters moisture availability and promotes convective activity over SWA. The unusual SST patterns characterised by warm anomalies near cyclonic eddies have been linked to intensified precipitation and upper-level circulation changes, potentially altering mid-tropospheric trough dynamics and vertical motion conducive to extreme weather. Composite analyses of the April 2024 event indicate strong low-level convergence, an intensified mid-level trough, and the presence of an upper-level subtropical jet stream collectively creating an unstable atmospheric profile over the UAE (Sian *et al.*, 2025). Recent modelling studies, such as Hussein *et al*. (2025), applied a physically-based distributed hydrologic model to the April 2024 Oman-UAE extreme rainfall event. The analysis revealed a low runoff ratio (~7.14%) due to high infiltration, yet severe flooding still occurred in urbanized areas. These findings emphasize the complexity of urban hydrology and the importance of advanced modelling approaches for improving flood prediction and management. These features promoted deep convective development and sustained precipitation, with areas in Dubai recording over 200 mm of rainfall over a few days. This complex interaction between a warming Arabian Sea and regional synoptic circulations suggests a shift in flood-risk profiles for the region, with potentially severe implications for disaster risk management and climate adaptation strategies.

This study aims to explore the extent to which Arabian Sea warming influenced the April 2024 Dubai flood by modulating large-scale atmospheric circulations, particularly through dynamics. The remaining part of the paper is arranged as follows. Section 2 includes data and methodology. Section 3 presents results and discussions. Section 4 presents a summary and conclusion.

1.1. *Area of study*

Dubai, the capital of the Emirate of Dubai, is among the world's fastest-growing urban cities, exerting significant pressure on natural resources, particularly water. This coastal metropolis is experiencing rapid expansion, characterized by extensive development of residential, tourism, and industrial infrastructures (Elhacham & Alpert, 2021; Elgaali *et al.,* 2019). Located in an arid zone of the SWA region, Dubai is subject to substantial variability in both precipitation and temperature (Syed *et al.,* 2019; Elhacham & Alpert, 2021). Approximately 75% of the city's annual rainfall occurs between November and April, while the months from May to October are typically dry. Notably, May and October account for only 4% and 5% of the yearly precipitation, respectively (Abbas, 2024).

2. Data and methodology

This study employs data from the fifth-generation reanalysis dataset provided by the European Centre for Medium-Range Weather Forecasts (ERA5; Hersbach *et al.,* 2020; Sunder *et al.,* 2023). ERA5 offers a globally consistent climate and weather record extending from 1940 to the present, with a horizontal resolution of 0.25° × 0.25° and vertical coverage from the Earth's surface up to 1 hPa. The dataset delivers hourly estimates of numerous atmospheric and land-surface variables, enabling detailed analysis of climatic conditions, including those preceding and during extreme precipitation events. The dataset comprises four principal subsets: hourly and monthly products for both single-level (land surface) and pressure-level (upper atmosphere) data, supporting a broad range of research applications. The reliability of ERA5 in representing observed climate conditions over the study region has been validated.

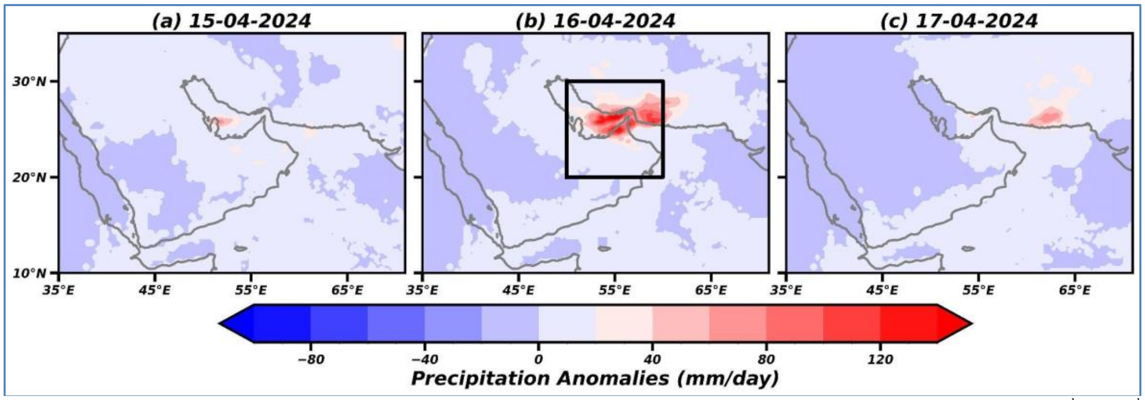
This study makes use of both hourly and daily data from the ERA5 reanalysis. The key variables analyzed at the single level include precipitation, sea level pressure, and sea surface temperature. Additionally, atmospheric variables such as geopotential height, relative humidity, zonal and meridional wind components are examined at multiple pressure levels. The analysis specifically focuses on the 850 hPa, 500 hPa, and 200 hPa levels, representing the lower, middle, and upper troposphere, respectively. These levels are crucial for examining atmospheric stability, moisture transport, and vertical motion. Additionally, vertical cross-sections are analysed from the surface (1000 hPa) up to 150 hPa to comprehensively assess atmospheric dynamics across multiple layers. For this study, we primarily utilized daily anomalies for all meteorological variables, ensuring that short-term fluctuations were appropriately highlighted while removing the influence of long-term climatological trends. An exception was made for precipitation, where hourly anomalies were employed to better capture the fine-scale temporal variability and the inherently intermittent nature of precipitation events. This higher temporal resolution was particularly important for accurately representing convective activity and short-lived precipitation extremes.

3. Results and discussions

3.1. *Rainfall anomalies over Dubai during the flood event*

Extreme rainfall events in arid regions such as Dubai are rare but can have significant socio-economic and environmental impacts when they occur. Understanding the underlying meteorological mechanisms leading to such anomalies is crucial for improving early warning systems and enhancing climate resilience. During the recent flood event, Dubai experienced an unusual spike in daily rainfall, far exceeding the climatological norms for the region (Sian *et al.,* 2025). This section investigates the atmospheric conditions and large-scale circulation patterns associated with the rainfall anomalies observed over Dubai during the flood day, aiming to identify the key drivers and possible teleconnections responsible for the extreme event.

Fig. 1 illustrates daily precipitation anomalies (mm/day) from 15 to 17 April, 2024, relative to the 1980–2023, April climatology, over the Arabian Peninsula and surrounding regions. On 15 April, the region remained largely dry, with below-average precipitation, particularly over central and southern parts of Saudi Arabia (Fig. 1a). On 16 April, a significant positive anomaly event was



Figs. 1(a-c). Spatial distribution of daily anomalies of precipitation (mm/day) over the Arabian Peninsula for the period 15th to 17th April, 2024. The black box highlights the Dubai flood region during the flood day

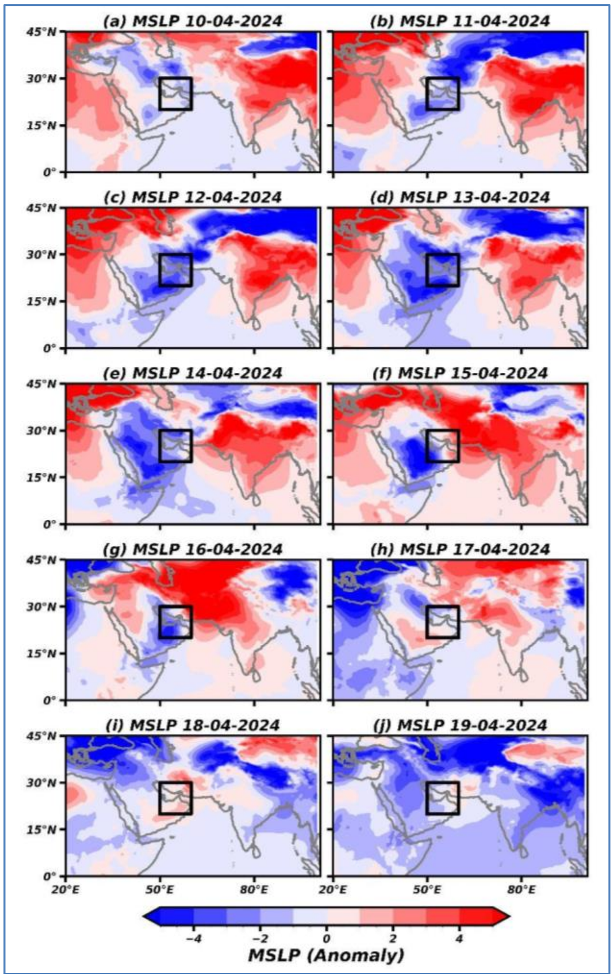
observed over northeastern Saudi Arabia and southern Iraq, where rainfall exceeded the climatological mean by up to more than 140 mm/day (Fig. 1b). On 17 April, rainfall anomalies weakened and became more scattered, with isolated regions of slightly above-average rainfall in eastern Iran and southeastern Iraq (Fig. 1c).

The pronounced increase in rainfall observed on 16 April, 2024, followed by a rapid decline on the subsequent day, suggests a short-lived but high-intensity rainfall observed. This pattern is indicative of a transient large-scale atmospheric disturbance, potentially linked to broader synoptic features such as an upper-level trough, tropical moisture incursion, or enhanced low-level convergence over the region. The spatial concentration and intensity of the anomalies point toward the influence of mesoscale convective systems, but these may have been initiated or intensified by favorable large-scale conditions, such as the interaction between mid-latitude westerlies and tropical easterlies, or the presence of a Trough. Such dynamics can significantly enhance convective development and moisture transport, leading to extreme precipitation and localized flooding, particularly over northeastern Saudi Arabia and southern Iraq.

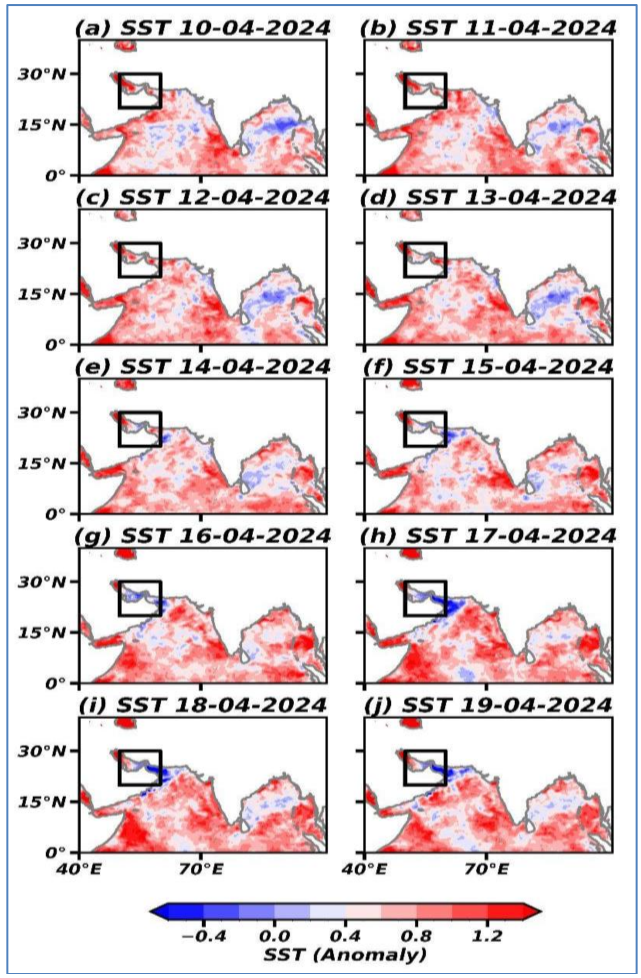
3.2. *Association between sea level pressure and sea surface temperature anomalies during the flood days*

Understanding the interplay between SLP and SST anomalies is essential for diagnosing the large-scale mechanisms that drive extreme weather events. During the flooding over Dubai on 16 April 2024, the atmospheric circulation patterns were strongly influenced by underlying oceanic conditions, particularly in the Arabian Sea and surrounding regions. Variations in SST can significantly impact atmospheric pressure distributions by modulating surface heat fluxes, convection, and moisture availability. In this context, analyzing the concurrent anomalies in SLP and SST during the days surrounding the flood event provides critical insight into the ocean–atmosphere interactions that may have contributed to the development and persistence of the low-pressure system over the Middle East, especially Dubai. This section aims to explore the spatial relationship between SST and SLP anomalies, highlighting their potential role in enhancing moisture transport, intensifying convective activity, and ultimately triggering the extreme rainfall event over Dubai.

Fig. 2 describes the MSLP anomalies during the days leading up to, during, and after the flood event on 16 April 2024, highlighting the synoptic-scale atmospheric features that contributed to the extreme rainfall over Dubai. A deepening low-pressure system was clearly evident over the Middle East, with the center of activity focused around Dubai. A sequence of pronounced negative SLP anomalies was observed from April 12th to 16th, Figs. 2(c-g), with the strongest and most spatially extensive anomaly occurring on the flood day (April 16; Figs. 2g). This anomaly is spatially concentrated and indicative of a high-impact rainfall event, likely driven by a pronounced "pressure squeeze" linked to significant anomalies in MSLP. The presence of an anomalously low MSLP at the surface points to the influence of a mesoscale convective system (Sian *et al.*, 2025). This persistent low-pressure anomaly corresponds to the development of a well-defined upper-level trough, which played a pivotal role in enhancing convective activity and sustaining the heavy precipitation that ultimately resulted in widespread flooding across the region (Mukherjee and Mishra, 2021). In contrast, positive MSLP anomalies dominated the northwestern Arabian Peninsula, the Indian subcontinent, and particularly the northwestern parts of India in the days leading up to the event Figs. 2(a-f). However, this pattern underwent a significant shift after the flood, with the same regions exhibiting negative SLP anomalies between April 17th to 19th Figs. 2(h-j). This reversal in the pressure pattern



Figs. 2(a-j). Spatial distribution of daily anomalies of Mean Sea Level Pressure (MSLP; hPa) over the region spanning 20° E–100° E and 0° N–40° N for the period 10th to 19th April 2024. Panel plots (a) to (j) represent the anomalies for each day, with red (blue) shading indicating positive (negative) MSLP anomalies. The black box highlights the region of Dubai flood region



Figs. 3(a-j). Spatial distribution of daily anomalies of Sea Surface Temperature (SST;°C) over the region spanning 40° E 100° E and 0° N–40° N for the period 10th to 19th April 2024. Panel plots (a) to (j) represent the anomalies for each day, with red (blue) shading indicating positive (negative) MSLP anomalies. The black box highlights the region of Dubai flood region

suggests a dynamically evolving pressure gradient, which likely enhanced moisture convergence and sustained moisture inflow into the Dubai region during the flood event. Over the Arabian Sea, the MSLP fields remained relatively disorganized throughout this period. Yet reanalysis observations indicated the formation of a weather depression that intensified prior to the flood and then rapidly weakened. This evolution may be indicative of a temperature inversion, likely suppressing convection over the Arabian Sea and redirecting moisture transport toward the Middle East.

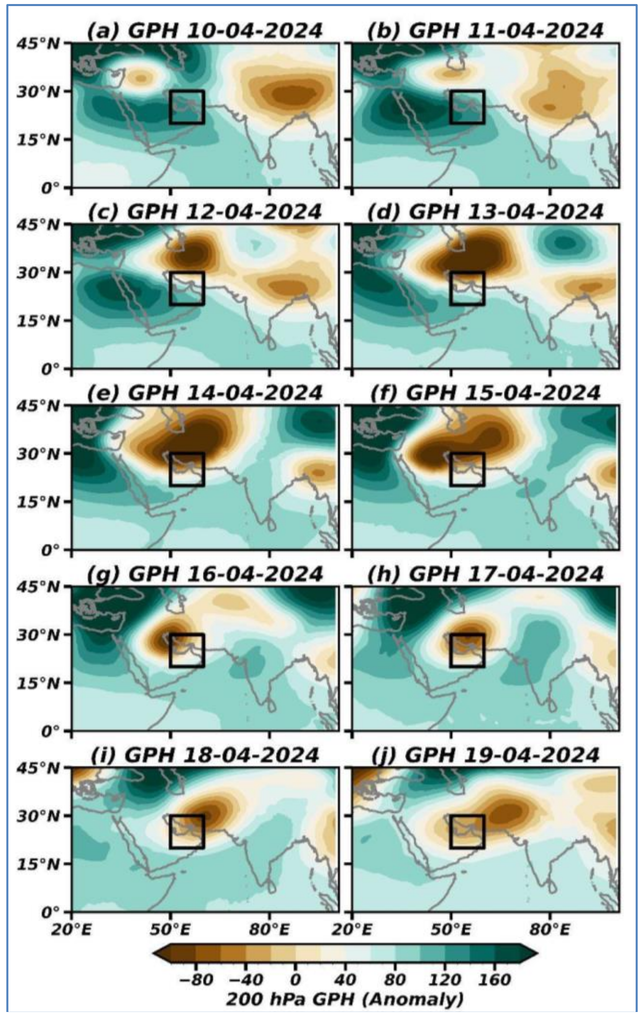
Figs. 3(a-j) presents the spatial distribution of daily SST anomalies from 10-19April, 2024, encompassing the period of the Dubai flood event. The analysis reveals persistent positive SST anomalies across the Arabian Sea, parts of the Red Sea, and the coastal waters near Dubai, with particularly pronounced warming observed from April 12 to 14, coinciding with the days leading up to and during the flood. This sustained anomalous oceanic warming, especially over the central and northern Arabian Sea, is of particular significance, as it likely played a key role in enhancing atmospheric instability and moisture fluxes into the Middle East (Roxy *et al.*, 2014). The elevated SSTs would have contributed to increased latent heat release and enhanced evaporation, providing a continuous source of moisture to the overlying atmosphere. This excess moisture, when coupled with the deepening low-pressure system identified in the MSLP anomalies Figs. 2(a-j), facilitated strong moisture convergence over Dubai and its surrounding regions. The spatial alignment between regions of strong SST warming and regions of negative SLP anomalies suggests a robust air–sea interaction, whereas the Arabian Sea warming actively supported the development and maintenance of the trough-like feature and associated low-pressure circulation over the Middle East.

Following the flood event, SST anomalies exhibited a gradual decline between April 17 & 19, Figs. 3(h–j), likely reflecting the post-event adjustment in ocean–atmosphere dynamics, including reduced surface fluxes and possible upwelling effects.

3.3. *Synoptic and large-scale atmospheric drivers of the Dubai flood event*

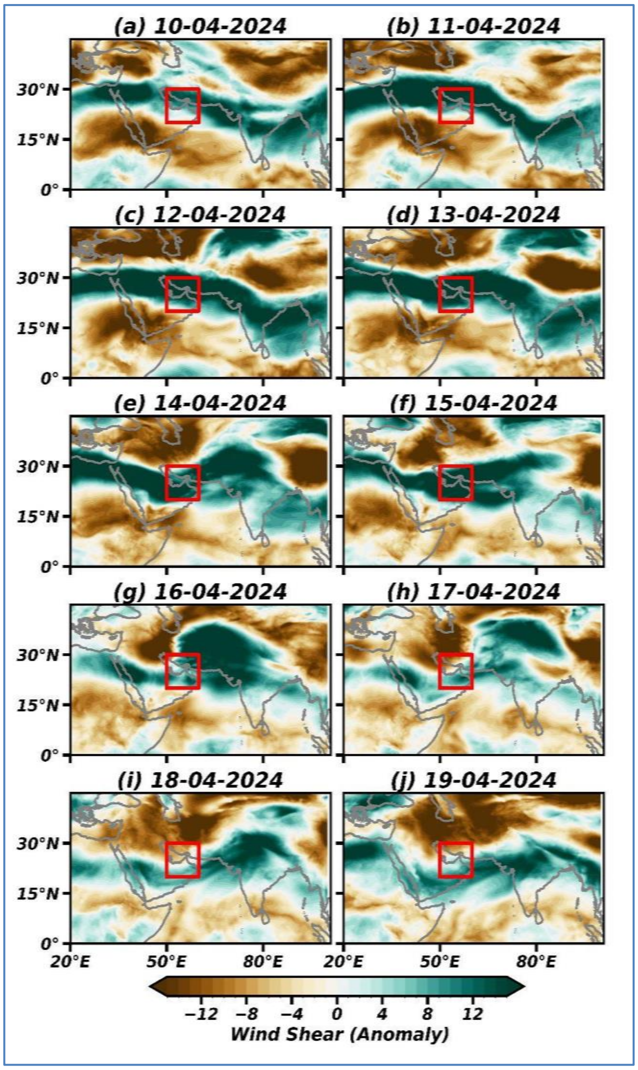
To understand the genesis and intensification of the extreme rainfall event over Dubai on 16 April 2024, it is essential to examine both large-scale circulation patterns and synoptic-scale atmospheric dynamics. This section explores that supported the flood, focusing on upper- and lower-tropospheric processes that contributed to moisture transport, atmospheric instability, and convective development. Key parameters analyzed include the GPH anomalies, which help identify large-scale trough-ridge patterns and upper-level divergence, and wind fields at 850 hPa and 200 hPa, which highlight the influence of low-level convergence and upper-level divergence (Gollapalli *et al.*, 2024; Sripathi *et al.*, 2024), respectively. The vertical wind shear between these levels is also examined, as it plays a crucial role in organizing and sustaining deep convection. Additionally, a vertical cross-section of relative humidity is used to assess the vertical distribution of moisture and identify regions of strong moisture accumulation and transport (Yano and Manzato 2022). Together, these diagnostics provide a comprehensive picture of the multi-scale atmospheric interactions that facilitated the development of the intense low-pressure system, enhanced vertical motion, and ultimately led to the heavy rainfall and flooding over the region.

Fig. 4 shows the daily 200 hPa GPH anomalies from April 10 to April 19, 2024, revealing key upper-tropospheric circulation features that likely influenced the Dubai flood event on April 16, 2024. Notably, a persistent and pronounced upper-level trough developed over the Middle East, evident from the negative GPH anomalies centered around Dubai from April 11 to April 16, Figs. 4(b-g). This anomalous trough pattern, characterized by strong upper-level divergence and cyclonic circulation, provided a favorable environment for enhanced vertical motion and deep convective activity in the region (Francis *et al.,* 2021). The anomaly reached its maximum amplitude between April 13 & April 15, Figs. 4(d-f), with values dipping below -40 m, indicating a well-established trough aloft. On April 16 the flood day, a weakening of the negative anomaly is observed (Fig. 4g), yet it remains sufficiently intense to sustain upper-level divergence, which likely aided in maintaining the deep convection that triggered the extreme rainfall event. In contrast, the days prior to April 11 (Fig 4b) and after April 17 (Fig 4h) show either a weak anomaly or the emergence of positive GPH anomalies, indicating a transition towards a more stable upper-level pattern. The temporal coherence between the deepening trough and the surface low-pressure system (see Fig 2) underscores the baroclinic coupling between upper and lower atmospheric layers that played a crucial role in enhancing vertical instability and sustaining the convective system over Dubai.

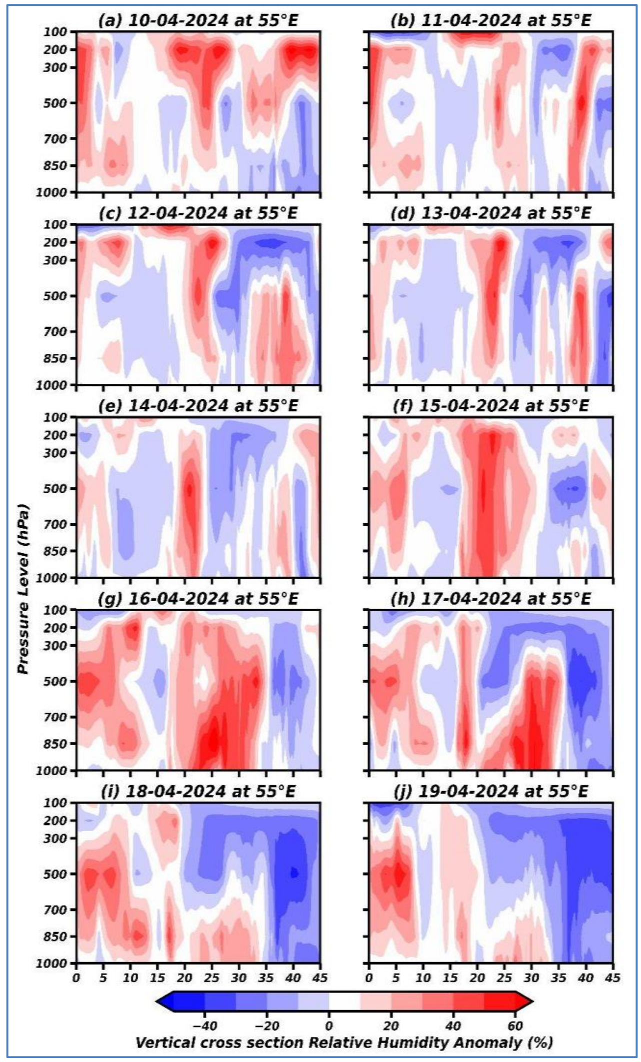


Figs. 4(a-j) Daily 200 hPa geopotential height anomalies (GPH; m) from April 10 to April 19, 2024. A persistent upper-level trough is observed over the Middle East, with pronounced negative anomalies centered over Dubai between April 11 and April 16, aligning with the extreme rainfall event on April 16. The black box highlights the region surrounding Dubai

Figs. 5(a-j) describes the daily vertical wind shear anomalies during the days leading up to and following the Dubai flood on April 16, 2024. A striking feature in the



Figs. 5(a-j). Daily anomalies of vertical wind shear (difference between 200 hPa and 850 hPa wind speed; m/s) from April 10 to April 19, 2024. The red box highlights the Dubai region



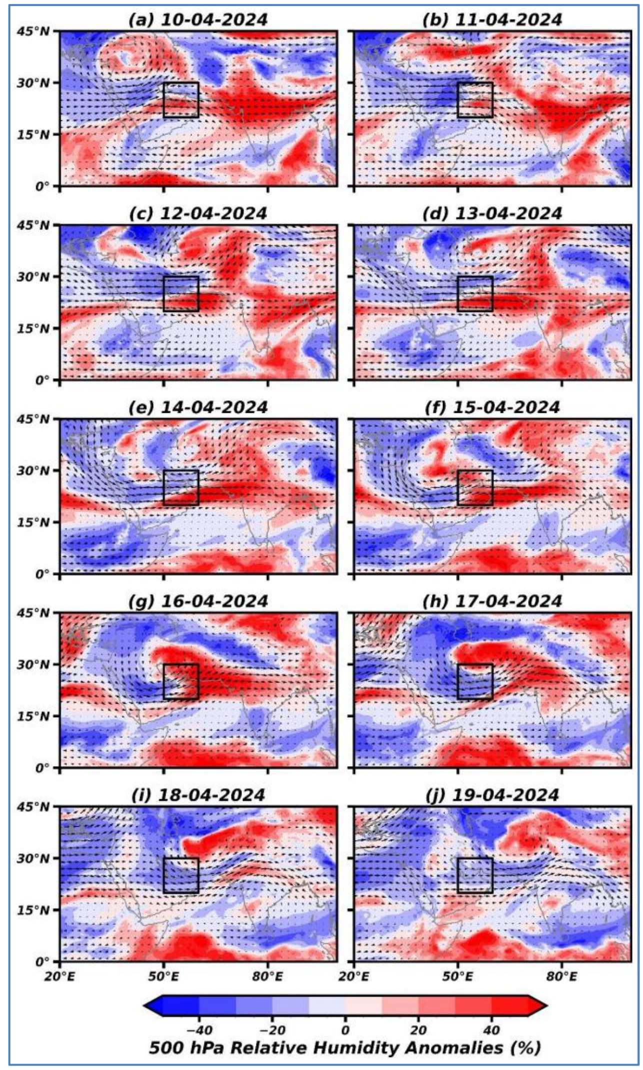
Figs. 6(a-j). Daily vertical cross-section of relative humidity anomalies (%) averaged at 55°E from April 10 to 19, 2024. Positive (red) anomalies indicate moistening, while negative (blue) anomalies signify drying relative to the climatological mean.

days preceding the flood, especially from 12-16, April Figs. 5(c-g), are the pronounced positive wind shear anomalies over the Arabian Peninsula, with a particular intensification centered over the UAE region. This elevated shear suggests a strong vertical gradient in wind velocity, indicative of dynamically unstable atmospheric conditions. High vertical wind shear is known to enhance convective system organization by supporting updraft tilting and separation of precipitation from the convective core, thereby allowing convective systems to sustain for longer durations and become more intense. This type of scenario was clearly observed and this shear supported to enhance the flood during April 16 (Fig. 5g).

The maximum shear anomaly is observed on April 16 (Fig. 5g), the day of the flood, implying an environment conducive to vigorous vertical development of clouds and severe convective activity. In the days following the flood (April, 17-19), a noticeable weakening of the wind shear anomaly is observed Figs. 5(h-j), reflecting a gradual stabilization of the upper and lower tropospheric flow fields. These observations support the notion that the extreme rainfall and associated flooding in Dubai were facilitated by a transient but intense period of enhanced vertical wind shear, which aligned with the presence of upper-level divergence and lower-tropospheric convergence (Al-Nassar *et al.,* 2020). Together, these conditions promoted deep convection and sustained precipitation over the region.

The vertical cross-section of relative humidity anomalies at 55° E Figs. 6(a-j) reveals critical insights into the moisture structure of the atmosphere during the Dubai flood event. Leading up to April 16, 2024, the day of the extreme rainfall was a notable moistening trend that can be observed through the mid and upper troposphere (Fig. 6). From April 12 to April 16 Figs. 6(c-g), there is a marked presence of positive humidity anomalies, especially in the 300-600 hPa layer, indicating enhanced mid-tropospheric moisture convergence. This moistening in the free troposphere provides a conducive thermodynamic environment for deep convection and sustained rainfall. On April 16 (Figs. 6g), the anomaly reached its peak, with significant moistening observed from 700 hPa up to 200 hPa, coinciding with the day of maximum precipitation in Dubai. It is linked with the vertical wind shear also from Fig. 5g. In contrast, the days following the flood event (April 17-19; Figs. 6(h-j) display a reversal of this trend, with widespread negative relative humidity anomalies across most vertical layers. This indicates post-event atmospheric stabilization and drying, limiting further convective development. The evolution of these vertical humidity anomalies strongly supports the role of preconditioning by moist static energy buildup in the mid-to-upper troposphere. This setup, when coupled with favorable dynamics such as enhanced wind shear and upper-level divergence, likely played a pivotal role in the genesis and intensification of the convective system that led to the Dubai flood. For further clarity, we also analyzed the horizontal distribution of relative humidity at 500 hPa and 850 hPa levels along with wind vectors, which clearly illustrate the moisture transport pathways and convergence zones that reinforced the vertical moistening and convective activity over this region (Yano and Manzato, 2022).

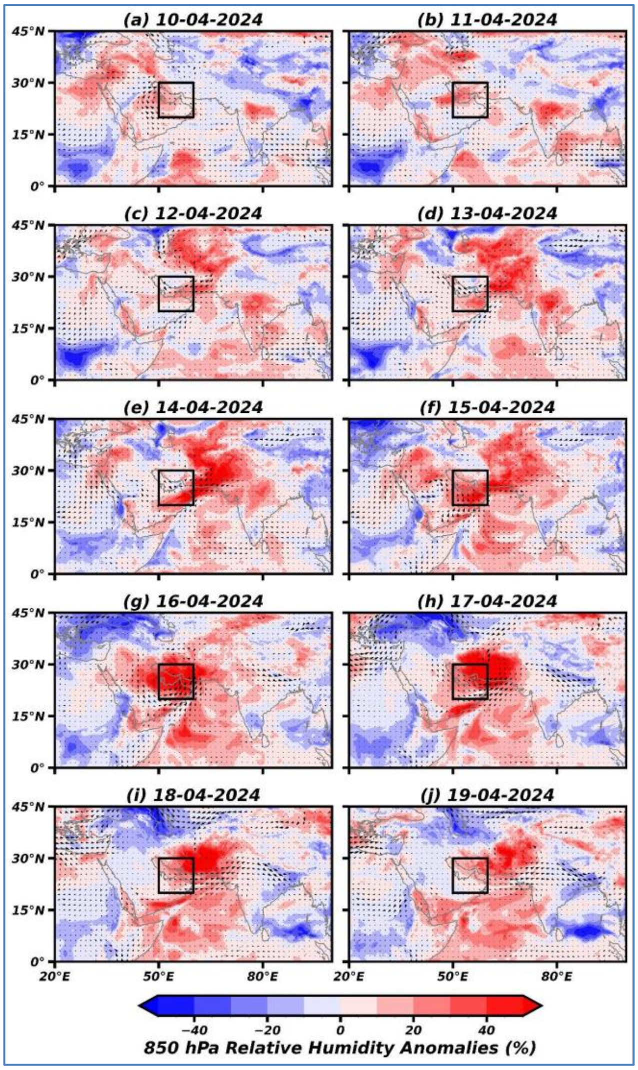
The spatial distribution of 500 hPa relative humidity anomalies and corresponding wind vectors (Fig. 7) illustrates the evolution of mid-tropospheric moisture and circulation patterns during the days surrounding the extreme rainfall event in Dubai. From April 10-12 Figs. 7(a-c), persistent positive RH anomalies are observed to the south and southwest of the UAE, indicating a buildup of moist air in the vicinity of the Arabian Sea and southern Arabian Peninsula. The wind vectors during this period reveal a zonal to southwesterly flow directed towards the UAE, acting as a conveyor belt for moisture transport into this region. By April 13-16 Figs. 7(d-g), strong anomalous moistening is evident directly over the UAE, peaking on April 16. On this day (Fig. 7g), the wind field shows a distinct cyclonic curvature with enhanced convergence over the flood region (boxed region), supporting vertical motion and moisture uplift. This dynamic setup was crucial in sustaining deep convection and heavy rainfall over Dubai. Post-event, from April 17-19 Figs. 7(h-j), the anomaly pattern shifts dramatically, with dominant drying signals (negative RH anomalies) across the UAE and



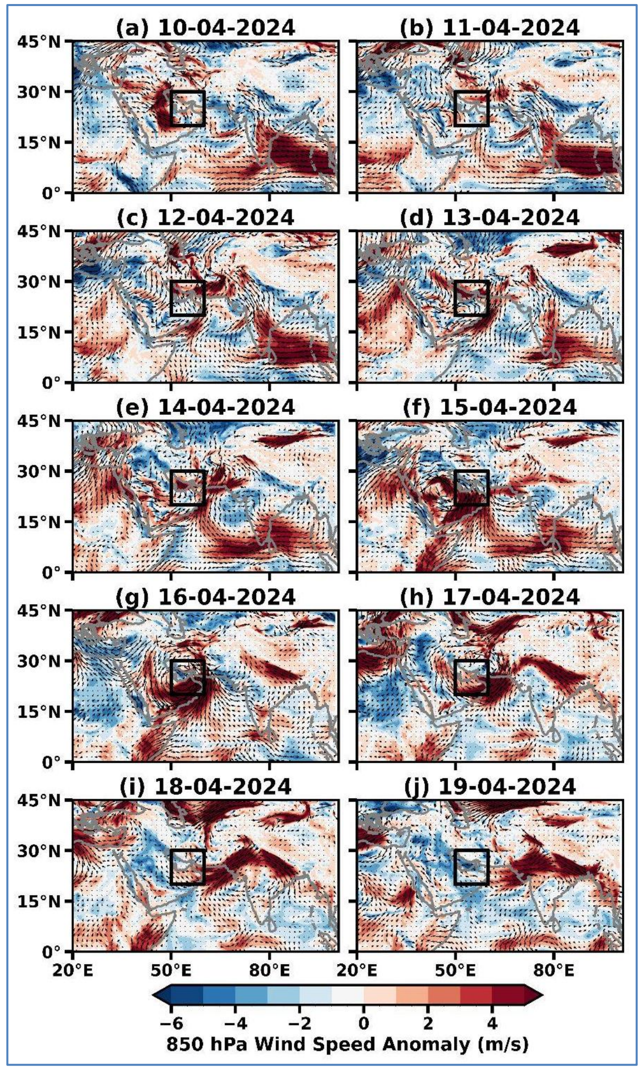
Figs 7(a-j). Daily horizontal distribution of 500 hPa relative humidity anomalies (shaded; %) and wind vectors (m/s) for April 10-19, 2024. The black box denotes the region over the UAE, including Dubai

surrounding areas. This drying trend is accompanied by changes in the wind direction, transitioning to a more northerly component, which is typically associated with subsidence and stabilization in the region. These results highlight the key role of mid-tropospheric moisture surges and favorable wind convergence in setting up the preconditions for the Dubai flood. The alignment of enhanced RH anomalies with converging winds at 500 hPa underscores the importance of both thermodynamic and dynamic precursors in extreme rainfall events over arid regions.

The spatial-temporal evolution of 850 hPa relative humidity (RH) anomalies and associated wind patterns (Fig. 8) provide insight into low - level moisture buildup



Figs. 8(a-j). Daily horizontal distribution of 850 hPa relative humidity anomalies (shaded; %) and wind vectors (m/s) from April 10–19, 2024. The black box highlights the region over the UAE, including Dubai



Figs. 9(a-j). Daily horizontal distribution of 850 hPa wind speed anomalies (shaded; %) and wind vectors (m/s) from April 10–19, 2024. The black box highlights the region over the UAE, including Dubai

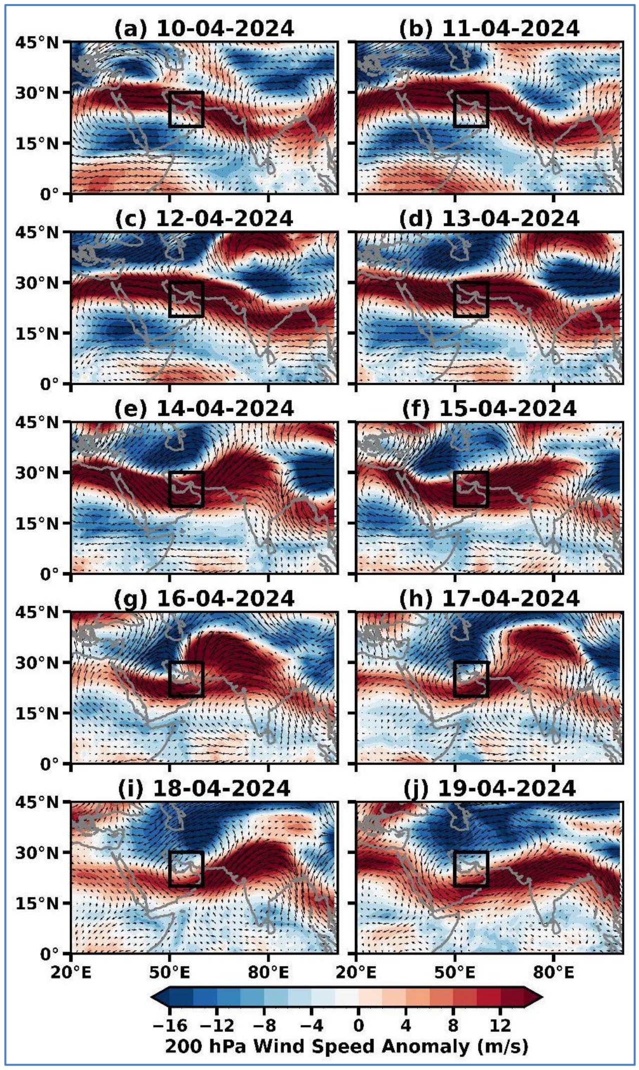
and convergence prior to and during the extreme rainfall event in Dubai. From April 10-13 Figs. 8(a-d), positive RH anomalies gradually develop over the Arabian Peninsula, especially over the UAE and surrounding regions. Notably, the wind vectors during this period indicate weak southwesterly to southeasterly flow, gradually organizing into a more convergent pattern. A significant intensification in positive RH anomalies is observed from April 14-16 Figs. 8(e-g), with peak moisture anomalies on April 16. On this day (Fig. 8g), strong convergence of southwesterly and southeasterly winds is evident over this flood region, indicating the presence of a well-defined low-level convergence zone. Such convergence supports upward motion and enhances convective activity, aligning temporally with the observed flooding event in Dubai.

From April 17-19 Figs. 8(h-j), while positive RH anomalies persist over parts of the UAE, the wind vectors show signs of divergence and weakening of the low-level convergence. This transition likely marks the dissipation phase of the convective system. The analysis confirms that the presence of strong low-level moisture anomalies and convergence at 850 hPa was enhancing convective development and triggering the extreme precipitation. The buildup of moisture from lower latitudes and its convergence over the UAE formed a critical component of the vertical moisture transport mechanism.

Wind direction and speed, which are largely determined by pressure differentials that produce cyclonic or anticyclonic circulation, are essential for the processes of precipitation, cloud formation, and moisture transport (Liu *et al.*, 2020). Studies have shown that increased moisture fluxes connected to cyclonic circulation patterns in the upper and lower atmosphere are frequently linked to significant precipitation occurrences in mid-latitude regions (Blackburn *et al.,* 2008).

Figs. 9(a-j) shows the 850 hPa wind speed anomalies and wind vectors during 10-19 April 2024, highlighting the dynamic conditions associated with the Dubai flood event. A persistent low-level cyclonic circulation and strong positive wind anomalies (greater than +6 m/s) were observed over the Arabian Peninsula, especially near the UAE, from 14 to 17 April Figs. 9(e-h). The wind vectors indicate anomalous southwesterly flows from the Arabian Sea and southeasterly flows from the western Indian Ocean converging over the UAE, marking the region as a major convergence zone. This sustained low-level convergence, especially peaking on 16 April, facilitated the uplift of moist air, leading to intense convective activity (Fig. 9g). The moisture source was primarily maritime, with advection from both the Arabian Sea and equatorial Indian Ocean. The dynamic convergence and moisture inflow created favorable conditions for deep convection and heavy rainfall, which culminated in the extreme flooding event observed in Dubai. After 17 April, the anomaly weakened, indicating a dissipation of the convergence zone Figs. 9(h-j). Similar synoptic features linked to extreme precipitation events over the Arabian Peninsula were observed in a recent modeling research (Attada *et al.,* 2022), which is consistent with this mechanism.

Figs. 10(a-j) illustrates the 200 hPa wind speed anomalies and wind vectors during 10-19 April 2024, capturing upper-tropospheric circulation changes associated with the Dubai flood. A prominent upper-level anticyclonic anomaly is evident over the Arabian Peninsula throughout the period, especially between 14 and 17 April Figs. 10(e-h). Positive wind speed anomalies (8–16 m/s) dominate the region, with wind vectors indicating strong upper-level divergence over the UAE (boxed area). The positioning of this anomaly suggests an enhancement of upper-tropospheric outflow, which favors vertical ascent and supports deep convective development in the lower troposphere (Gollapalli *et al.,* 2024; Sripathi *et al.,* 2024). Between 14 and 16 April, the subtropical westerly jet appears displaced equatorward, interacting with the upper-level anticyclone and reinforcing diffluent flow over the region Figs. 10(e-g). This dynamic setup likely aided the evacuation of air aloft, promoting strong underlying upward motion, as indicated by convergence at 850 hPa in Figs. 9(a-j). These results point to a strong coupling between upper-level divergence and lower-level convergence during the flood. The observed upper-level



Figs. 10(a-j). Daily horizontal distribution of 200 hPa wind speed anomalies (shaded, %) and wind vectors (m/s) from April 10–19, 2024. The black box highlights the region over the UAE, including Dubai

anomaly can be linked to the South Asian Jet Stream and potential influence from an upper-level trough over the eastern Mediterranean (Tyrlis *et al.,* 2013). The persistent upper-tropospheric divergence over the UAE created a favorable large-scale environment for sustained convection and heavy rainfall (Attada *et al.,* 2022). A related study (Saini and Attada, 2023) found that jets had an impact on extreme precipitation, connecting the enhanced subtropical westerly jet to extreme precipitation episodes in the western Himalayan region. The study also found that the main source of moisture in the western Himalayas is the Arabian Sea. The alignment of upper-level divergence (200 hPa) with low-level moisture convergence (850 hPa) reflects a baroclinic structure conducive to extreme precipitation. Additionally, the strengthening of the subtropical jet and its interaction with the convective system suggests a role of synoptic-scale forcing, possibly modulated by intraseasonal or planetary-scale waves.

4. Conclusions

In summary, the flooding over Dubai was driven by a persistent and intensifying low-pressure system, reinforced by a dynamic pressure gradient and supported by anomalous atmospheric conditions across the Arabian Peninsula, Indian subcontinent, and Arabian Sea. These synoptic-scale interactions collectively contributed to the extreme rainfall and subsequent flooding observed on 16 April 2024. An in-depth synoptic and thermodynamic investigation of the Dubai flood event from April 10–19, 2024, reveals a complex multi-layered atmospheric setup favorable for extreme rainfall. The following key findings emerge from the analyses:

Sea Level Pressure (SLP) Anomalies: A notable SLP dip (negative anomalies) was observed over the Arabian Peninsula and adjacent Arabian Sea, forming a localized cyclonic circulation. This depression facilitated inland moisture transport and surface convergence, enhancing the lifting mechanisms required for convective development. The low SLP core shifted northeastward during April 13–16, coinciding with the peak flooding in Dubai. A key driver of the extreme rainfall event in Dubai in April 2024 was a pronounced "pressure squeeze" associated with significant anomalies in MSLP. This pattern was characterized by an anomalously low SLP at the surface, which coincided with a marked trough in GPH at the 200 hPa level. The interaction between this upper-level trough and the surface low-pressure system intensified vertical motion and convergence over the region. The steep pressure gradient between high pressure to the north and the deepening low over the Arabian Peninsula contributed to strong uplift and convective instability.

Sea Surface Temperature (SST) Anomalies and Arabian Sea Warming: SST anomalies over the western and central Arabian Sea were significantly positive, exceeding +1.0 °C in certain patches. This abnormal warming increased latent heat fluxes and evaporation, enriching the overlying atmosphere with moisture. The enhanced thermal contrast between land and sea intensified the pressure gradient, promoting a steady onshore flow and feeding moisture into the lower troposphere. The Arabian Sea acted as a key moisture source, especially for the low-level southwesterlies observed in 850 hPa wind fields.

Vertical Moisture Transport and Anomaly Development: The vertical cross-section of relative humidity anomalies shows a pronounced mid-tropospheric moistening from April 13 onward, especially between 700-400 hPa, indicating the onset of deep-layer moisture convergence over the UAE region. These anomalies intensified through April 16, coinciding with the peak rainfall observed in Dubai (Fig. 6g).

Middle-atmospheric Dynamics (at 500 hPa): The horizontal distribution of relative humidity anomalies at 500 hPa, along with wind vectors, highlights a persistent positive moisture anomaly core over the UAE during April 13-17. This layer shows dynamically favorable mid-tropospheric southeasterly to southwesterly winds, aiding moisture advection into the region. The 500 hPa wind field suggests upper-level support and moisture transport that would sustain and elevate convective development (Fig. 7).

Low-Level Moisture Convergence (at 850 hPa): The 850 hPa anomaly and wind vector figures reveal a significant enhancement of low-level moisture starting from April 12. A well-defined convergence zone established itself over the UAE, peaking around April 15-16, with positive RH anomalies exceeding 60% in some areas. The convergence of southwesterly and southeasterly winds created a strong dynamical uplift zone that primed the lower troposphere for vertical motion (Fig. 8).

Moisture Coupling and Sustained Updrafts: The joint evolution of both 500 hPa & 850 hPa RH anomalies indicates a vertically coupled system with strong moisture availability from lower to mid - troposphere. This coupling facilitated deep convection and the persistence of rainfall, a critical factor in flash flooding.

Temporal Evolution Aligns with Observed Impacts: The peak moisture anomalies and convergence signatures closely align with the most intense rainfall days, validating the role of these dynamic and thermodynamic anomalies in triggering and sustaining the flood event.

The Dubai flood of April 2024 was driven by a synergistic interaction of low-level moisture convergence and mid-tropospheric moistening, supported by favorable wind patterns across multiple vertical levels. The alignment of relative humidity anomalies and wind convergence at 850 hPa and 500 hPa provided the essential ingredients for deep convection and prolonged rainfall. The persistent moisture advection and vertical coupling between layers underscore the necessity of multi-level atmospheric diagnostics for early detection and forecasting of extreme weather events in arid regions like the UAE.

This work was undertaken as a case study of the 2024 Dubai flood to better understand the underlying dynamical and thermodynamical processes that contributed to this unprecedented extreme rainfall event over the Arabian Peninsula. The findings provide important insights into the role of large-scale circulation features, moisture transport pathways, and regional atmospheric dynamics in triggering such floods. By documenting and analyzing this event, our study contributes to improved understanding of high-impact weather systems in the Middle East, offering valuable information for forecasting, disaster preparedness, and climate risk assessment in a region highly vulnerable to extreme hydrometeorological events.

Data availability statement

The data supporting this study's findings are freely available and the codes are available from the corresponding authors upon request.

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Declaration of Competing Interest

The authors declare that they have no known competing interests for this publication.

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Authors' contributions

G Sripathi: Conceptualizations, Methodology, Formal Analysis, Visualization, Writing- Original Draft, Writing - Review & Editing.
Krishna K Osuri: Conceptualizations, Methodology, Supervision, Formal Analysis, Writing Review & Editing, Funding acquisition.
Dandi A. Ramu: Conceptualizations, Methodology, Formal Analysis, Visualization, Review & Editing.
Nagalakshmi Katru: Supervision, Formal Analysis, Review & Editing.

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References

Abbas, W., 2024, "Urban climate of the middle east and north Africa region: a comprehensive anatomization", In *Hydroclimatic Extremes in the Middle East and North Africa*, Elsevier, pp. 177-228

Albert, J., Krishnan, A., Bhaskaran, P.K. and Singh, K.S., 2021, "Role and influence of key atmospheric parameters in large-scale environmental flow associated with tropical cyclogenesis and ENSO in the North Indian Ocean basin", *Climate Dynamics*, 1-18.

Aljazeera, 2024, "Dubai Reels from Flood Chaos as Record Rains Lash UAE. retrieved on 18 June June 2024 from", https://www.aljazeera.com/gallery/2024/4/17/dubai-reels-from-flood-chaos-as-record-rains-lash-uae

Al-Nassar, A.R.T., Pelegrí, J.L., Sangrà, P., Alarcón Jordán, M. and Jansà, A., 2020, "Cut-off low systems over Iraq: Contribution to annual precipitation and synoptic analysis of extreme events"

Attada, R., Dasari, H.P., Ghostine, R., Kondapalli, N.K., Kunchala, R.K., Luong, T.M. and Hoteit, I., 2022, "Diagnostic evaluation of extreme winter rainfall events over the Arabian Peninsula using high-resolution weather research and forecasting simulations", *Meteorological Applications*, ***29,*** 5, p.e2095

Blackburn, M., Methven, J. and Roberts, N., 2008, "Large-scale context for the UK floods in summer 2007", *Weather*, ***63,*** 9, pp.280-288

Chen, Y., Zhou, H., Zhang, H., Du, G., Zhou, J., 2015, "Urban flood risk warning under rapid urbanization", Environ. Res. **139**, 3–10. https://doi.org/10.1016/j. envres.2015.02.028

Elgaali, E., Ziadat, A.H. and Alzyoud, S., 2019, "Environmental effects of new developments in the coastal zones of Dubai" In *2019 Advances in Science and Engineering Technology International Conferences (ASET)* (pp. 1-4), IEEE

Elhacham, E. and Alpert, P., 2021, "Temperature patterns along an arid coastline experiencing extreme and rapid urbanization, case study: Dubai", *Science of the Total Environment*, ***784***, p.147168

Farahat, A., Abuelgasim, A., 2022, "Effect of cloud seeding on aerosol properties and particulate matter variability in the United Arab Emirates", Int. J. Environ. Sci. Technol. **19**, 951–968, https://doi.org/10.1007/s13762-020-03057-5.

Francis, D., Temimi, M., Fonseca, R., Nelli, N.R., Abida, R., Weston, M. and Whebe, Y., 2021, On the analysis of a summertime convective event in a hyperarid environment, *Quarterly Journal of the Royal Meteorological Society*, ***147,*** 734, pp.501-525.

Gollapalli, S., Osuri, K.K., Dandi, A.R. and Rao, A.S., 2024, "Impact of shifting patterns of the South Asian High on interannual variability of Indian summer monsoon rainfall in homogeneous regions", Quarterly Journal of the Royal Meteorological Society, **150,** 765, 5583-5604.

Gulakaram, V.S., Vissa, N.K. and Bhaskaran, P.K., 2023, "Mesoscale eddies with anomalous sea surface temperature and its relation with atmospheric convection over the North Indian Ocean", *International Journal of Climatology*, **43, 7**, 3094-3113.

Haggag, M. and El-Badry, H., 2013, "Mesoscale numerical study of quasi-stationary convective system over Jeddah in November 2009".

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J., Peubey, C., Radu, R., Schepers, D. and Simmons, A., 2020, "The ERA5 global reanalysis. *Quarterly journal of the royal meteorological society", **146,*** 730, 1999-2049.

Hussein, K., Alhosani, N., Al-Areeq, A.M., Al Aghbari, A.A., Elkamali, M., Alsumaiti, T., Sharif, H.O., Almurshidi, A.M. and Abdalati, W., 2025, "Unprecedented rainfall in the United Arab Emirates: hydrologic and flood impact analysis of the April 2024 event", *Natural Hazards*, 1-23.

IPCC, 2021, Summary for Policymakers. In: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., P´ean, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., Zhou, B. (Eds.), "Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change", Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 3–32, https://doi.org/10.1017/9781009157896.001.

IPCC, 2022, Summary for policymakers. In: P¨ortner, H.-O., Roberts, D.C., Poloczanska, E. S., Mintenbeck, K., Tignor, M., Alegría, A., Craig, M., Langsdorf, S., L¨oschke, S., M¨oller, V., Okem, A. (Eds.), "Climate Change 2022: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change", Cambridge University Press, Cambridge, UK and New York, NY, USA, 3–33, https://doi.org/ 10.1017/9781009325844.001.

Kulkarni, A., Sabin, T.P., Chowdary, J.S., Rao, K.K., Priya, P., Gandhi, N., Bhaskar, P., Buri, V.K., Sabade, S.S., Pai, D.S. and Ashok, K., 2020, "Precipitation changes in India", *Assessment of climate change over the Indian region: a report of the ministry of earth sciences (MoES), Government of India*, 47-72.

Liu, W.; Xie, S.-P.; Lu, J, 2016, "Tracking ocean heat uptake during the surface warming hiatus", Nat. Commun, **7**, 10926.

Mukherjee, S. and Mishra, A. K., 2021, "Cascading effect of meteorological forcing on extreme precipitation events: Role of atmospheric rivers in southeastern US", *Journal of Hydrology*, **601**, p.126641.

Nelli, N.R., Francis, D., Fonseca, R., Abida, R., Weston, M., Wehbe, Y. and Al Hosary, T., 2021, "The atmospheric controls of extreme convective events over the southern Arabian Peninsula during the spring season", *Atmospheric Research*, **262**, p.105788.

Nekkali, Y.S., Osuri, K.K. and Mohapatra, M., 2024, "On magnitudes of rapid intensification and destruction of tropical cyclones over the North Indian Ocean", *International Journal of Climatology*, **44,** 4, 1074-1086.

Paul S, Sharif HO, 2018, "Analysis of damage caused by hydrometeorological disasters in Texas, 1960–2016", Geosciences **8,** 10, 384, https://doi.org/10.3390/geosciences 8100384.

Rao, K.K., Al Mandous, A., Al Ebri, M., Al Hameli, N., Rakib, M. and Al Kaabi, S., 2024, "Future changes in the precipitation regime over the Arabian Peninsula with special emphasis on UAE: insights from NEX-GDDP CMIP6 model simulations", *Scientific Reports*, **14,** 1, p.151.

Roxy, M.K., Ritika, K., Terray, P. and Masson, S., 2014, "The curious case of Indian Ocean warming", *Journal of Climate*, **27,** 22, 8501-8509.

Rupa Kumar, K., Krishna Kumar, K., Ashrit, R.G., Patwardhan, S.K. and Pant, G.B., 2002, "Climate change in India: observations and model projections. *Climate Change and India: Issues, Concerns and Opportunities", Tata McGraw-Hill Publishing Company Limited, New Delhi*

Saini, R. and Attada, R., 2023*, "*Analysis of Himalayan summer monsoon rainfall characteristics using Indian high-resolution regional reanalysis", *International Journal of Climatology*, **43,** 9, 4286-4307.

Sian, K.T.C.L.K., Sagero, P., Kebacho, L.L. and Ongoma, V., 2025, "Dubai's record precipitation event of 16 April 2024–A diagnosis", Atmospheric Research, **315**, p.107924.

Sharma, A., Sharma, D., Panda, S.K., Sunder, M.S.S. and Kumar Dubey, S., 2024, "Seasonal analysis of long-term (1970–2020) rainfall variability using clustering and wavelet transform approach in the Mahi River Basin, India", *Acta Geophysica*, ***72,*** 3, 1879-1894.

Sripathi, G., Ramu, D.A., Saikrishna, T.S., Osuri, K.K. and Rao, A.S., 2024, "Dynamic relationship between Indian summer monsoon rainfall and South Asian high in seasonal coupled models", *Climate Dynamics*, ***62,*** 3, 1925-1944.

Sunder, M.S., Tikkiwal, V.A., Kumar, A. and Tyagi, B., 2023, "Unveiling the transparency of prediction models for spatial PM2. 5 over Singapore: comparison of different machine learning approaches with explainable artificial intelligence", *AI*, ***4,*** 4, 787-811.

Syed, F.S., Latif, M., Al-Maashi, A. and Ghulam, A., 2019, "Regional climate model RCA4 simulations of temperature and precipitation over the Arabian Peninsula: sensitivity to CORDEX domain and lateral boundary conditions", *Climate Dynamics*, **53,** 11, pp.7045-7064.

Taguchi R, Tanoue M, Yamazaki D, Hirabayashi Y, 2022, "Global-scale assessment of economic losses caused by flood-related business interruption", *Water* **14,** 6, 967, https://doi.org/10.3390/ w14060967.

Tyrlis, E., Lelieveld, J. and Steil, B., 2013, “The summer circulation over the eastern Mediterranean and the Middle East: influence of the South Asian monsoon”, *Climate Dynamics*, **40,** 5, 1103-1123.

Vinodhkumar, B., Nambeesan, A.U., Ullah, S., KUNDETI, K., Osuri, K.K. and Al-Ghamdi, S.G., 2025, “Projected impact of heat stress on work performance, population exposure, and mortality in the Arabian Peninsula”, *Environmental Research Letters*

Vinodhkumar, B., Ullah, S., Kumar, T.L. and Al-Ghamdi, S.G., 2024, “Amplification of temperature extremes in Arabian Peninsula under warmer worlds”, *Scientific Reports*, **14,** 1, p.16604.

Wehbe, Y., Temimi, M., Weston, M., Chaouch, N., Branch, O., Schwitalla, T., Wulfmeyer, V., Zhan, X., Liu, J. and Al Mandous, A., 2019, “Analysis of an extreme weather event in a hyper-arid region using WRF-Hydro coupling, station, and satellite data”, *Natural Hazards and Earth System Sciences*, ***19*****(6)**, pp.1129-1149

Yano, J.I. and Manzato, A., 2022, “Does more moisture in the atmosphere lead to more intense rains?”, Journal of the Atmospheric Sciences, **79**, 3, 663-6.