Numerical Analysis of the Mesoscale Dynamics of an Extreme Rainfall and Flood Event in Sri Lanka in May 2016

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(Manuscript received 25 August 2018, in final form 5 April 2019)

Abstract

In this present study, we analyzed the synoptic and mesoscale dynamics and underlying mechanism of an extreme rainfall and flood event that occurred in Sri Lanka between 14–17 May 2016, using the Weather Research and Forecasting Model simulations with a horizontal grid size of 3 km and observational data. This extreme rainfall event was associated with a low-pressure system (LPS) that originated over the Bay of Bengal in the Indian Ocean and passed over Sri Lanka. The observed maximum accumulation of rainfall during the event exceeded 300 mm at several weather stations on 15–16 May and it resulted in severe flooding and landslides, particularly in the western part of the island. The model closely simulated the timing of the initiation of the LPS and its development along the east coast of Sri Lanka. The model could capture the overall rainfall tendency and pattern of this event. Synoptic and mesoscale analyses indicated that this extreme rainfall event occurred as the cumulative effect of a sustained low-level convergence zone, generated by an enhanced westerly monsoon flow and the circulation of the LPS, alongside a continuous supply of high-magnitude moisture, strong vertical motion, and orographic effects of the Central Mountains of Sri Lanka. Model sensitivity experiments indicated that the rainfall over the western slope area of the mountains was enhanced by mountain lifting, whereas western coastal rainfall was reduced because the mountains blocked the northeasterly flow of the LPS.

Keywords heavy rainfall; Weather Research and Forecasting Model; extreme event; low-pressure system


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J-stage Advance Published Date: 22 April 2019

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1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report documents the increasing frequency of extreme weather events, such as extreme heat and heavy rainfall events, in a number of regions worldwide (IPCC 2014). Temperatures of the Indian Ocean have exhibited an increasing trend (Goswami et al. 2006; Rajeevan et al. 2008), which may be related to the increase of extreme weather events in the region. Particularly the South Asian summer monsoon rainfall is projected to increase in a future warmer world, both in terms of the long-term mean rainfall and inter-annual variability of rainfall, leading to extreme rainfall events (Kitoh 2017; Ogata et al. 2014). The IPCC further predicts increased summer monsoon rainfall over the Indian subcontinent and increased extreme rainfall over the coasts of the Bay of Bengal (BoB), caused by cyclogenesis in the BoB and Arabian Sea (IPCC 2013). Extreme rainfall events can cause dramatic social effects, such as severe socioeconomic losses due to flooding, reservoir replenishment, agricultural damage or loss, and damaged infrastructure (Easterling et al. 2000; Groisman et al. 1999). Damage is particularly extensive when these events occur over metropolitan areas consisting of dense populations and concentrated economic activity (van Oldenborgh et al. 2016; Promchote et al. 2016).

To prevent or mitigate severe losses caused by extreme rainfall, it is vital to understand the atmospheric processes leading to heavy rainfall events within recognized weather patterns. Disturbances such as tropical cyclones (TCs), low-pressure systems (LPSs), monsoonal flow, and mesoscale convective systems are mostly thermally driven and powered by the latent heat of condensed water vapor carried by trade winds. Most of these types of disturbances form and develop over the warmer parts of the oceans where there is an almost unlimited supply of heat and moisture (Saha 2010; Trenberth et al. 2003). Usually, heavy rainfall occurs because of moisture availability, moisture transport, storm propagation, and rainfall efficiency. The interaction between low-level winds and the local topography also plays an important role in heavy rainfall events. The presence of an orographic obstacle across the moisture flow further contributes to extreme rainfalls (Chen et al. 2005; Juneng et al. 2007; Lin and Chen 2002). During a TC or LPS, the higher terrain elevations tend to enhance the rainfall mostly on the windward side of the mountains, because the steep terrain tends to lift the airflow and produce strong upward motions (Tang et al. 2012; Yang et al. 2008).

Among these disturbances, LPSs are renowned for their frequent contribution to extreme rainfall events, particularly over the BoB region (Krishnamurthy 2012). TCs and LPSs occur during two peak periods in the BoB region. The first peak period is the premonsoon/spring season (March–May), which is known to produce low-intensity disturbances/LPSs, and the second peak period is the postmonsoon/fall season (October–December), which is known to produce severely intense cyclonic disturbances (Chand and Singh 2017; Pattanaik and Mohapatra 2016). Deep convecions that occur over South Asia and the Indian subcontinent (Zipser et al. 2006) are also known to be associated with the premonsoon and monsoon seasons (Saha 2010; Webster et al. 1998). Generally, depressions and LPSs form over the moisture-rich BoB and involve mesoscale convective systems (Houze and Churchill 1987).

The various thermodynamic and dynamic effects of a local area further aid the development of weather systems. Sri Lanka, being an island nation in the BoB region, is vulnerable to TCs, particularly those generated over the southern part of the BoB. According to the Disaster Management Center’s (DMC) ranking of natural disasters in Sri Lanka, cyclone events are ranked second, and flood events are ranked fourth, in terms of the number of human lives lost. In terms of the frequency of natural disaster events, flood events are ranked first, and cyclone events are ranked fourth (Disaster Management Centre and the United Nations Development Program 2012).

A LPS that originated in the BoB southeast of Sri Lanka developed into a tropical cyclone named Roanu in May 2016. This system prevailed over Sri Lanka from 14–17 May 2016, and over 300 mm of maximum accumulation rainfall was recorded at several weather stations during 15–16 May 2016 (Fig. 1a), particularly in the western and northern parts of Sri Lanka (Alahacoon et al. 2016). Initially, widely scattered rainfall fell across the country, but more intense rainfalls were observed in western and northeastern parts of the island, which resulted in prolonged flooding in those areas, which persisted until 22 May. The intense rainfall moved northward along with the movement of the LPS. The LPS triggered extensive flooding and landslides that affected thousands of lives and livelihoods (United Nations Office for the Coordination of Humanitarian Affairs 2016) (Figs. 1a, b). This torrential rainfall event caused the worst floods in the last 25 years in the densely populated Western Province of Sri Lanka (United Nations Office
for the Coordination of Humanitarian Affairs 2016). Three large-scale landslides were also reported during the event over the western slopes of the Central Mountains. A total of 22 administrative districts out of the 25 in Sri Lanka were affected by the event (Fig. 1b). According to the DMC, the whole event resulted in over 200 fatalities, with 100,000 homes and other property being damaged and more than 450,000 people being displaced (DesInventar 2016; United Nations Office for the Coordination of Humanitarian Affairs 2016). The estimated economic loss calculated by total damage exceeded US$ 2 billion throughout the country (Samantha 2018). Overall, the event is considered to be one of the biggest natural disasters in the recent history of Sri Lanka.

Sri Lanka frequently experiences extreme rainfalls under the influence of two monsoon systems and atmospheric disturbances from the BoB. However, detailed analyses of both the synoptic and mesoscale dynamics in extreme events in Sri Lanka using a numerical model are rare. Further, while a number of studies stressed the importance of topography on heavy rainfall events, to the best of our knowledge, the effects of Sri Lanka’s topography on heavy rainfalls have not been investigated. Thus, this research sought to understand the dynamics of the extreme rainfall event from 14–17 May 2016 using the Advanced Research Weather Research and Forecasting Model (WRF-ARW, hereafter WRF). Through the analysis of model results, we seek to fill the scale gap between the synoptic and mesoscale, and clarify the role of topography in Sri Lanka in the extreme event. Improving knowledge concerning the mechanisms of this extreme event can help meteorological services to effectively identify and forecast similar events in the future. The present study is, to the best of our knowledge, one of the first in the literature to examine the effects of Sri Lanka’s topography on heavy rainfall events, to the best of our knowledge, and to effectively identify and forecast similar events in the future. The present study is, to the best of our knowledge, one of the first in the literature to examine the effects of Sri Lanka’s topography on heavy rainfall events.

2. Data sources and methodology

2.1 Data sources

The 6-hourly National Center for Environment Prediction Climate Forecast System version 2 data (NCEP-CFSv2) (Saha et al. 2011) at 0.5 degrees and 37 vertical levels were used for initial and lateral boundary conditions in this study. The data are available online at the research data archive website of the National Center for Atmospheric Research (http://rda.ucar.edu/datasets/ds094.0/).

The rainfall data in the simulation results were validated against the observation data from the ground weather stations of the Department of Meteorology of Sri Lanka. Because of the limited availability of continuous high temporal resolution quality-controlled data, most of the analysis of observation data was conducted using daily rainfall data; the hourly rainfall data from the Colombo station data were the only hourly data analyzed. The European Organization for the Exploitation of Meteorological Satellites’ (EUMETSAT) Meteosat-7 visible and infrared spin-scan radiometer (VISSR) Indian Ocean data coverage infrared cloud imageries available at the Dundee Satellite Receiving Station (http://www.sat.dundee.ac.uk) were used to justify the LPS development and rainfall structure of the simulated model results.

2.2 Model and experimental setup

The simulations constructed in this study were based on Version 3.6.1 of the WRF model, which was designed to serve and support both atmospheric research and operational forecasting requirements (Skamarock and Klemp 2008). The WRF model system is composed of a new-generation mesoscale forecasting model featuring multiple dynamical cores, which are nonhydrostatic, fully compressible, and have a terrain-following hydrostatic-pressure vertical coordinate system. More details concerning the WRF model can be found in Skamarock et al. (2008) and Skamarock and Klemp (2008).

All experiments were conducted over a single domain (Fig. 1c). To provide the model with enough area for the weather system development and initiation, the domain extended beyond the island of Sri Lanka. Model resolution is an important aspect in simulating the spatial distribution of rainfall (Gao et al. 2006; Mass et al. 2002). The horizontal grid size was set to 3 km throughout the model domain. The model simulation was initialized at 0000 Coordinated Universal Time (UTC) 14 May 2016, a day before the LPS began affecting Sri Lanka, and it ended at 0000 UTC 21 May 2016. To control for the accumulation of errors in the model simulation, a four-dimensional data assimilation scheme was applied that incorporated the boundary conditions every 6h from the NCEP-CFSv2 dataset. The first 12 hours of the simulation were treated as the spin-up time for the model and excluded from the analysis. The model results from 1200 UTC 14 May–0200 UTC 17 May were used...
Fig. 1. (a) Accumulated rainfall distribution of the event from 15–16 May 2016, observed by the Department of Meteorology weather stations. (The elevation is shaded with 250 m contours, showing areas above 250 m of the central mountains.) (b) Distribution map of the number of people affected by the floods and landslides due to the extreme event from 14–20 May 2016 (Disaster Management Centre 2016). (c) Map of the study domain with topography. The shaded point circle refers to the location of the Colombo weather station (6.90°N; 79.87°E) in the western coast of Sri Lanka. The A–B transect used in vertical cross sections.
for detailed analysis because that period represents the peak period of the event over the heavily affected western part of Sri Lanka.

Depending on the strength of the synoptic-scale forcing and season, a proper cumulus parameterization scheme (CPS) is required when simulating certain atmospheric settings (Gilliland and Rowe 2007). Deep convections in the gray zone resolutions (2–10 km) are partly resolved and partly subgrid. Thus, such cases stress the necessity of a CPS for numerical predictions of convective weather, even at high resolutions (Gerard 2007). In the current study, we opted to use a CPS at the fairly high resolution of 3 km. The details of the model configuration and physics and dynamics employed are summarized in Table 1. The output simulation results from the described model configuration were further analyzed and discussed.

In addition to the control simulation as described above, a series of simulations were performed to check the rainfall sensitivity with respect to the topographic height of the model. Three sensitivity studies were conducted, where all model configurations are similar to the control simulation, except for the terrain height being reduced to 0 % (case Topo-Z), 25 % (case Topo-Q), and 50 % (case Topo-H) of the control simulation. Conclusions from these sensitivity studies are presented in Section 3.3.c.

### Table 1. Overview of the configurations of physics and dynamics used in the WRF model.

<table>
<thead>
<tr>
<th>Model features</th>
<th>Configurations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dynamics</td>
<td>Non-hydrostatic</td>
</tr>
<tr>
<td>Model domain</td>
<td>1 (3°18′N–14°12′N, 74°14′E–88°9′E)</td>
</tr>
<tr>
<td>Center of the domain</td>
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<tr>
<td>Horizontal grid</td>
<td>500 × 400 (zonal and meridional respectively)</td>
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<tr>
<td>Horizontal grid distance</td>
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</tr>
<tr>
<td>Map projection</td>
<td>Mercator</td>
</tr>
<tr>
<td>Horizontal grid system</td>
<td>Arakawa C-grid</td>
</tr>
<tr>
<td>Vertical coordinates/levels</td>
<td>Terrain-following hydrostatic pressure vertical coordinate with 45 vertical levels</td>
</tr>
<tr>
<td>Model top</td>
<td>50hPa</td>
</tr>
<tr>
<td>Four-dimensional data assimilation (FDDA)</td>
<td>Yes (Gird nudging)</td>
</tr>
<tr>
<td>Feedback</td>
<td>No</td>
</tr>
<tr>
<td>Microphysics</td>
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</tr>
<tr>
<td>Longwave Radiation scheme</td>
<td>Rapid Radiative Transfer Model (RRTM) scheme (Mlawer et al. 1997)</td>
</tr>
<tr>
<td>Shortwave Radiation scheme</td>
<td>Dudhia scheme (Dudhia 1989)</td>
</tr>
<tr>
<td>Surface layer parameterization</td>
<td>Monin–Obukhov surface layer scheme (Beljaars 1995)</td>
</tr>
<tr>
<td>Planetary boundary layer (PBL)</td>
<td>Yonsei University (YSU) scheme (Hong et al. 2006)</td>
</tr>
<tr>
<td>Cumulus scheme (CPS)</td>
<td>Kain-Fritsch (new Eta) scheme (Kain 2004)</td>
</tr>
<tr>
<td>Land surface processes</td>
<td>Unified Noah land surface model (Tewari et al. 2004)</td>
</tr>
</tbody>
</table>

### 3. Results and discussion

#### 3.1 Synoptic conditions and rainfall

The NCEP-CFSv2 data indicated a weak cyclonic circulation originating over the southwest of the BoB off the southeast coast of Sri Lanka on 14 May 2016, which was attributable to a LPS. The disturbance lingered over the southeast of Sri Lanka and then drifted offshore of the east coast of Sri Lanka early on 15 May. The sea surface pressure data from the origin of the LPS to the time it passed along Sri Lanka indicated that it was a well-defined but weak system that would only be categorized as a low-pressure area or depression (Figs. 2a–c). From 16 May, the LPS moved from north to northwest, intensified into a deep depression, and then became the cyclonic storm Roanu (India Meteorological Department 2016). The cyclonic flow of the LPS was maintained from the surface to upper air. The mid-troposphere steering-flow patterns up to 500 hPa and beyond also indicated the presence of the closed LPS on a broader scale (Figs. 2a–c). The NCEP-CFSv2 data clearly demonstrated the origin, intensification, and development of the LPS in the BoB and along the east coast of Sri Lanka (Figs. 2a–c). It is evident from the 500-hPa-level geopotential height (Fig. 2a) that a northwest- to southeast-oriented trough was over the Indian Ocean next to the LPS origin area. In general, these monsoon troughs lead to
Fig. 2. The sea level pressure (hPa) (blue colored contours in the 2 hPa interval), surface winds (10 m) (m s$^{-1}$) (in vector arrows colored based on the magnitude), and the 500 hPa-level geopotential height (green colored contours in 10 m interval in the range 5700–6000 m) from 6-hourly National Centers for Environmental Prediction Climate Forecast System version 2 (NCEP-CFSv2) data valid at (a) 0600 UTC 14 May (b) 0600 UTC 15 May and (c) 0600 UTC 16 May 2016. Meteosat-7 VISSR (visible and infrared spin-scan radiometer) Indian Ocean data coverage thermal infrared cloud imageries (Dundee 2016) 2 (d, e, f) valid at corresponding time as in 2 (a, b, c).
a cyclonic system formation, particularly during the pre-monsoon period in the BoB (Wang et al. 2013; Wu et al. 2011). The thermal infrared images from the EUMETSAT Meteosat-7 satellite displayed in Figs. 2d and 2f clearly depict the transformation of the cloud pattern associated with the LPS during its time over Sri Lanka. The images also help to identify the development of the LPS and the well-established cloud cover over most of Sri Lanka during this period. These infrared satellite images depict the development of the cyclonic cloud bands during this event and the cloud system persistently covering the entire of Sri Lanka (Fig. 2e). These cloud images also correspond to the continuous moisture transport from the west-erlies and strengthening of the wind (Fig. 2f). Most of the thick cloud cover and patterns in the satellite imagery matched the observations of heavy rainfall and the LPS development.

The NCEP-CFSv2 data revealed persistently strong westerly winds at sea level with maximum values ranging between 15 and 20 m s$^{-1}$ over the west coast of Sri Lanka and the southwest quadrant of the LPS (Figs. 2a–c). These westerly winds were extending from the Somali jet, a strong cross-equatorial flow (next to the East African coast, pronounced between 5°S and 10°N; Figs. 2a–c). This Somali jet stream acts as one of the main suppliers of moisture for South Asian rainfall (Cadet and Desbois 1981; Saha 2010). Our results also indicated a continuous supply of moisture from the westerlies to Sri Lanka and the BoB region during the study period. The westerlies and the wind from the LPS collided over the west coast of Sri Lanka to create a convergence zone over the western slopes of the Central Mountains, resulting in heavy rainfall in the adjacent areas (see Section 3.3.1).

Regions of high water vapor and rainfall moved toward Sri Lanka from the southeast and western directions, crossed the island from 14 to 16 May, and left Sri Lanka, heading toward the northeast. Rainfall continued during this period, following the direction of the LPS and mainly centered over the western slopes of the Central Mountains. The relatively limited number of ground weather stations in Sri Lanka recorded this particular event, and several stations reported over 300 mm of accumulation rainfall between 15 and 16 May (Fig. 1a). One of the highest daily rainfalls recorded for 15 May was 350 mm at Deraniyagala (Fig. 3a). Unfortunately, data were only available on 15 May for this station. The western slopes of the Central Mountains of Sri Lanka received an excessive amount of rainfall that triggered large-scale landslides, particularly in the Kegalle District. The Maha Illuppallama weather station located in the Anuradhapura District in north-central Sri Lanka recorded the maximum rainfall of 267.8 mm for 16 May (Fig. 3b). The highest rainfall totals were recorded on 15 and 16 May when the center of the LPS was located over the east coast of Sri Lanka. These observations highlight that the locations of maximum rainfall followed the movement of the LPS. Overall rainfall on the west coast was relatively higher than on the east coast during this event. Compared with the rest of the island, the southeastern coastal area of the island experienced comparably light rainfall throughout this period.

3.2 Model validation

The model validation was performed by comparing the observations and model simulations in terms of rainfall and circulation during the peak period of the event. A successful simulation of the rainfall was a key objective of this study. Figures 3a and 3b illustrates the observed daily rainfall, and they can be compared with Figs. 3c and 3d, which present the model-simulated rainfall for 15–16 May 2016. The LPS moved northwestwards and lingered as a pronounced LPS over the east coast of Sri Lanka on 15 May. The highest rainfall on 15 May over the southwestern part of Sri Lanka was captured by the model, particularly the rainfall over the western slopes of the Central Mountains. The model-derived 24-h results of rainfall accumulation indicated that the areas receiving over 150 mm of rainfall stretched from the west coast eastward to the Central Mountains (Fig. 3c), which was similar to the real observations (Fig. 3a). However, the simulation showed a lower rainfall accumulation over the northern part of Sri Lanka (Fig. 3c) compared with observations (Fig. 3a). Heavy rainfall on the west coast and northwest side of the Central Mountains on 16 May was captured by the model, but an overestimation occurred for the middle of the Central Mountains region. The spatial patterns of the model-derived daily rainfall amounts for 15 and 16 May were closely related to the observations. During 16 May, the system moved along the east coast of Sri Lanka, and by the end of 17 May the LPS had already passed the northern territory of Sri Lanka.

A more detailed comparison was conducted with the hourly rainfall variations at the Colombo weather station (the starred station in Fig. 1a). Colombo and the surrounding suburban areas experienced record-breaking rainfall, and it was the area worst affected by the subsequent floods. Figure 4 depicts the hourly development of the observed and model-simulated
Fig. 3. Accumulated daily rainfall for 15 and 16 May 2016, (a–b) observed by the Department of Meteorology and corresponding accumulated rainfall from the model simulation (c–d). Pointed locations correspond to the stations with maximum daily rainfall amount. The elevation shows above 250 m of the mean sea level only.
rainfall for the Colombo weather station during the period from 0000 Local Standard Time (LST) 15 May to 0800 LST 17 May 2016. This period coincides with the daily rainfall of 15–16 May (daily rainfall is calculated by Sri Lanka’s Department of Meteorology from 0830 LST to 0830 LST the following day) and also with the peak period of the event over this area. Rainfall data from the Colombo station indicated that the extreme rainfall event started at approximately 0300 LST 15 May and lasted continuously until the middle of 16 May, exhibiting several peak rainfall spells in between. The model-derived hourly rainfall variation followed the observed trend of the Colombo weather station. Although the model could not capture the exact magnitude of the initial peak rainfall spell that occurred early on 15 May, the subsequent rainfall spells of late 15 May and 16 May were reasonably modeled (Fig. 4).

To further validate the model, we also computed the following statistical indicators: coefficient of determination ($R^2$), standard error of the regression ($S$), mean absolute error (MAE), and mean fractional bias (MFB). All the indices were calculated for the Colombo weather station in Sri Lanka using the nearest model grid point rainfall and the hourly rainfall data from ground observations, and Eqs. (1)–(4), respectively,

$$R^2 = 1 - \frac{SS_{Regression}}{SS_{Total}},$$

(1)

$$S = \sqrt{\frac{\sum_{i=1}^{n} (P_i - O_i)^2}{n}},$$

(2)

$$MAE = \frac{\sum_{i=1}^{n} |P_i - O_i|}{n},$$

(3)

$$MFB = \frac{1}{n} \sum_{i=1}^{n} \frac{(P_i - O_i)}{(P_i + O_i)}$$

(4)

where $SS_{Regression}$ is the sum squared regression error, and $SS_{Total}$ is the sum squared total error. Model predictions are $P_i$ ($i = 1, 2, ..., n$), and observations are $O_i$ ($i = 1, 2, ..., n$). All these indices are indicators of the goodness of fit of the model results with the observations. R-squared is a statistical index used to determine how close the data are to the fitted regression line. The statistical indicator $S$ is the average distance that the values fall from the regression line, given in natural units of the variable. The MAE gives the average of the magnitudes of difference, and $MFB$ indicates both the direction and probable magnitude of the error. Figure 5 illustrates the scatter plot of hourly rainfall derived from the model results versus the observed hourly rainfall for the Colombo weather station. Although the R-squared value for this regression was 0.6 (Table 2), the other statistical indices reflect that the model-derived rainfall was reasonably close to the observations with lower bias. We found it challenging to validate the model results for some parts of Sri Lanka because of the limited availability of high spatial and temporal resolution quality–controlled weather data from Sri Lanka. Thus, we only used the Colombo weather station data for this detailed analysis, because it represented the primary area affected by this extreme rainfall event.

The model results were validated by comparing the 10 m wind vectors (Figs. 6a, b, f) against those derived from the NCEP-CFSv2 data. Because the LPS was still a depression and had no clear LPS center when it passed along Sri Lanka, comparing the exact path of the system was challenging; yet, the model simulations captured the LPS center and the wind field...
well as it developed. The simulation data indicated the strengthening of the cyclonic winds at the LPS center (Figs. 6e, f). Overall, the simulated vortex managed to maintain an LPS center similar to the NCEP-CFSv2 data. The model also accurately simulated the wind speed, which increased from 5 to 20 m s\(^{-1}\) as the LPS developed.

As evident from the comparison, the analysis of rainfall and the circulation system, and the supporting satellite images, the simulation reconstructed the circulation and the rainfall system for this particular extreme event with reasonably accuracy. Thus, the modeling result can be subjected to further diagnostic analysis.

3.3 Mechanisms responsible for extreme rainfall

a. Moisture transport

The airflow over the west coast of Sri Lanka mainly came from the moisture-rich westerlies over the Indian Ocean and Arabian Sea. The BoB area also exhibited high water vapor content. The continuous moisture supplies from each of these areas played a notable role in the development of the LPS. To analyze the moisture level and distribution, the water vapor flux (WVF) was calculated using Eq. (5):

\[
WVF = q\bar{u} + q\bar{v},
\]

where \(q\) is specific humidity, and \(\bar{u}\) and \(\bar{v}\) are the zonal wind component and meridional wind component, respectively. The WVF was relatively weak prior to 15 May over the northwest coast of Sri Lanka, the Palk Strait (the Strait between India and Sri Lanka), and the east coast of India (Fig. 6a). The highest WVF values for 15 and 16 May (Figs. 6b–f) occurred on the west coast and around the center of the LPS when the system passed along the east coast of the island. In particular, the atmospheric moisture content over the west coast and surrounding areas of Sri Lanka gradually increased and then leveled off, as reflected in Figs. 6d–f, because the northerly flow of the LPS and the westerly monsoon flow interacted with the Central Mountains. Figure 7 illustrates the simulated low-level (925 hPa) wind convergence (negative), divergence (positive), and zonal and meridional divergent wind vectors that occurred during the study period. The distribution of the low-level convergence zone throughout this period indicated that the heavy rainfall areas (Fig. 3b) were located next to the area of significant convergence (Figs. 7c, d). Concurrently, the model results indicated heavy rainfall occurred over the southwest to west coasts (Fig. 3e). The low rainfall in the southeast coastal region and at the eastern slopes of the Central Mountains on 16 May (Fig. 3f) was mainly attributable to the LPS tracking north (Figs. 6e, f); divergence clearly dominated (Figs. 7e, f) in this region. Reduced moisture content was evident near the center of the LPS, and a slowing of the development of the LPS from 1200 UTC 16 May through 1200 UTC 17 May was also evident (not illustrated here; see Supplementary Figs. S1, 2, a–e). These phenomena were possibly attributable to the blocking of the structure of the LPS by Sri Lanka’s landmass and discontinued moisture supply from the westerlies. However, after 0600 UTC on the afternoon of 17 May the LPS again intensified and developed into a TC when moisture support from the BoB resumed and favorable conditions prevailed (not illustrated here; see Supplementary Figs. S1, 2, c–f).

b. Locally enhanced convection and potential instability

Heavy rainfall is usually associated with strong convection. The synoptic environmental conditions such as the moisture-rich lower atmospheric flow were favorable in generating convective rainfall in this event. Convective available potential energy (CAPE) is a measure of the potential updraft strength of thunderstorms and has been used in the analyses of various weather systems (Bhat et al. 1996; Murugavel et al. 2012). The CAPE values greater than 2500 J kg\(^{-1}\) are usually associated with severe weather (Storm Prediction Center 2017). Figure 8 shows model simulated CAPE and equivalent potential temperature (EPT) at the lowest model level (~160 m above surface). During the rainfall event, the CAPE values greater than 3000 J kg\(^{-1}\) persisted on the west coast of Sri Lanka and west coast of southern India (Figs. 8a–c). On the other hand, the CAPE and EPT values over land were much lower than those over the ocean (Figs. 8b, c). The low-level moistening of the

<table>
<thead>
<tr>
<th>Index</th>
<th>Abbreviation</th>
<th>Value</th>
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<tr>
<td>Coefficient of determination (R-squared)</td>
<td>( R^2 )</td>
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<tr>
<td>Mean Absolute Error (mm)</td>
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<tr>
<td>Mean Fractional Bias (%)</td>
<td>( MFB )</td>
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Fig. 6. Model simulated water vapor fluxes at 925 hPa and 10 m wind vectors at (a) 1200 UTC 14 May, (b) 0600 UTC, (c) 1200 UTC, (d) 1500 UTC 15 May and (e) 0000 UTC, (f) 0600 UTC 16 May 2016. The elevation shows above 250 m of the mean sea level only (shaded/line terrain contour interval 250 m).
Fig. 7. Model simulated low-level (925 hPa) wind convergence (negative), divergence (positive), and zonal and meridional divergent wind vectors at (a) 1200 UTC 14 May, (b) 0600 UTC, (c) 1200 UTC, (d) 1500 UTC 15 May and (e) 0000 UTC, (f) 0600 UTC 16 May 2016. The elevation shows above 250 m of the mean sea level only (terrain contour [line] interval 250 m).
synoptic environment near Sri Lanka’s coastal areas (particularly on the west coast) increased the EPT of the boundary layer air (Fig. 8b). A high EPT together with a high WVF facilitated the increase of instability and convective development in this area. Favorable conditions for the creation of a deep and moist convection include high CAPE values and a strong ascending air current that can reach the free convection level (Schultz et al. 2000). Generally, the results also highlight that even with high CAPE values (> 2500 J kg⁻¹), the resulting rainfall would not be strong or even occur at all if the available moisture was low and the vertical motion was weak (as evident on the eastern side of the island). On the other hand, high CAPE values with a high moisture supply and strong vertical motion (as evident on the western side of the island) generate strong rainfall. Similar conditions were seen during typhoon Morakot in Taiwan (Lin et al. 2011).

The strong upward motion and deep convection were further examined by the cross-section plot of EPT and vertical velocity (Figs. 9a–d). Steep vertical gradients in the EPT cross section to the west of the heavy rainfall area on the west coast of Sri Lanka suggested that low-level moist air flows with an EPT greater than 350 K were the main energy source driving the weather system (Figs. 9a–c). These relatively high EPT (EPT ridges) in the low-level are often the burst points of thermodynamically induced events like this (Figs. 9a–d). Lifting of moisture-rich air parcel from its original pressure level to the upper levels of the troposphere will release the more latent heat of condensation in that parcel. This also could be confirmed with the follow-up heavy radar reflectivity in these areas (Figs. 9f–h). At 0600 UTC 15 May, dry air with EPT values less than 351 K was prevalent in the middle levels over Sri Lanka (Fig. 9a). A relatively low echo top height at this time (Fig. 9e) suggests that the vertical development of convection was first suppressed by the dry air capping. Later, this resulted in an explosive deep convection and strong upward motion (Fig. 9d). The simulated radar reflectivity can also be used as a proxy to indicate the deep cloud convection and rainfall in the area. Figures 9e–h illustrate the cross sections of the radar reflectivity that can be used to identify the vertical distribution of convective cores. The strongest upward motions were associated with the largest reflectivity up to 60 dBZ. The overall effect during the period resulted in strong uplift of moisture, leading to a heavy rainfall event in the area.

c. Role of topography

The dynamical forcing of the local topography was
Fig. 9. Model simulated equivalent potential temperature (in line contours at an interval of 3 K), vertical velocity (shaded contours) in vertical cross section of the A–B transect (given in Fig. 1c) valid at (a) 0600 UTC, (b) 1200 UTC, (c) 1500 UTC and (d) 2100 UTC 15 May 2016. Simulated radar reflectivity and wind vectors (e–h) in corresponding times respectively as in Fig. 9 (a, b, c, d).
also a critical aspect of this event. To further examine the effects of topography on precipitation, sensitivity studies with the terrain height changed to zero (case Topo-Z), a quarter (case Topo-Q), and half (case Topo-H) of the control run were conducted. Figures 10a–c show the differences between the sensitivity cases (Topo-Z, Topo-Q, and Topo-H) and the control run for the 48-h accumulated rainfall (15–16 May) over Sri Lanka. To further analyze the difference, two rectangular areas over the western part of the island were selected. Rectangle A in Figs. 10a–c is the Colombo metropolitan region, which represents the area in which the most flooding over the coastal and plain areas occurred, as indicated in Fig. 1a. Rectangle B in Figs. 10a–c is the western slope of the Central Mountains where another heavy accumulation of rainfall was observed, as displayed in Fig. 1a. The differences of rainfall amounts over Rectangle A indicate that coastal precipitation is enhanced as the topographic height is reduced. The difference in 48-h accumulated rainfall between case Topo-Z and the control could be as high as 400 mm (Fig. 10a). The northeasterly airflow associated with the LPS easily penetrated the island in the case Topo-Z because of the absence of the mountains’ blocking effect, and then the flow interacted with the westerly monsoon flow over the western coastal area. However, the different rainfall amounts over Rectangle B indicate that the precipitation amount is reduced as the topographic height is reduced (Figs. 10a–c) because the effect of mountain lifting on the westerly airflow is reduced. The 48-h accumulated rainfall over Rectangle B in Topo-Z was approximately 400 mm less than that in the control run. Figure 11 depicts the percentage changes of the accumulated total rainfall in both rectangles. Over the Colombo municipal region (Rectangle A), both the maximum and average accumulated rainfall increased as the topographic height was reduced. In the Topo-Z case, the maximum and average accumulated rainfall over Rectangle A increased by 60 % and 13 % relative to the control, respectively. However, over the western mountain slope area (Rectangle B), the maximum and area-average accumulated rainfall decreased as the topographic height was reduced (Figs. 11a, b). In the case Topo-Z, the maximum and average accumulated rainfall decreased by 33 % and 17 % relative to the control, respectively. These results over Rectangle B demonstrated that the mountains again critically affected the air mass lifting and then enhanced the upward motion over the western slope area.

The detailed mechanism of this event is summarized and illustrated in Fig. 12. According to the results,
we suggest that the interaction of westerlies with the land mass and the northward-propagating LPS modified the low-level moisture convergence structure. This low-level convergence zone was sustained for a relatively long period of approximately 20 h, with a constant moisture supply. This persistent low-level convergence enabled a deep convection to occur, which was supported by a continuous moisture supply in this area. This was the primary mechanism that caused the enhanced rainfall over the western coastal
bent. The Central Mountains blocked the northeasterly flow of the LPS, whereas the western slopes of the mountains uplift the westerly monsoon. Consequently, the rainfall was particularly enhanced over the western slopes of the Central Mountains of the island.

4. Summary and conclusion

This study numerically simulated and examined the mechanism behind the heavy rainfall event that occurred in Sri Lanka from 14–17 May 2016. The WRF was used to simulate the event and the physical conditions that led to it, and the model performance was also assessed. The extreme rainfall was examined based on the analysis of NCEP-CFSv2 data, satellite imagery, ground weather station data, and model simulation results. A single domain with a fixed horizontal resolution of 3 km was used with the best-selected model configuration in the simulations for detailed analysis of the event.

Model simulation captured the synoptic-scale features of atmospheric circulation involved in the heavy rainfall event. The model results satisfactorily estimated the path of the LPS and its timing, and they captured the overall rainfall trend of the heavy rainfall event over Sri Lanka. However, some spatial and temporal deviations with respect to the total rainfall were apparent at certain locations. Overall, the continuous low-level moisture supplies from the BoB and from the Arabian Sea/Indian Ocean, the sustaining low-level convergence zone that resulted from the interaction of the LPS and the westerlies, and the locally enhanced deep convection together with a strong vertical motion appeared to be the prominent features of this event that resulted in the unprecedented heavy rainfall. Sensitivity studies indicated that rainfall over the western slope area of the mountains was enhanced by mountain lifting, whereas western coastal rainfall was reduced because the mountains blocked the northeasterly flow of the LPS. The results indicated that the observed extreme rainfall event over the western part of the island was the result of interactions among the following phenomena: (1) the LPS in the BoB, (2) moisture-rich westerlies from the Indian Ocean and the Arabian Sea, (3) persistent low-level convergence, and (4) the orographic effect from the Central Mountains of Sri Lanka.

The findings of this study verified the usefulness of numerical mesoscale models, such as the WRF for predicting and studying the dynamics of extreme events such as the heavy rainfall event in May 2016 over Sri Lanka. The WRF model demonstrated satisfactory ability for predicting the major features of this extreme event. Longer lead time warnings for extreme rainfall and flood events through the use of a single unified modeling system such as the WRF could have a considerable value in disaster preparedness and management in Sri Lanka.

Supplements

The supplementary material contains Figs. S1 and S2, which present the model simulated WVFs and wind convergence/divergence areas at 925 hPa during 16–17 May 2016. The purpose of these plots is to provide supporting information for the detail processes of the WVF and the locations of convergence/divergence areas in Figs. 6 and 7.

Acknowledgments

The authors acknowledge two anonymous reviewers for their valuable comments. The authors are grateful to the Department of Meteorology of Sri Lanka for the ground observation data. We also acknowledge Ms. Anusha R. Warnasooriya at the Department of Meteorology of Sri Lanka for some insights of the event and observations and Mr. R. B. Koralegedara and Mr. Susantha Udagedara for the initial coordination with the data purchase. Further, we would like to thank NCEP, National Center for Atmospheric Research for the initial/boundary conditions data. This research was produced with the financial support of the Ministry of Science and Technology, Taiwan (MOST 105-2111-M-001-003 and MOST 106-2111-M-001-009), and the Cuomo Foundation, Monaco. The contents of this document are solely the liability of its authors and under no circumstances may be considered as a reflection of the position of the Cuomo Foundation and/or the IPCC.

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