

RESEARCH ARTICLE

Impact of Madden Julian oscillation (MJO) and other meteorological phenomena on the heavy rainfall event from 19th – 28th December, 2014 over Sri Lanka

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Abstract: This study revealed the influence of Madden Julian oscillation (MJO) and cold surge (CS) on the extreme rainfall events that occurred in Sri Lanka from 19th to 28th December 2014. During this period, the Northeast Monsoon winds over the Bay of Bengal were strengthened by a CS, which intensified convective activity over the Bay of Bengal. Simultaneously, convective phase 3 of the MJO, which was located over the eastern Indian Ocean is associated with a positive rainfall anomaly over Sri Lanka. Westerly wind anomalies associated with MJO phase 3 shifted southward due to the strengthening of northeasterly winds by the CS, forming an incipient vortex to the southeast of Sri Lanka. The low level moisture transport was enhanced by this vortex circulation together with strong cross-equatorial moisture flux transportation. The convectively active phase of MJO provided favourable conditions such as low level convergence, cyclonic relative vorticity, and deep convection for the intensification of vortex into a tropical depression over the southwest Bay of Bengal. Strong upward motion and combination of strong low level convergence with upper-level divergence allowed evacuation of the ascending air mass, aiding the intensification of deep convection. This persistent vertical coupling structure allowed deep convection of moist warm air, which led to heavy rainfall during the period. Combination of a number of factors, such as local terrain effects, CS at low levels, MJO wet phase and a vortex to southeast of Sri Lanka led to an intensification of the tropical depression that caused an extreme rainfall event over the Eastern and Northeastern parts of Sri Lanka.

Keywords: Cold surge, convection, convergence, divergence, MJO.

INTRODUCTION

The nine consecutive days of torrential rains that occurred over the Northeastern, Eastern and Southeastern parts of Sri Lanka (Figure 1) from 19th to 28th December 2014 resulted in one of the worst flooding events in the island (<http://www.dmc.gov.lk>).

According to the Disaster Management Centre, during this period 1.1 million people were affected by floods, landslides, and strong winds in 22 out of 25 districts. There were reports of 39 deaths, 20 cases of injury and 2 cases of missing persons. The Government of Sri Lanka announced that sluice gates had to be opened in the affected provinces, as hundreds of reservoirs (300 in Anuradhapura District alone) had exceeded danger levels. The North-Central and Eastern Provinces appeared to be worst affected.

Figure 1 shows the daily rainfall distribution from 19th to 28th December 2014. It is evident that between 19th and 21st December, heavy rainfall distribution was confined to the Eastern, and North Central Provinces (Figure 1), while heavy rainfall events extended to the Southern, Uva and Central Provinces during the period 24th to 25th. Again fairly heavy rainfall was confined to the Eastern and Northeastern parts of the island on 26th and 27th December.

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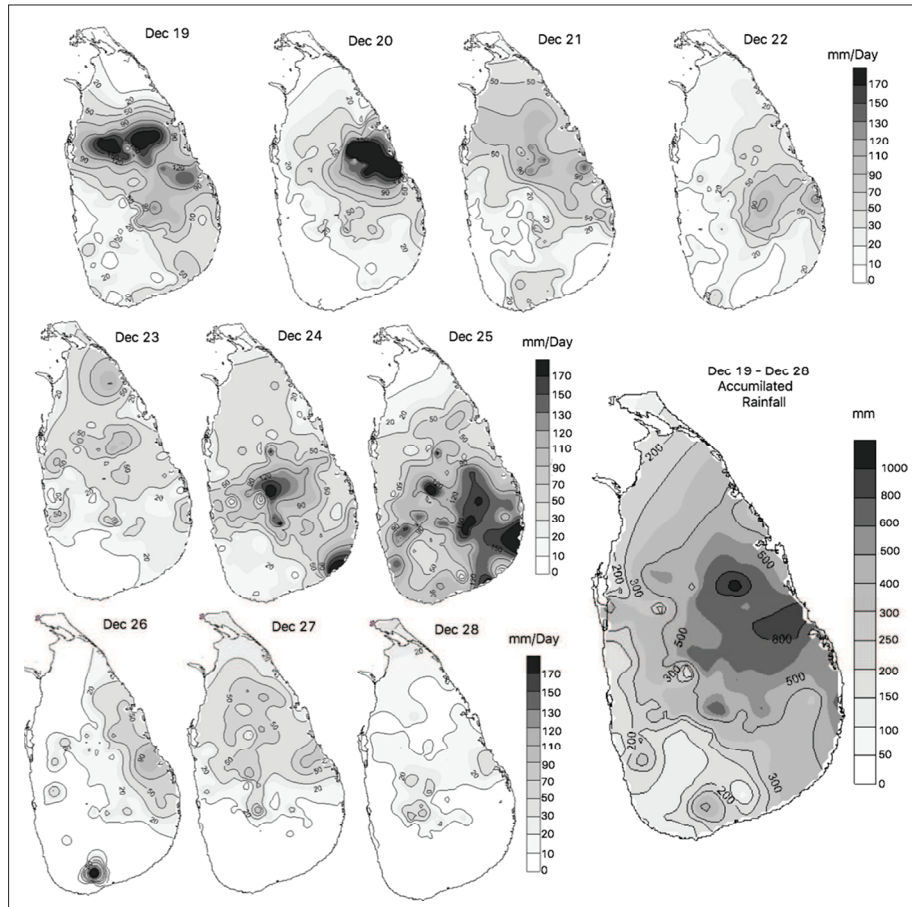


Figure 1: Daily rainfall (mm/day) distribution and total rainfall (mm) from 19th to 28th December 2014

During the period more than 100 mm of rainfall was recorded over most parts of the island and more than 500 mm of rainfall was received in the Eastern, North Central, Uva and Central Provinces with some areas in the Polonnaruwa District receiving more than 1000 mm of rainfall, which is nearly 2/3 of the annual rainfall of this district.

In order to investigate the cause of extreme heavy rain spells, we examined the occurrence and propagation of the Madden Julian oscillation (MJO) and its influence associated with the large-scale atmospheric circulations during the extreme rain event that occurred over the island.

Madden Julian oscillation (MJO) and its impacts on the extreme high rainfall event

Intra-seasonal oscillation (ISO) is a global pattern of anomalous atmospheric circulation that is closely related to variations in precipitation in many regions of the

tropics. The first documentation of ISO based on data from modern instruments was given by Madden and Julian in their pioneering studies (Madden & Julian, 1971; 1972), and hence often referred to as the Madden-Julian oscillation (MJO).

The importance of MJO to tropical and global weather and climate has become increasingly apparent. Direct impacts of the MJO on tropical weather and climate phenomena have been widely documented (Zhang, 2013). Weather events due to the influence of MJO include precipitation, surface temperature, tropical cyclones, tornados, floods, wildfires, and lightning (Zhang, 2013).

The influence of MJO on precipitation could lead to extreme events, such as record breaking precipitation. On a global scale, extreme rainfall events during active MJO periods (situations of strong convective activity anomalies related to the MJO) are about 40 % higher than in its quiescent periods (Jones *et al.*, 2004).

MJO influences on extreme rainfall in boreal winter over the contiguous United States are substantial (Jones & Carvalho, 2012). Extreme rainfall events occur twice more frequently when the MJO is active (in any phase) compared to the inactive phase (MJO with weak convective activity anomalies), and most frequently when the MJO convection centre is over the Indian Ocean. Observational studies have suggested that certain flooding events might have occurred under the influence of the MJO. The examples include a series of severe floods during the summer of 1998 in Eastern China (Zhu *et al.*, 2003), the Afghanistan flood of April 2002 (Barlow *et al.*, 2005), the extreme 2006 - 2007 flood in the Southern Peninsula of Malaysia (Tangang *et al.*, 2008), and the heavy floods on record in Jakarta during 2002, 2007, and 2008 (Aldrian, 2008). Early winter (November – December) floods in the northwest US tend to occur when MJO convection is active over the Indian Ocean (Bond & Vecchi, 2003).

Cold surge

Cold surge (CS) is known as an episodic southward progression of cold, mid-latitude air in the lower troposphere, along the eastern flank of the Tibetan Plateau during the Northern Hemisphere winter. The CS signal propagates southward into the tropics. After arriving at the South China Sea (SCS), the CS intensifies convective activity over the SCS, Borneo Island, and sometimes the Maritime Continent in the Southern Hemisphere (Johnson & Priegnitz, 1981; Chang *et al.*, 2005). There is a possibility that the westerly deflection of cold surges extend into the Bay of Bengal (Chang *et al.*, 2005). Deep convection is likely to develop as the cold dry air moistened by the overwater trajectory (Johnson & Houze, 1987) and after it is transformed by substantial surface sensible and latent heat fluxes (Johnson & Zimmerman, 1986).

METHODOLOGY

Outgoing longwave radiation (OLR)

OLR data from the National Oceanic and Atmospheric Administration (NOAA) was used as a proxy for deep tropical convection. Interpolation is applied separately to the ‘day’ and ‘night’ maps to remove missing data, and these maps were then averaged to provide a single daily map on a 2.5 ° grid as described by Liebmann and Smith (1996).

NCEP-NCAR reanalysis data

Global analyses of winds from 1981 to 2010 were obtained from the NCEP-NCAR (National Centres for Environmental Prediction - National Centre for Atmospheric Research). Reanalysis (Kalnay *et al.*, 1996) on a 2.5° grid was done to create composite maps of circulation and vertical cross sections.

MJO index

Real-time multivariate MJO (RMM) index developed by Wheeler and Hendon (2004) defined the MJO through projection of daily anomaly data onto the leading pair of empirical orthogonal functions (EOFs) of combined fields of equatorially-averaged (15 °S – 15 °N) OLR, 850 hPa zonal wind, and 200 hPa zonal wind, to obtain two principal component time series (RMM1 and RMM2). The RMM1 and RMM2 indexes defined a 2D phase space. This phase space was used to define 8 ‘strong’ MJO phases, each corresponding to the geographical position of its active convective centre (labelled 1 – 8 in Figure 2), and a ‘weak MJO’ category defined when the amplitude is less than 1. These phases make up a full MJO cycle originating from the western Indian Ocean and decaying over the central Pacific. For instance, phases 2 and 3 mark the time when the MJO’s convective envelopes are centred near the western and eastern Indian Ocean and phases 7 and 8 mark the time when it is near the dateline in the Pacific.

MJO activity during the event

According to the RMM index (Wheeler & Hendon, 2004), strengthening of MJO during the week from 18th to 28th December with the enhanced phase with an intensity of 1.5 centred over phase 3 in the eastern Indian Ocean is evident in Figure 2. During that week, enhanced convection was stronger over the Indian Ocean (Figure 4) and a weaker suppressed convection was observed, at least briefly over the West Pacific, consistent with the current MJO signal. The MJO signal propagated towards the East and centred over phase 4, the Maritime continent from 28th to 30th December 2014 (Figure 4).

Daily rainfall data

Daily rainfall data from 19th – 28th December 2014 from the Department of Meteorology, Sri Lanka were used in this study.

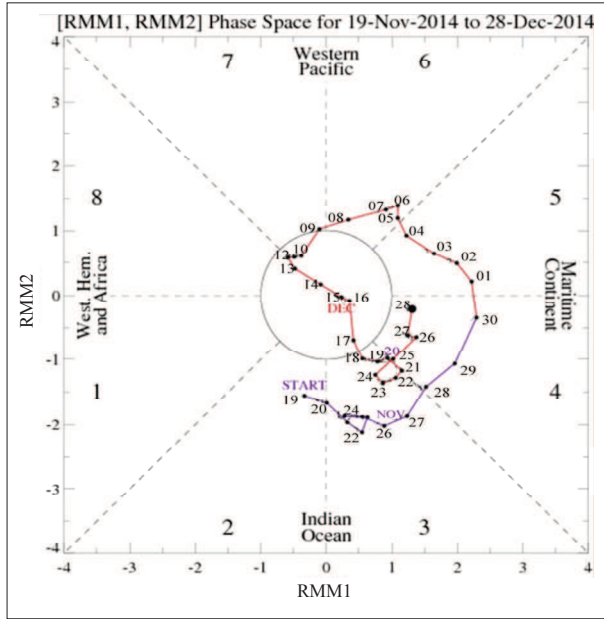


Figure 2: Phase diagram of RMM index (Wheeler & Hendon, 2004) from 19th November 2014 to 28th December 2014. Each point represents a day. Eight phases and corresponding approximate locations of enhanced convective signals of the MJO are labelled. Points within the circle represent weak or no MJO (Source: www.cpc.ncep.noaa.gov/)

GFS re-analysis data

Global forecast system (GFS) is a weather forecast model produced by the NCEP (Compo *et al.*, 2011). GFS analysis data with 0.50 grids from 19th to 28th December 2014 were used to observe the circulation features during the heavy rainfall event.

RESULTS AND DISCUSSION

MJO activity during the event

Figure 3 illustrates the power spectra of the time series of daily OLR anomaly data averaged over 75°E to 85°E and equator to 10°N for the period from 15th November 2014 to 31st January 2015. It is clearly observed that 30 – 40 day spectral peak is evident during this period. The data were temporally filtered using a Lanczos band-pass filter (Duchon, 1979) with cutoff frequencies of 0.05 day⁻¹ and 0.015 day⁻¹, which correspond to periods of 20 and 70 days, respectively to isolate the MJO signal from other high frequency synoptic scale disturbance.

The Hovmöller diagram reveals zonal displacement of atmospheric processes. Temporally filtered daily OLR anomaly data for the period from 1st November 2014 to 31st January 2015 were used to create Hovmöller diagrams to identify the MJO location. Time-longitude cross sections were created along 08°N to see the East-West propagation of MJO (Figure 4).

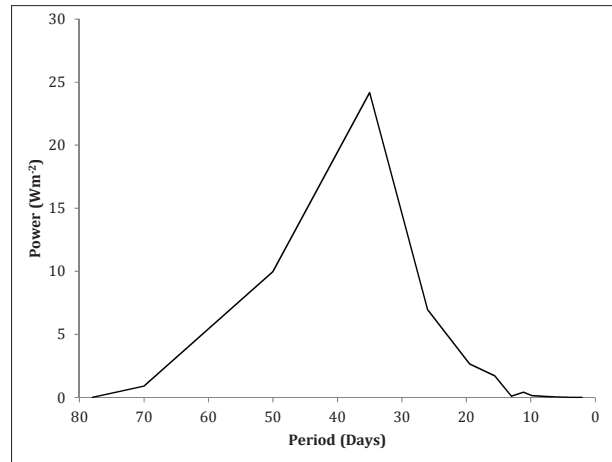


Figure 3: Power spectra of daily OLR anomaly averaged for the Sri Lankan region (00 – 10°N, 75°E – 85°E) for the period from 15th November 2014 to 31st January 2015, using fast fourier transformation

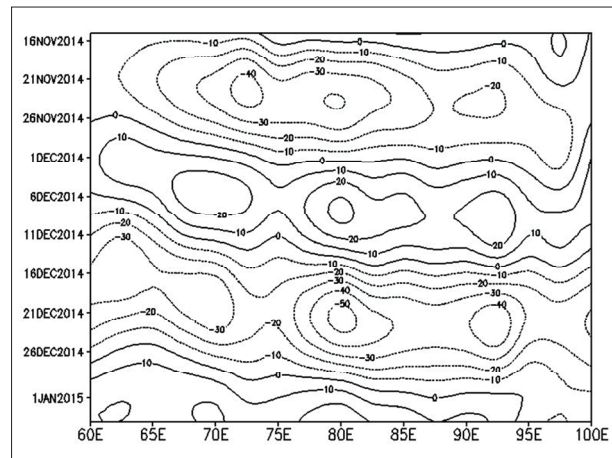


Figure 4: Time-longitude cross section of daily OLR anomaly (Wm⁻²) along 08°N (Sri Lankan region), between 60°E to 100°E, from 15th November 2014 to 05th January 2015 (temporally filtered)

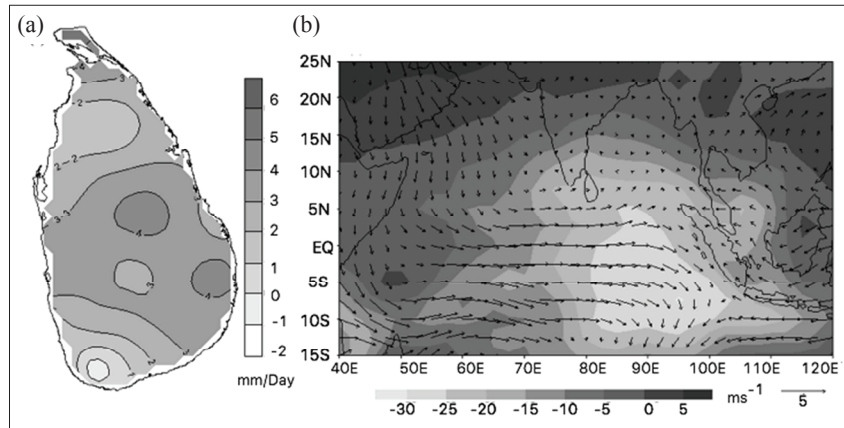


Figure 5: Map of composite rainfall anomaly (mm/day) (left) and composite daily OLR anomaly (Wm^{-2}) superposed with composite 850 hPa wind vector anomaly (right) with respect to phase 3 of MJO derived for Northeast Monsoon season (DJF) from 1981 – 2010

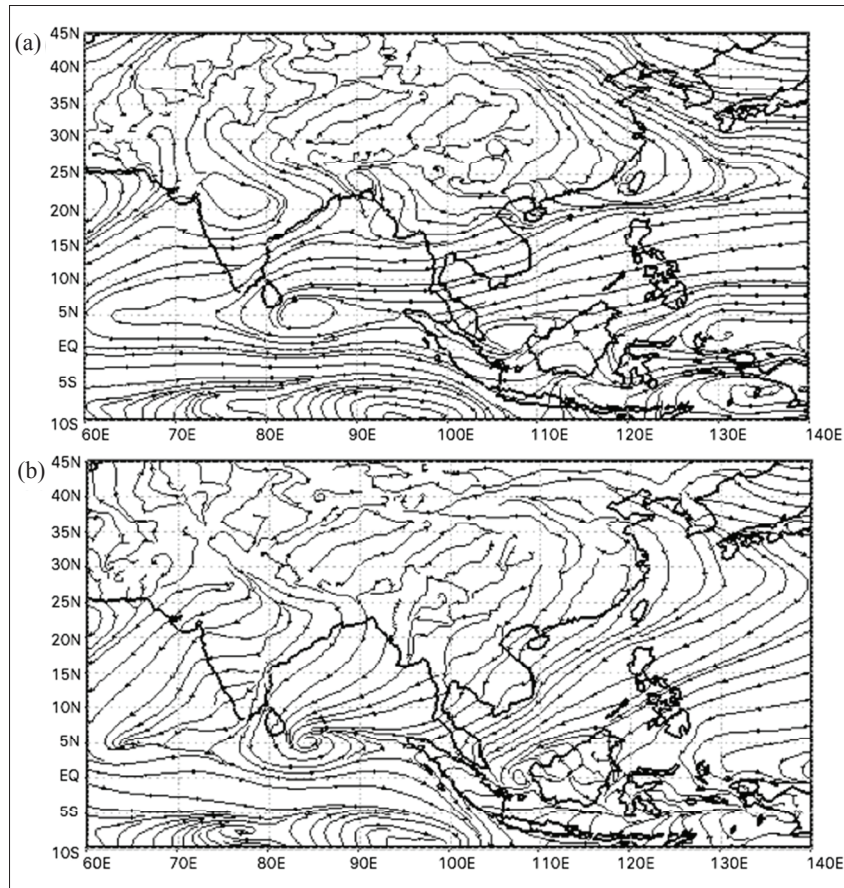


Figure 6: Streamlines averaged for the period from 19th to 28th December 2014 at (a) 850 hPa level and; (b) surface with wind speed

The time-longitude cross section revealed eastward propagation of MJO (Figure 4) with a convectively active phase (i.e., convective activities with large scale upward motion) and the opposite, namely, convectively suppressed phase (large-scale downward motion) as clearly seen by negative OLR anomaly and positive OLR anomaly, respectively. The negative OLR anomaly is evident in Figure 4 from 19th to 26th December 2014 between 80 °E to 85 °E (Figure 4) and it is associated with the convectively active phase of MJO in phase 3 (Indian Ocean).

Impact of MJO phase 3 during Northeast Monsoon season on rainfall distribution in Sri Lanka and low level circulation pattern

Daily anomalies of rainfall, 850 hPa wind vector and OLR were computed by subtracting the daily climatology from the daily actual value for all 90 days of the Northeast Monsoon (NEM) season (December - February) for the

period of 1981 – 2010. During the 30 NEM seasons of the period analysed (1981 – 2010) in this study, the number of days under MJO phase 3 is 234. For examining the intra-seasonal variation in rainfall distribution over Sri Lanka during phase 3 of MJO evolution, composite daily rainfall maps were prepared (Figure 5a). In order to examine the corresponding changes in circulation and convective anomalies, composite maps of daily 850 hPa wind vector anomalies and OLR anomalies were also prepared for phase 3 of MJO (Figure 5b).

During phase 3, widespread positive rainfall anomalies were evident over the Sri Lanka region (Figure 5a) and negative OLR anomaly associated with convective anomaly was seen to the southeast of Sri Lanka (Figure 5b). Anomalous westerly winds were seen to the south and southeast of Sri Lanka (Figure 5b). The suppression of general Northeasterly Monsoon flow in the Northern Hemisphere over the Indian Ocean is also evident (Figure 5b).

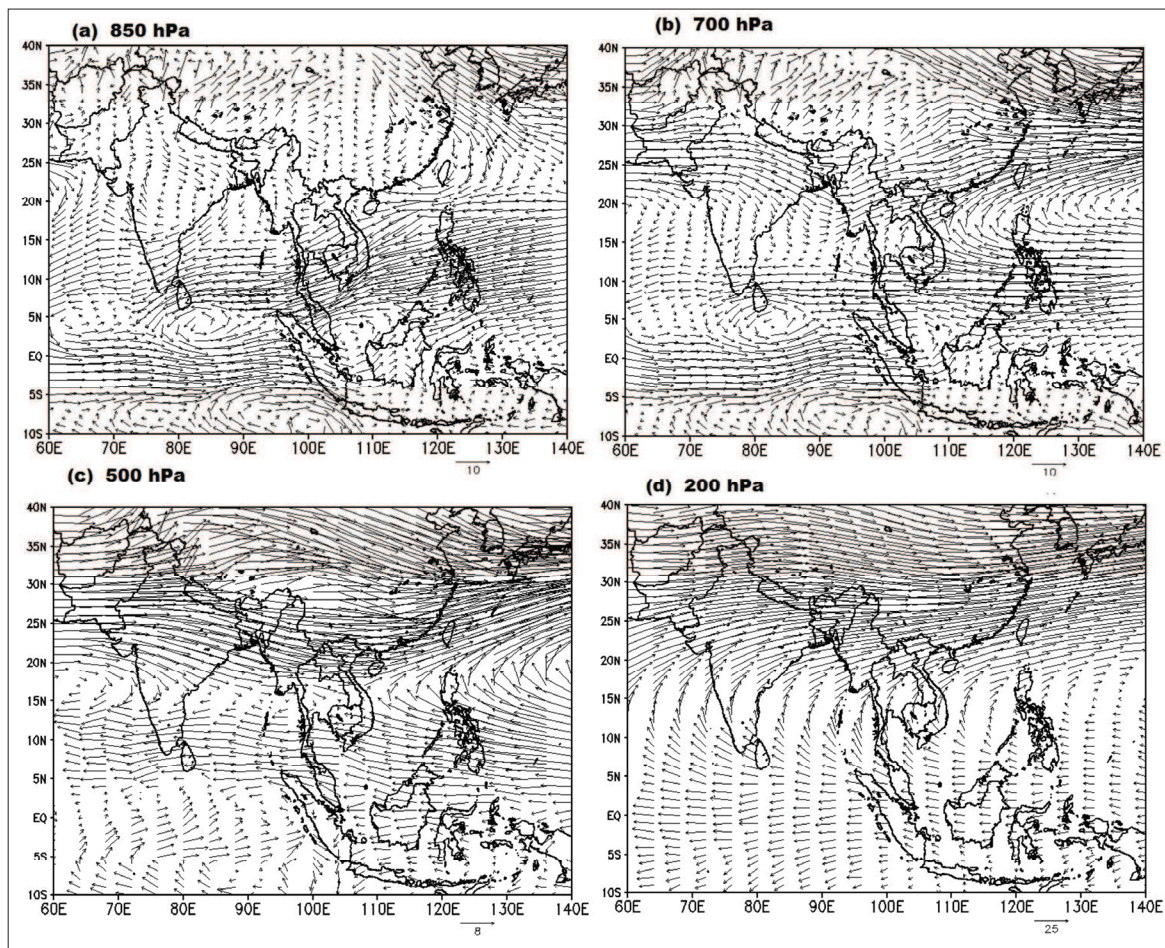


Figure 7: Mean wind vectors at different levels for the period from 19th to 28th December 2014 at (a) 850 hPa; (b) 700 hPa; (c) 500 hPa and (d) 200 hPa

Circulation patterns during the heavy rainfall event

During this period, strong northeasterly winds over the central South China Sea penetrated further southwest through the Bay of Bengal towards the Sri Lanka region in a straight trajectory at low levels (Figure 6). This CS strengthens the northeasterly winds near the surface (Chang *et al.*, 2005). Westerly wind anomaly (Figure 5b) associated with MJO phase 3 shifted southward due to the strengthening of northeasterly winds from the cold surge (Figures 6a and 6b).

The incipient vortex formed to the southeast of Sri Lanka (Figures 6a, 6b, 7a, 7b) when a monsoon easterly flow in the Bay of Bengal became stronger in association with the westerly wind burst of MJO phase 3 along the equator. A westward tilt of the vortex axis is evident with the height (Figures 6a, 6b, 7a, 7b, 7c). The vertical extension of the vortex has reached up to the 500 hPa level as seen from the horizontal wind analysis from different levels (Figure 7).

Moisture transport, convergence and the precipitation

To investigate the moisture transport process, the meridional and zonal water vapour flux, and water vapour flux vectors were computed.

The vortex circulation with strong cross-equatorial flow together with near surface northeasterly flow strengthened by CS, enhances the low level moisture transportation towards Sri Lanka. This is indicated by the strong low level moisture flux convergence over the eastern and southern parts of Sri Lanka (Figure 8) during this period. The pronounced counter-clockwise turning of the northeasterly winds and the formation of vortex during this period were associated with enhanced westerly winds south of the equator (Figure 7). The existence of strong westerly winds to the south of equator is associated with MJO (Figure 5). This vortex brings cross-equatorial flow moisture flux to the southeast of Sri Lanka at 700 hPa and 500 hPa levels (Figure 8).

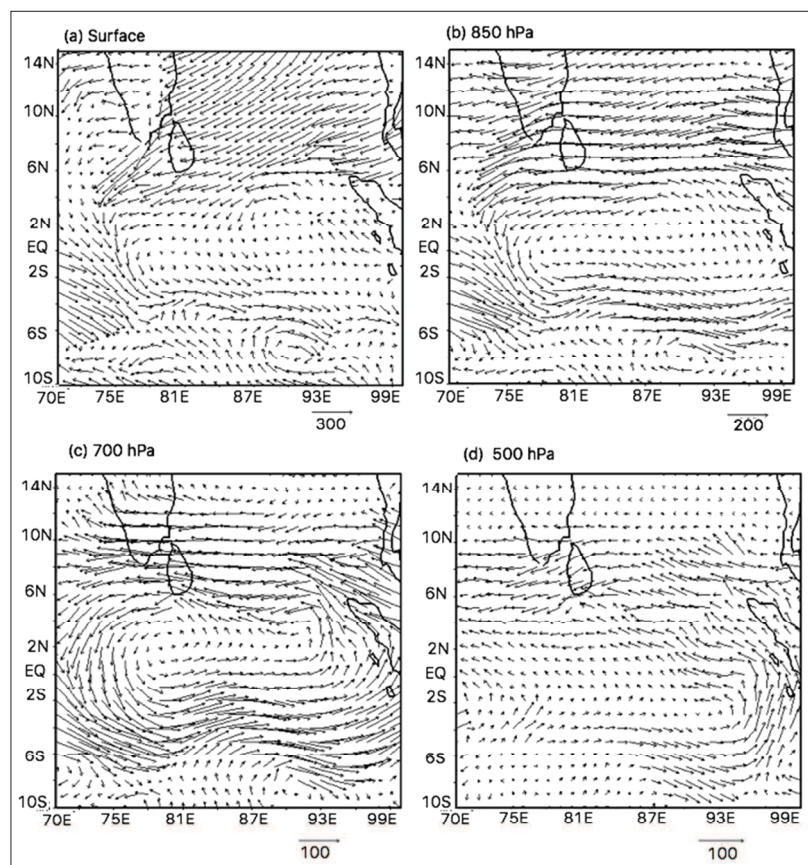


Figure 8: Mean moisture flux vectors (g/kg ms^{-1}) at different levels for the period from 19th to 28th December 2014 at (a) surface; (b) 850 hPa; (c) 700 hPa and (d) 500 hPa

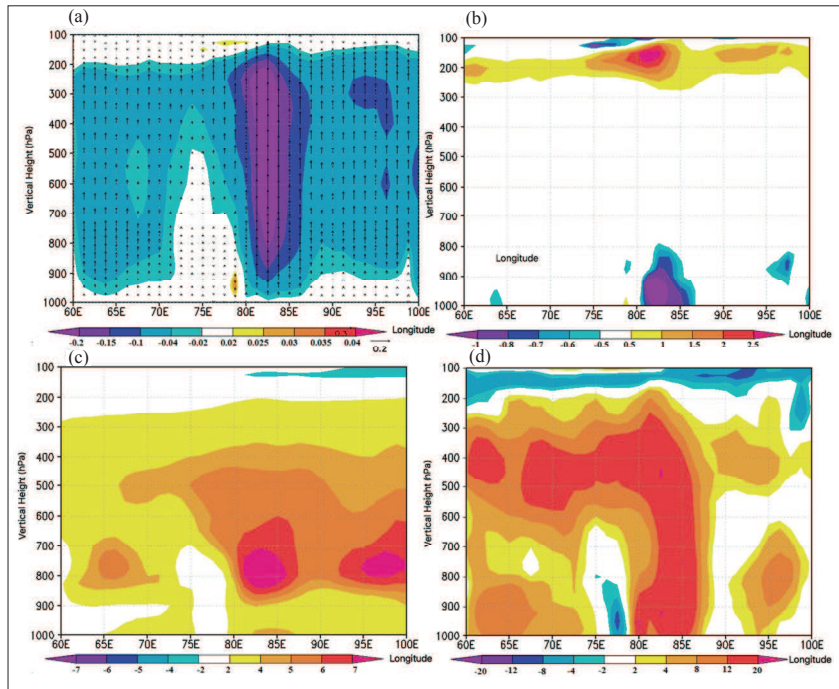


Figure 9: Pressure-longitude cross sections (averaged over Sri Lanka region from 05 °N – 10 °N) of (a) pressure vertical velocity anomaly (Pa s^{-1} , shaded); (b) relative divergence anomaly (10^{-6} s^{-1} , shaded); (c) equivalent potential temperature anomaly (K, shaded); (d) relative vorticity (10^{-6} s^{-1}) for the period from 19th to 28th December 2014

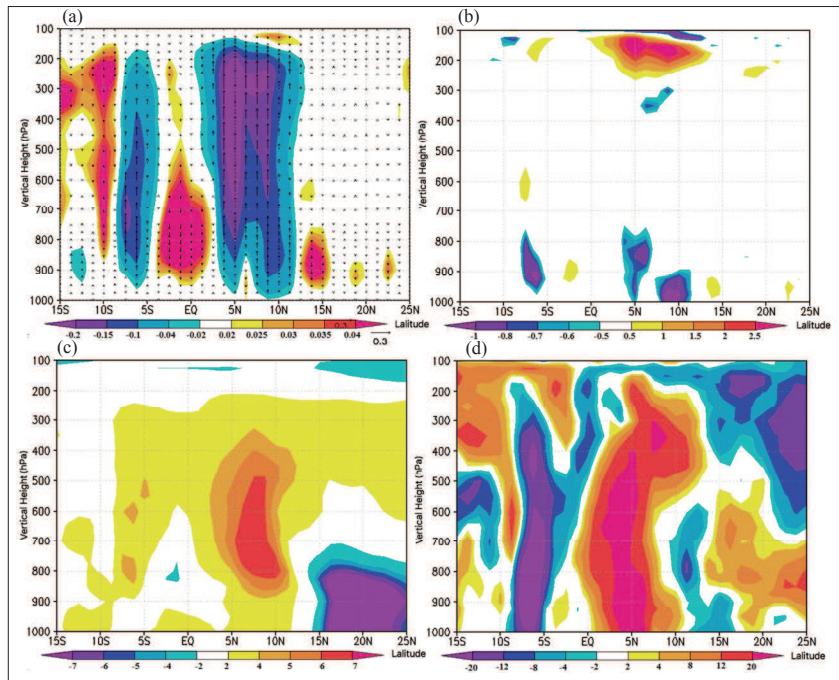


Figure 10: Pressure-latitude cross sections (averaged over Sri Lanka region from 05 °N – 10 °N) of (a) pressure vertical velocity anomaly (Pa s^{-1} , shaded); (b) relative divergence anomaly (10^{-6} s^{-1} , shaded); (c) equivalent potential temperature anomaly (K, shaded); (d) relative vorticity (10^{-6} s^{-1}) for period from 19th to 28th December 2014

The moisture convergence band along the northeast coast is related to the interaction of the Northeasterly Monsoon flow with the terrain. The moisture convergence centre southeast of Sri Lanka is in the region of the counter-clockwise turning of the winds associated with the vortex, which is coincident with the wind convergence, moisture convergence and relative vorticity maxima between 81 °E to 85 °E in 950 hPa (Figures 9d and 10d).

Circulations as revealed from vertical cross sections

To observe the associated dynamical parameters during the heavy rainfall event, the vertical profile of vertical velocity anomaly, relative divergence, equivalent potential temperature anomaly (θ_e) as a measure of convective instability, moisture flux vectors, moisture convergence and relative vorticity across and along the Sri Lanka region were analysed using NCEP reanalysis data (Figures 9 and 10).

Three conditions that must be present for the development of convection are, (i) moisture in the lower and mid levels of the atmosphere, (ii) air instability and (iii) buoyancy processes, which creates an upward force. This force causes the air parcel to accelerate vertically.

A vigorous upward motion can be seen near Sri Lanka between 80 °E and 83 °E as well as between 02 °N and 09 °N (Figures 9a and 10a). The vertical velocity is strongest between 900 and 700 hPa with values of 4 cm s⁻¹. It can be pointed out that the strong vertical velocity is not only due to dynamical forcing but is also significantly contributed by latent heat release. Latent heat release is crucial to maintain a maximum vertical velocity.

The vertical profile of θ_e anomaly indicates a lower level moisture and instability maxima between 800 hPa and 700 hPa levels (Figures 9c and 10c). Rising motion with negative pressure vertical velocity (Figures 9a and 10a) and relative vorticity (Figures 9d and 10d) are evident from the low levels to upper levels.

The cross section of the wind divergence field seen in Figures 9b and 10b shows that strong low level wind convergence mainly exists below 800 hPa. Strong upper-level divergence is apparent above 200 hPa. This situation allows evacuation of the ascending air mass, aiding its intensification. The combination of strong low level convergence and upper-level divergence is an important characteristic of deep convection with the low level moisture source, which in this case is mainly from the Bay of Bengal.

The θ_e is used operationally to map out which regions have the most unstable and thus positively buoyant air. The θ_e of an air parcel increases with increasing temperature and increasing moisture content. Therefore, in a region with adequate instability, areas of relatively high θ_e are often the burst points for thermodynamically induced convection.

Steep vertical gradients in the θ_e cross section at low levels between 950 and 700 hPa near Sri Lanka between 80 °E and 85 °E and 05 °N and 10 °N, suggest that cold dry air from the CS moistened from the Bay of Bengal with high θ_e (Figures 9c and 10c) is the main energy source driving the heavy rainfall event at low levels.

Positive relative vorticity evident across Sri Lanka from low level to mid level (Figures 9d and 10d) indicates the presence of a cyclonic relative vorticity in the vicinity of Sri Lanka. This is associated with the vortex circulations in low levels (Figures 7a and 7b) and mid levels (Figure 7c) in the vicinity of Sri Lanka.

Influence of MJO on the formation of tropical depression (TD)

Over the Indian and western Pacific Oceans, tropical cyclones preferentially occur during the convective phase of the MJO and cluster at the poleward sides of its low level equatorial westerly wind (Liebmann *et al.*, 1994). A global survey (Frank & Roundy, 2006) has indicated a consistent pattern for tropical cyclones to be most effectively modulated by the MJO. More tropical cyclones tend to occur near the poleward side of the low level westerly wind anomalies of the MJO, which enhances favourable conditions for the genesis of tropical cyclones, including their low level convergence, cyclonic relative vorticity, and deep convection, as well as reduces vertical wind shear.

The vortex, which appeared to the southeast of Sri Lanka intensified into a low pressure area on 22nd December centred near 4.9 °N, 82.8 °E and stagnated till 25th December, then moved slowly towards the north from 26th December with the eastward shift of MJO towards the phase 4 in the maritime continent from 26th December. The tropical depression (TD) can be regarded as a result of an equatorial Rossby wave response to a large-scale convective anomaly over the southwest Bay of Bengal associated with the wet phase of MJO. The disturbance dissipated at northwest Bay of Bengal near 14.6 °N, 84.4 °E on 31st December 2014. With the northward movement of the TD, extreme weather condition over Sri Lanka terminated.

CONCLUSION

This study revealed the influence of MJO and CS on extreme rainfall events that occurred in Sri Lanka on 19th – 28th December 2014. During that period, lower-tropospheric Northeasterly Monsoon winds over the Bay of Bengal were strengthened by a CS; northeasterly wind signal originated near 40 °N in Northern China, propagated southward, followed by deflecting westward, penetrating further through the Bay of Bengal into the Sri Lanka region. This CS strengthened the northeasterly winds near the surface. The westerly wind anomaly associated with MJO phase 3 shifted southward due to the strengthening of northeasterly winds from the CS, forming an incipient vortex to the southeast of Sri Lanka. This vortex intensified into a low pressure area and then into a depression. Low level moisture transport was enhanced by this vortex circulation, and strong low level moisture flux convergence over eastern and southern parts of Sri Lanka by strong cross-equatorial moisture flux transportation at mid-levels (700 – 500 hPa level). The moisture convergence in the northeast part is related to the interaction of the low level northeasterly monsoon flow with the terrain effects.

Steep vertical gradients in the equivalent potential temperature (θ_e) at low levels suggest that the cold dry air from the CS gathered moisture from the Bay of Bengal with high θ_e and is the main energy source driving the heavy rainfall event at low levels.

Strong upward motion and the combination of strong low level convergence and upper-level divergence allowed evacuation of the ascending air mass, aiding intensification of deep convection. This persistent vertical coupling structure allowed deep convection of moist warm air to occur, leading to heavy rainfall during the period.

The combination of local terrain effects, CS at low levels, MJO wet phase and a vortex to southeast Sri Lanka caused heavy rainfall that led to extreme floods over the Eastern and northeastern parts of Sri Lanka. This extreme precipitation event that occurred in phase 3 of the MJO may have important implications for the predictability of extreme events, as the MJO is predictable up to approximately two weeks.

Acknowledgement

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