

Twin tropical cyclones in the Indian Ocean: the role of equatorial waves

Sujata K. Mandke¹ · A. K. Sahai¹

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Abstract This study explores the background atmospheric conditions that led to the development of recent two sets of twin tropical cyclones in the Indian Ocean. One set of twins formed in late December 2011 (“pair A”) and other in May 2013 (“pair B”). An extensive area of active convection prevailing over wide-equatorial region and low-level westerly wind over near-equatorial region is major precursors to the two cases of twins. Convection and accompanying westerlies slowly strengthen, and the two sets of twins tend to emerge within it. The atmospheric equatorial convectively coupled Kelvin wave (CCKW) and convectively coupled equatorial Rossby (CCER) wave played key role in the formation of the two twins’ events. Wave-enhanced equatorial convection and low-level westerly anomalies produced by the combination of CCKW and CCER wave are crucial for the development of “pair A” twins. CCKW prior to “pair B” twins produced convection and westerly anomalies over equatorial region. The equatorial westerlies are further modulated by CCER wave favoring twins of “pair B.” Moreover, convection reinforced by CCER wave in OLR aided occurrence of Northern Hemispheric cyclone of “pair A” and Southern Hemispheric cyclone of “pair B.” While the CCKW and CCER wave appear to be associated with the formation of the two twin cyclone cases, more thorough understanding of the mechanisms involved needs considerable attention in forthcoming research.

Keywords Twin tropical cyclones · Indian Ocean · Kelvin wave · Equatorial Rossby wave

✉ Sujata K. Mandke
amin@tropmet.res.in; sujatamandke@gmail.com

¹ Indian Institute of Tropical Meteorology, Dr. Homi Bhabha Road, Pashan, Pune, Maharashtra 4110 08, India

1 Introduction

Two tropical cyclones (TCs) occasionally form nearly simultaneously on both sides of the equator at low latitude and near the same longitude. This cross-equatorial TCs pair is more commonly called as “twin tropical cyclones.” Twin TCs are roughly symmetric about the equator. Several researchers (Keen 1982; Nitta 1989; Lander 1990; Harrison and Giese 1991; Ferreira et al. 1996; Schreck and Molinari 2009; Shen et al. 2012) examined the twin TCs, majority of which occurred in the Pacific Ocean. However, May 2002 presents a notable case where two sets of twin tropical cyclogenesis occurred concurrently in the Indian Ocean (IO) (Shen et al. 2012).

El Niño can favor formation of twin TCs in the central Pacific Ocean (Keen 1982; Schreck and Molinari 2009). The importance of paired TCs in the initiation, maintenance and enhancement of “El Niño–Southern Oscillation” is also emphasized (Keen 1982; Nitta and Motoki 1987; Nitta 1989). The “Madden–Julian Oscillation” (MJO) (Madden and Julian 1971, 1972) creates regions of climatologically favorable conditions for tropical cyclogenesis (Liebmann et al. 1994; Maloney and Hartmann 2000a, b, Bessafi and Wheeler 2006; Schreck et al. 2012). While none of these studies looked at twin TCs specifically, MJO is also found to have strong impact on twin tropical cyclogenesis (Ferreira et al. 1996; Shen et al. 2012).

The convectively coupled equatorial waves in the tropical atmosphere are found to play major role in causing tropical cyclogenesis (Frank and Roundy 2006; Bessafi and Wheeler 2006; Schreck et al. 2012 and references therein) by considerably altering the large-scale atmospheric fields (Wheeler et al. 2000). These waves include equatorial Rossby (ER) wave, Kelvin wave and mixed Rossby-gravity (MRG) wave (Wheeler and Kiladis 1999). Recently, few others (Schreck and Molinari 2009; Shen et al. 2012) have showed that these waves can also enhance potential for twin tropical cyclogenesis. The idea that twin TCs tend to develop within the ER waves that were forced responses to stationary convection (Lander 1990; Ferreira et al. 1996), is not new.

The present study will examine the factors that caused the development of recent two twin TCs events in the IO. One set of the twins happened in late December 2011 and another in May 2013. The precursors such as increased equatorial convection and low-level westerly wind in the equatorial IO that preceded the two twin cyclone pairs will be identified. It will be shown that the favorable combination of equatorial atmospheric convectively coupled Kelvin wave (CCKW) and convectively coupled equatorial Rossby (CCER) wave might be a key ingredient for the two sets of twin tropical cyclogenesis. The criteria used for identifying a pair of twin TCs are considered in Sect. 2. Section 3 describes details of the observed data sets and methods used. Results are investigated in subsequent two subsections—background conditions in Sect. 4.1 and the role of atmospheric Kelvin waves and ER waves in Sect. 4.2, respectively. Finally, Sect. 5 presents a summary.

2 Criteria used for identification of a pair of twin tropical cyclones

Several studies have proposed widely varying definitions of twin TCs. The differences are due to the disparity in regions considered, time lag between initial formation of two systems and their longitude and latitude separation. Twin TCs were defined by Keen (1982) as two TCs forming within 8–9 days of each other, about 22° latitude separation

and with a longitudinal difference in the range 9° – 17° . Definition by Lander (1990) is restrictive that requires two TCs forming “nearly simultaneously” between the latitude of 5°N – 5°S and along the same longitude. Harrison and Giese (1991) studied twin TCs in the central Pacific Ocean forming between 20°N and 20°S and named within 8 days of each other. In the present study, two storms forming on either sides of the equator in the IO are classified as “twins,” only if they satisfy the following criteria:

1. The initial systems form at low latitudes within 15° on both sides of equator.
2. The longitudinal separation of the initial disturbances is not more than 15° of each other.
3. The initial formation of the two systems is within 8 days of each other.
4. Both the systems in the pair should reach the minimum intensity of depression during its life span. (A low-pressure system over the ocean with wind speed of 17–27 knots is defined as depression by India Meteorological Department.)

3 Data and methodology

Wind and velocity potential from NCEP reanalysis are used. NOAA interpolated daily mean outgoing longwave radiation (OLR) data are used as a proxy for convection. *Wind, velocity potential and OLR data provided by the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, are obtained from the Web site at <http://www.esrl.noaa.gov/psd/>*. Details of NCEP reanalysis data are reported (Kalnay et al. 1996), and OLR data are described by Liebmann and Smith (1996).

Kelvin waves and ER waves are identified by filtering OLR as convection proxy and also zonal wind at 850 hPa. Space–time filter for specific regions of wave number–frequency domain, originally proposed by Wheeler and Kiladis (1999), is used for isolating Kelvin wave and ER wave signal. Kelvin wave band is defined as in Straub and Kiladis (2002), which consists of 2.5- to 20-day period, eastward propagation at zonal wave numbers 1–14, and is confined between the shallow-water Kelvin wave dispersion curves for equivalent depths of 8–90 m. Following Kiladis et al. (2009), the ER wave band includes periods of 9–72 days and westward propagation at zonal wave numbers 1–10 and is bounded by the shallow-water Rossby wave dispersion curves for a range in equivalent depths of 0–90 m. The choice of equivalent depth effectively isolates the convectively coupled wave signals.

4 Results

A very severe cyclonic storm “Thane” over Bay of Bengal during December 25–30, 2011, and its southern hemisphere counterpart “Benilde” (December 28, 2011–January 4, 2012) over south IO form the first pair of the twins considered in the study. Another set is comprised of cyclonic storm “Viyaru” (May 10–16, 2013) in the Bay of Bengal competing with moderate tropical storm “Jamala” (May 8–11, 2013) in the southwest IO. In the rest of the paper, set of twins’ occurrence in December 2011 will be referred as “pair A” and in May 2013 as “pair B,” respectively. Detail account of individual TCs is available in separate reports, namely “Thane” (IMD 2011), “Benilde” (JTCW 2012), “Viyaru” (IMD 2013) and “Jamala” (JTCW 2013), and thus is not described here.

4.1 Background conditions

Throughout the literature, there has been a prevalence of studies relating twin TCs development with large-scale conditions of the environment (Nitta 1989; Lander 1990; Harrison and Giese 1991; Ferreira et al. 1996; Schreck and Molinari 2009). These studies proposed that the development of convection together with initiation and gradual strengthening of surface westerlies along and near the equator is associated with the initial stage of twin TCs formation. Accordingly, atmospheric conditions encompassing the two pairs of twin cyclogenesis events are considered in this section. Simultaneous evolution of equatorial low-level wind and convection is explored. OLR is reasonably a good representation of deep tropical convection and is used as an indicator of convection. Time–longitude illustrations of U-wind at 850 hPa (contours) averaged 5°S – 5°N and OLR (shading) averaged 10°S – 10°N over 30°E – 120°E are shown during December 11, 2011–

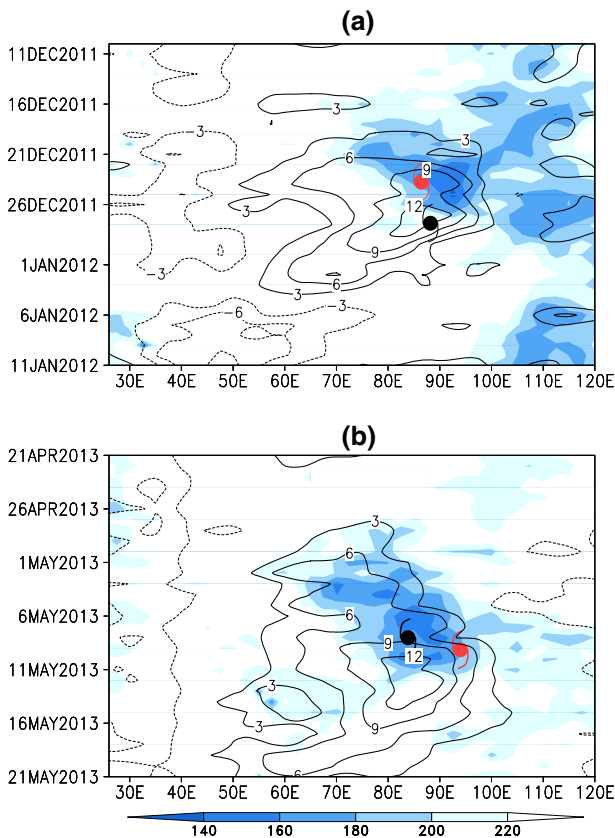


Fig. 1 **a** Longitude–time plot of 850-hPa U-wind averaged 5°S – 5°N (contours) and OLR averaged 10°S – 10°N (shading), for the period from December 11, 2011, to January 11, 2012. Contours of U-wind are plotted every 3 m s^{-1} with positive (westerly) in solid and negative (easterly) in dash, overlaid with twin tropical cyclogenesis events, for twin tropical cyclones “pair A.” The approximate genesis location of each of the TCs is overlaid using cyclone symbols (as defined by the time and longitude of their initial classification at tropical depression stage). Red-filled cyclone symbol represents Northern Hemispheric tropical cyclone, and black-filled symbol represents Southern Hemispheric tropical cyclone. **b** Same as in **a** except for the period April 21, 2013–May 21, 2013, for twin tropical cyclones “pair B”

January 11, 2012, for twins of “pair A” in Fig. 1a. Analog features of “pair B” twins are depicted from April 21 to May 21, 2013, in Fig. 1b. The approximate genesis location of each of the TCs is overlaid using cyclone symbols (as defined by the time and longitude of their initial classification at tropical depression stage) in Fig. 1a, b. *Prominent features are extensive low-level westerlies and accompanying convection initiating much prior to the both sets of twins’ occurrence.* Former work (Gottschalck et al. 2013) using “Dynamics of Madden Julian Oscillation” (DYNAMO) field campaign data (Yoneyama et al. 2013) also observed prolonged period of large westerly wind from late December 2011 to early January 2012 over central equatorial IO. *Convection is observed within and to the eastward side of the westerlies during “pair A” (Fig. 1a), while pronounced convection tends to be collocated with the westerlies in “pair B” (Fig. 1b).* Eastward shift of westerlies and convection is clearly evident (Fig. 1a, b) before the two sets of twins. Convection and westerlies further intensify within which the two sets of twins originate. Westerlies persisted long after the two pairs of twins formation, exhibit marked westward progression accompanied by gradual decrease subsequent to the formation of two sets of twins.

The cyclone “Benilde” of twin “pair A” appears to form in a region of poor convection (Fig. 1a). The reason is that the genesis location of cyclone “Benilde” is at the latitude 12.18°S, which is outside the wide-equatorial averaged region (10°S–10°N), illustrated in Fig. 1a. Nevertheless, the convection during occurrences of each of the cyclones specifically is also examined. OLR at cyclone location during the life span of all four cyclones that appeared as the twin cyclones “pair A” and “pair B” is given in Table 1. It is clear from Table 1 that all cyclones emerged in a region of increased convection (as indicated by $OLR < 220 \text{ W m}^{-2}$).

4.2 Role of Kelvin and equatorial Rossby waves

Three aspects of tropical intraseasonal variability, namely MJO, atmospheric equatorial Kelvin waves and ER waves, are known to influence twin TCs over IO (Ferreira et al. 1996; Schreck and Molinari 2009; Shen et al. 2012; Gottschalck et al. 2013) and are appraised in this section. The status of MJO, Kelvin waves and ER waves from earlier observational studies encompassing the “pair A” and “pair B” twins is described briefly prior to the analysis.

Detailed instrumental observations were collected over the central equatorial IO during international field campaign organized under the “DYNAMO” program (Yoneyama et al. 2013). Highlights of MJO and equatorial wave activity during the formation of twins “pair A” observed in the “DYNAMO” campaign spanning period from December 9, 2011, to

Table 1 Outgoing longwave radiation (W m^{-2}) during the life span of four cyclones forming two twin cyclone pairs named as “pair A” and “pair B”

Day	Thane	Benilde	Viyaru	Jamala
Day 1	132.75	210.75	148.25	152
Day 2	138	196	156.25	126.75
Day 3	149.95	161.75	176.25	115.75
Day 4	127.75	163.75	91.5	112.5
Day 5	132.5	109	95	
Day 6	191.75	180	150.6	
Day 7		205.5	195.25	
Day 8		273.5		

January 31, 2012 (Gottschalck et al. 2013) are: (1) MJO was weak, but a distinct sub-seasonal event with MJO-like dynamical properties occurred from approximately December 21, 2011, till January 4, 2012, (2) ER wave was amplified within the convective phase of the MJO-like event over the eastern IO and reached its convective maximum on December 28, 2011, (3) this ER wave constructively interacted with the MJO-like event leading to the formation of twin TCs “Thane” and “Benilde” over eastern IO. The prime features of MJO and equatorial waves (Baxter et al. 2014) at the time of “pair B” twins are: (1) Strong MJO ended during April 2013, when atmospheric ER waves and Kelvin waves became dominant in the tropical atmosphere, (2) MJO was followed by a prolonged rapidly propagating Kelvin waves over global tropical atmosphere from April to June 2013, with its enhanced convective phase over IO in early May 2013, (3) consequent upon demise of the MJO, short-lived ER waves which lasted from April till early May 2013 were prominent over Pacific Ocean.

The MJO-like subseasonal event from mid-to-late December 2011 till early January 2012 is ambiguous (Gottschalck et al. 2013). Some contradictory and diverge perspectives provided on this event by Gottschalck et al. (2013) are reproduced below to reveal its features more precisely as follows:

MJO-like event during the December 2011 was particularly interesting and controversial. The event was MJO-like in many ways with respect to dynamics. However, it also could be considered a hybrid event as it showed some characteristics of a convectively coupled atmospheric Kelvin wave (i.e., smaller spatial scale and fast propagation speed). The filtering band utilized to extract MJO signals in this study included periods of 20–100 days. It is important to note that this range is an arbitrary choice and application of this filter to OLR data placed this event into the MJO category. The cutoff period between the MJO and Kelvin wave filters could have been assigned to the traditional 30 days, which would have classified this event closer to the Kelvin wave band and not the MJO. Assignment of the 20- to 100-day band for the MJO was a choice made by the authors after viewing several different types of data and in our opinion seeing dynamics consistent with the MJO, even though it lacked some traditional attributes of the MJO.

Aforementioned results from two observational studies collectively indicate that MJO was absent/weak, whereas ER wave and Kelvin waves were the leading modes of sub-seasonal tropical atmospheric variability during the formation of the two twins’ cases. Besides, unfiltered OLR and associated westerlies over equatorial region depict eastward movement prior to both twin cyclones pairs (Fig. 1a, b), raising the presumption of the equatorial atmospheric CCKW. In view of the westward movement (in addition to eastward movement) of convection ahead of “pair A” (Fig. 1a), there is also likelihood of atmospheric CCER wave. Kelvin and ER waves greatly impact large-scale atmospheric fields although their contribution to subseasonal variability is less than the MJO (Wheeler et al. 2000) and usually have amplitude adequate to be discernible in unfiltered data (Straub and Kiladis 2002; Wheeler and McBride 2005) and consequently may be associated with TCs development. These waves have been noticed coupled with large-scale convection (Wheeler and Kiladis 1999). Hence, the MJO evolution is reviewed followed by the assessment of the role of atmospheric CCKW and CCER waves in the development of two sets of twins in this section.

State of MJO is diagnosed using 5-day running mean of daily velocity potential anomalies at 200 hPa. These data are averaged over 10°S–10°N with the period mean removed at each longitude, and its time–longitude section for twin cyclones “pair A” and

“pair B” is depicted in Fig. 2a, b, respectively. velocity potential (200 hPa) is generally used to examine the full global propagation of MJO through the tropics, as it is appropriate in those areas where other features such as OLR and low-level winds are less obvious. Strong MJO that dissipated prior to twins “pair A” is observed in Fig. 2a. Likewise, an absence of MJO is observed during twins “pair B” in Fig. 2b.

Time–longitude plot of unfiltered OLR (shading) overlaid with Kelvin wave-filtered OLR (contours), averaged 5°S–5°N from December 10, 2011, to January 10, 2012, is shown in Fig. 3a for “pair A.” Like OLR, unfiltered zonal wind at 850 hPa (shading) and Kelvin wave-filtered 850-hPa zonal wind (contours) averaged 5°S–5°N are illustrated in Fig. 3b. Similar representation for “pair B” during the period April 26–May 31, 2013, is delineated for OLR and zonal wind at 850 hPa in Fig. 4a, b, respectively. *TCs of “pair A” tend to arise within the enhanced convective and westerly phase of CCKW (Fig. 3a, b). Equatorial convection and low-level westerlies produced by CCKW preceding “pair B” twins (Fig. 4a, b) may have influenced its genesis.* Schreck and Molinari (2011) showed the role of series Kelvin waves within convective phase of MJO in the formation of two TCs.

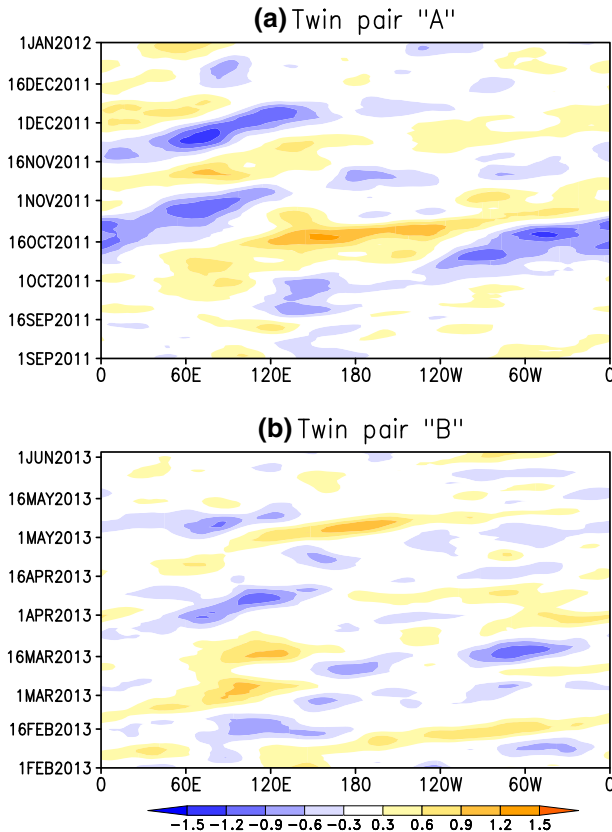
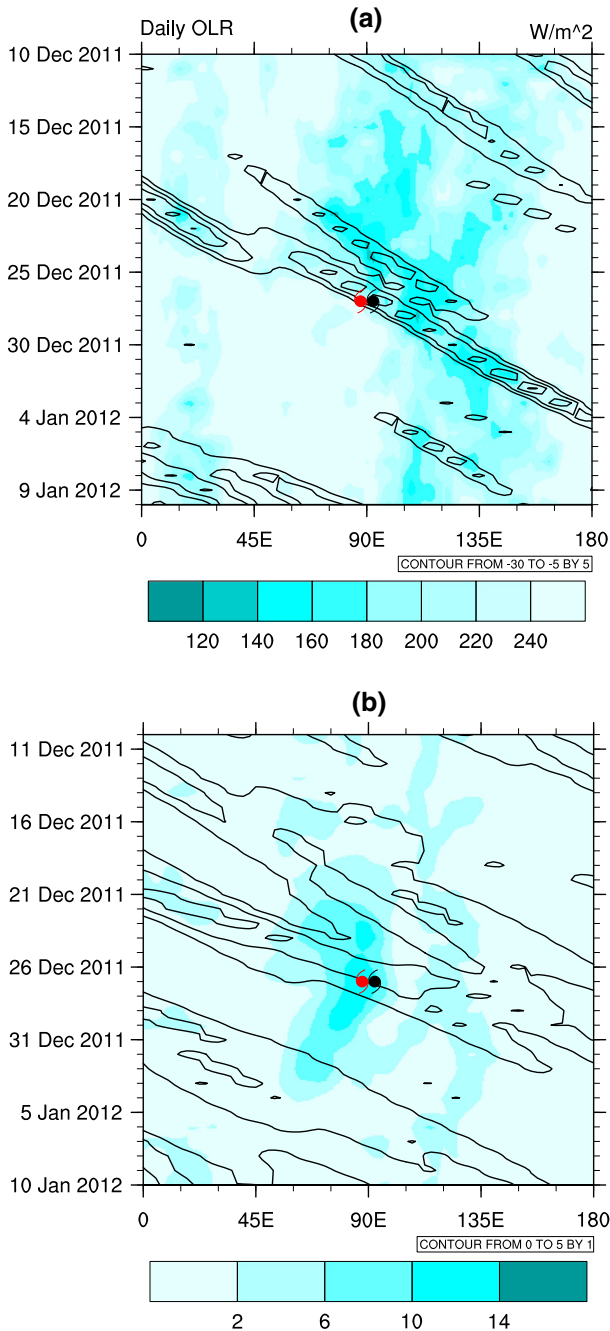


Fig. 2 **a** Time–longitude plot of 5-day running mean of daily 200-hPa velocity potential anomalies for the period from September 1, 2011, to January 1, 2012, for twin cyclone “pair A.” The data are averaged 10°S–10°N with period mean removed. The anomalies are calculated from base period 1981–2010. **b** Same as in **a** except for the period from February 1, 2013, to June 1, 2013, for twin cyclone “pair B”



ER waves in OLR and zonal wind are delineated identical to Kelvin waves. The plots for twins “pair A” show unfiltered OLR (shading) overlaid with ER wave-filtered OLR (contours) in Fig. 5a and unfiltered zonal wind at 850 hPa (shading) with ER wave-filtered zonal wind at 850 hPa (contours) in Fig. 5b. Likewise for “pair B,” ER waves in OLR and

Fig. 3 a A time–longitude plot averaging unfiltered OLR (*shaded*) and only negative Kelvin wave-filtered OLR anomalies (*contour: solid black*) averaged in the 5°S–5°N latitude band, overlaid with twin tropical cyclogenesis events for twins “pair A.” Twin tropical cyclones are plotted as in Fig. 1. Contour begins at -30 W m^{-2} , and contour interval is 5 W m^{-2} ; shade interval is 20 W m^{-2} . **b** Same as in **a** except for unfiltered 850-hPa U-wind (*shaded*) and only positive Kelvin wave-filtered 850-hPa U-wind anomalies (*contour: solid black*). Contour begins at 0 m s^{-1} , and contour interval is 1 m s^{-1} ; shade interval is 4 m s^{-1}

zonal wind at 850 hPa are presented in Fig. 6a, b, respectively. Exception is only one case of ER wave in OLR for twins “pair A,” which is shown averaged 2.5°N–15°N in Fig. 5a, although all other ER wave illustrations are presented averaged over 5°S–5°N. This exceptional case of ER wave is observed to be more organized over northern latitudes in comparison with 5°S–5°N. The structure of westward-propagating ER waves in zonal wind and OLR are consistent with each other in “pair A” and “pair B” twins, confirming that these are convectively coupled waves. *Both sets of twins tend to originate within the westerly anomalies of CCER wave in zonal wind* (Figs. 5b, 6b). Twins of “pair A” are formed within the peak of this CCER wave, whereas “pair B” cyclones emerged within the initial weak westerly anomalies of this wave. In addition, Northern Hemispheric cyclone of “pair A” (“Thane”) and Southern Hemispheric cyclone of “pair B” (“Jamala”) occurred in the enhanced convective phase of CCER wave (Figs. 5a, 6a).

The contribution of CCER wave along with CCKW is crucial in the genesis of twins “Thane” and “Benilde” forming “pair A.” This is consistent with the findings of Gottschalck et al. (2013). They showed that the interaction of ER wave with MJO-like event that could be envisaged to be hybrid and resembled features of atmospheric CCKW, lead to twin cyclones “Thane” and “Benilde.” Low-level westerly wind generated by CCKW previous to “pair B” is thereafter strengthened by CCER wave in zonal wind aiding formation of “pair B” twins.

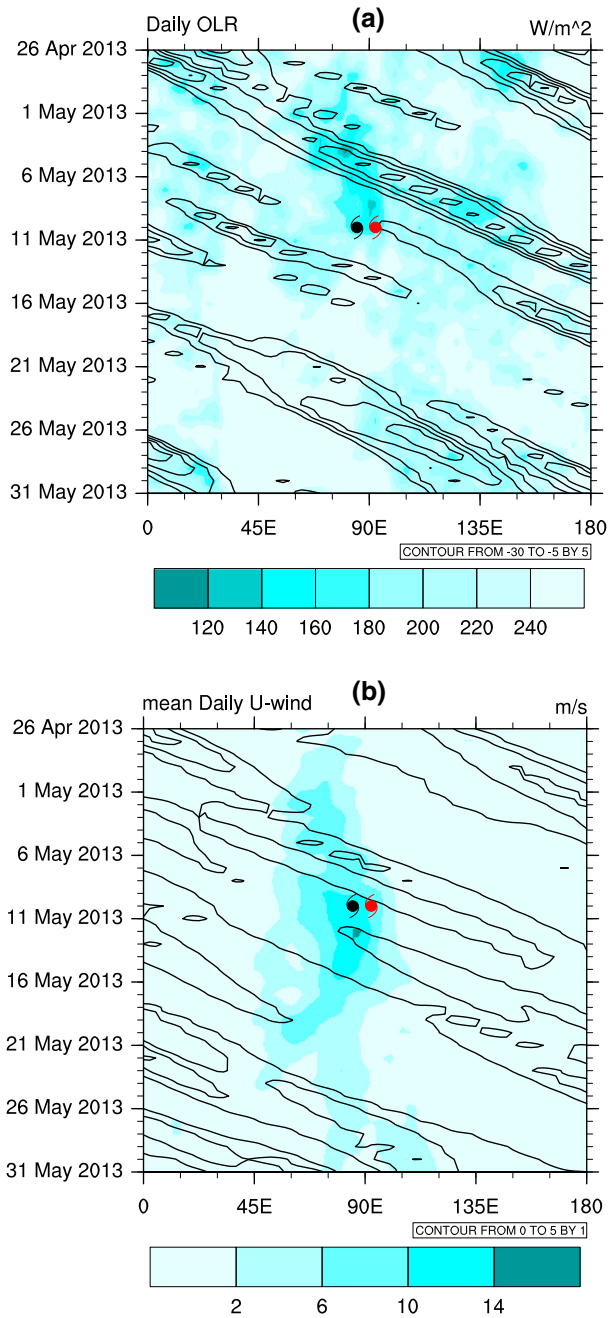
5 Summary

This study examined two sets of twin tropical cyclones that formed in the IO in late December 2011 and May 2013, respectively. Our aim has been to elucidate and advance understanding of the background atmospheric conditions within which the two sets of twins occurred. Multiple observed data sets are used for the purpose. *The role of atmospheric equatorial CCKW and CCER waves in the development of two pairs of twin cyclones is explored.* Except for the work of (Ferreira et al. 1996; Shen et al. 2012, Gottschalck et al. 2013), little can be found in the previous published literature on twin TCs in the IO. Thus, the present study gains importance.

The two pairs of twin tropical cyclones considered are formed within a large and long-lasting active convection over wide-equatorial region associated with low-level westerlies along and near equator. A major outbreak of convection accompanied by low-level westerly wind over equatorial region may thus be considered as potential early warning to TCs occurring as twins in the IO.

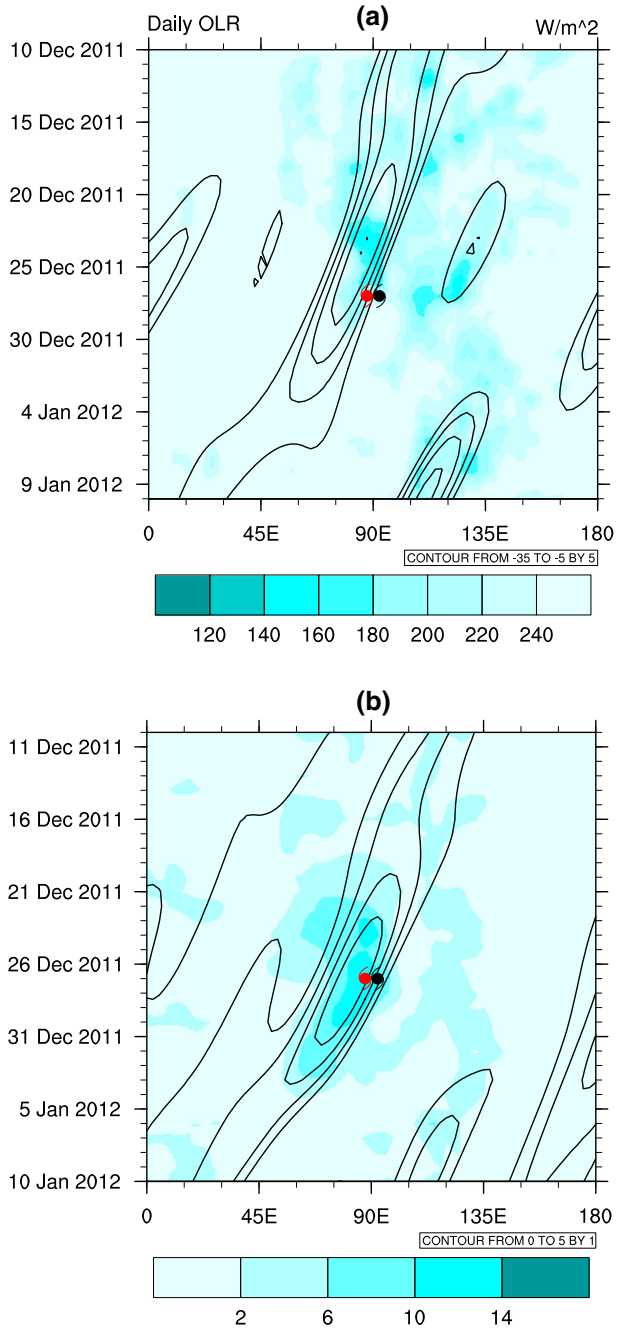
Formation of “pair A” twins is attributed to wave-enhanced convection and westerly anomalies from both CCKW and CCER wave. Antecedent CCKW initiated the background equatorial low-level westerlies and convection for “pair B.” Favorable background generated by CCKW is subsequently amplified by CCER wave in zonal wind encouraging formation of TCs forming “pair B.” Besides, convective phase of ER wave in OLR seem to be conducive for Northern Hemispheric cyclone of “pair A” and Southern Hemispheric

Fig. 4 **a** Same as in Fig. 3a except for twin tropical cyclones “pair B.” **b** Same as in Fig. 3b except for twin tropical cyclones “pair B”



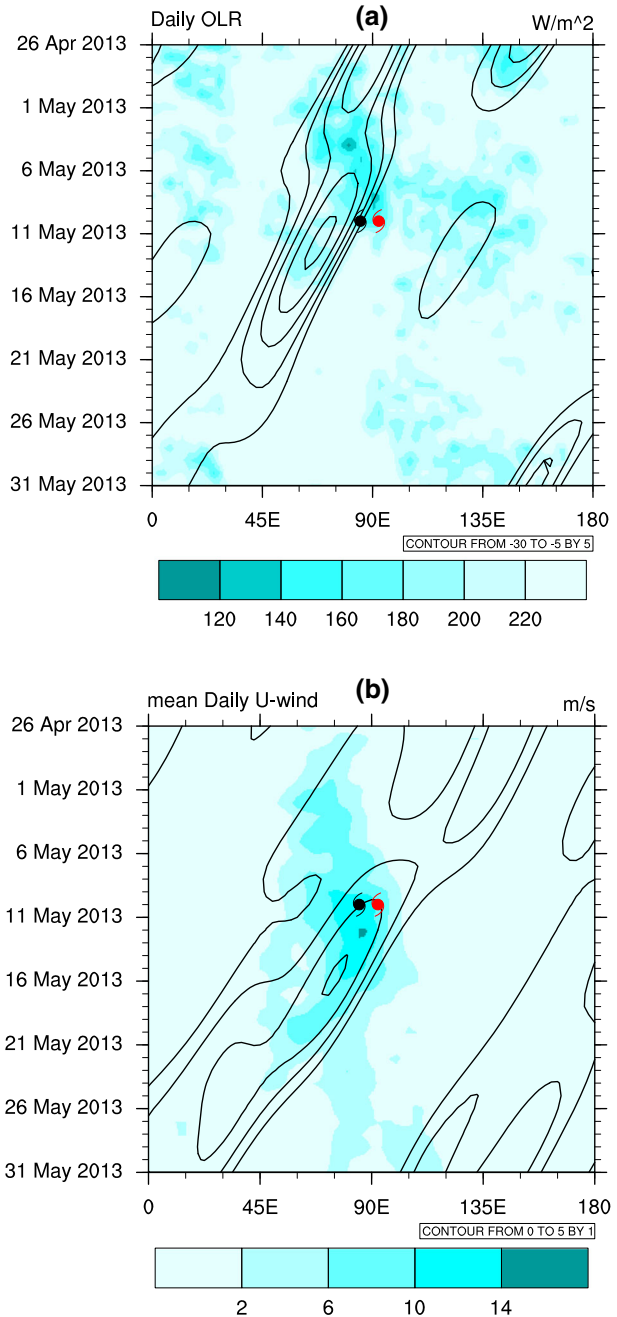
cyclone of “pair B.” Persistent strong near-surface westerly winds observed along the equator as possible precursors to two twin cyclone pairs may be related to CCER wave and CCKW as noted by studies (Kiladis et al. 1994; Kiladis and Wheeler 1995; Kiladis et al. 2009; Schreck and Molinari 2009, Moum et al. 2014).

Fig. 5 a A time–longitude plot averaging unfiltered OLR (shaded) and only negative equatorial Rossby wave-filtered OLR anomalies (contour: solid black) averaged in the 2.5°N–15°N latitude band overlaid with twin tropical cyclogenesis events for twins “pair A.” Twin tropical cyclones are denoted as in Fig. 1. Contour begins at -35 W m^{-2} , and contour interval is 5 W m^{-2} ; shade interval is 20 W m^{-2} . **b** Same as in **a** except for unfiltered 850-hPa U-wind (shaded) and only positive equatorial Rossby wave-filtered 850-hPa U-wind anomalies (contour: solid black) averaged in the 5°S–5°N latitude band. Contour begins at 0 m s^{-1} , and contour interval is 1 m s^{-1} ; shade interval is 4 m s^{-1}



Though the above results support the importance of CCKW and CCER waves for the two twin tropical cyclogenesis events, much remains to be learned about the mechanisms involved. Quantitative analysis in much greater detail is required in future, which may also be relevant to forecast twin tropical cyclones.

Fig. 6 a Same as in Fig. 5a except for twin tropical cyclones “pair B” and averaged in the 5°S–5°N latitude band. Contour begins at -30 W m^{-2} , and contour interval is 5 W m^{-2} ; shade interval is 20 W m^{-2} . **b** Same as in Fig. 5b except for twin tropical cyclones “pair B”



It is imperative to substantiate the results with some more number of cases of twin TCs in the IO. The role of the oceanic conditions in the ER waves remains unclear and deserves attention. Rather limited climatology of twin TCs that exist (Keen 1982; Lander 1990; Harrison and Giese 1991) uses widely varying definitions producing divergent results.

Besides, they had relied on very meager data. Thus, present study presents interesting prospects for future research to develop systematic definition, improved climatology and early warning of twin tropical cyclones in the IO with the aid of satellite data.

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