Effects of the Topography of Sumatra on Tropical Cyclone Formation over the Indian Ocean

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ABSTRACT. One-quarter of the world's tropical cyclones (TCs) occur in the Indian Ocean (IO) basin. The mechanisms for TC initiation in the IO are varied, but one recently discovered process involves the flow around the steep topography of Sumatra. When the low-level flow impinges on Sumatra, it is partially blocked under typical environmental stratification. Easterly low-level flow, which is commonplace over northern Sumatra during boreal winter and southern Sumatra during boreal summer, frequently generates wake vortices at the northern and southern island ends of the island that shed and move downstream over the IO. The wake vortices originating from the island tips are counter-rotating, but since Sumatra straddles the equator, the circulations are cyclonic in both hemispheres and thus have the potential for TC development. Using data from 2.5 years of observations from DYNAMO and YOTC, over three hundred wake vortices originating from Sumatra were tracked, one-third of which shed and moved away from the island over the IO. Thirteen of these vortices became TCs, constituting 25% of the TCs that occurred over IO basin during the 2.5-year period. A more recent analysis for a longer period (2008-17) has shown that vortex counts at the north and south ends of Sumatra are highest during the initiation phase of the Madden-Julian Oscillation (MJO) when low-level easterly flow maximizes at these locations. A secondary peak in vortex formation occurs during the MJO active phase when low-level westerlies exist near the equator west of Sumatra. The latter finding suggests that MJO-related, low-level westerly surges on the equator impinging on Sumatra contribute to an increase in wake vortex development. Numerical simulations have shown that circulations farther to the east, such as western Pacific remnant TCs and the Borneo vortex, can influence the development of Sumatra wake vortices and their growth into TCs over the IO.

1. Introduction

The island of Sumatra is uniquely situated in the equatorial tropics. It is the only island on the globe that extends across the equator adjacent to a major ocean basin. Given its location and steep topography (Figure 1), it is capable of significantly modifying the low-level flow in the eastern part of the Indian Ocean (IO). Of particular interest is the impact of Sumatra under conditions of low-level easterly flow, which can result in counter-rotating wake circulations being generated downstream on opposite ends of the barrier. While counter-rotating, both circulations are cyclonic since Sumatra straddles the equator, leading to the potential for these circulations to be precursors to tropical cyclones (TCs). This possibility was first postulated by Kuettner (1967, 1989) who was inspired by satellite images showing double tropical cyclones developing downstream of Sumatra over the IO. This idea laid dormant over several decades until observations obtained during the 2011 Dynamics of the MJO (DYNAMO) field campaign sparked renewed interest in this phenomenon. In particular, Fine et al. (2016) used data from DYNAMO and the 2008-2010 Years of Tropical Convection (YOTC) "virtual" field campaigns to reassess Kuettner's findings and to explore in greater detail the role of Sumatra in TC formation over the IO. More recently, Ciesielski and Johnson (2022) used reanalysis data for the period 2008-2017 to reconfirm the results of Fine et al. (2016) and investigate the relationship of the Sumatra wake vortices to atmospheric phenomena on intraseasonal to interannual time scales. Wang et al. (2020) looked further into the origins of IO TCs and found that some of the circulations can be traced back farther east to the Philippine Sea and Western Pacific Ocean. This review summarizes key findings from those studies.

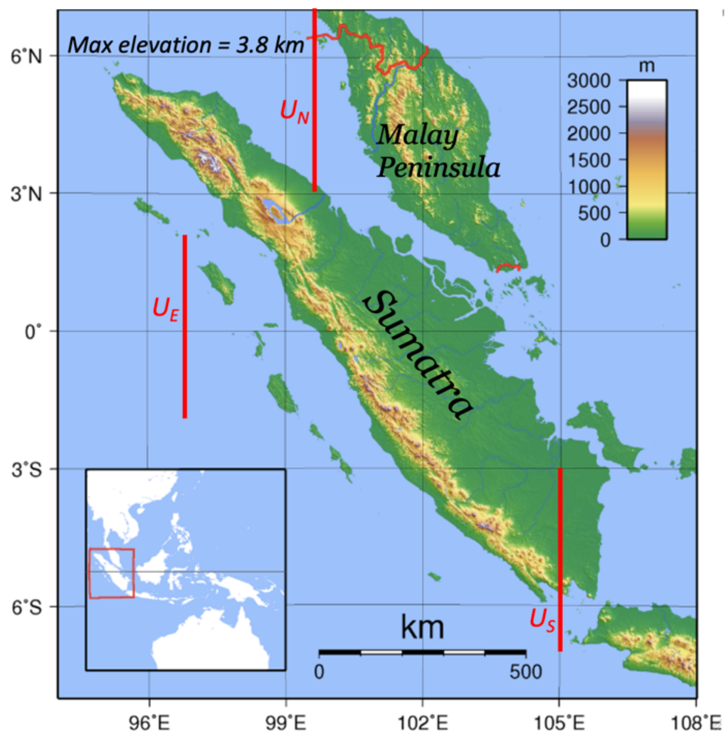

Figure 1. Topography of Sumatra and surrounding region. Red line segments labeled U_N, U_E, and U_S denote the regions over which the zonal flow U is averaged upstream of northern Sumatra (N), west of Sumatra along the equator (E), and at the southern end of Sumatra (S), respectively.

2. A 2.5-year DYNAMO/YOTC study of Sumatra wake vortices

The study by Fine et al. (2016) used the YOTC reanalysis dataset (May 1, 2008, to April 30, 2010) and the DYNAMO operational analysis (OA) dataset (October 1, 2011, to March 31, 2012) produced by the European Centre for Medium-range Weather Forecasting (ECMWF). The datasets used in their study had a spatial resolution of 0.25°, 18 pressure levels between the surface and 50 hPa, and a 6-hourly temporal resolution. The identification of vortices coming off Sumatra was based on the objective tracking code of Hodges (1995) applied to the relative vorticity field. Prior to applying the tracking code, DYNAMO and YOTC data were vertically averaged over the 925-850 hPa layer and then smoothed to retain spatial scales greater than 450 km. Analysis was carried out on wake vortices that remained in proximity to the island (non-shed cases) and those that were shed and moved westward over the IO. Information on the criteria for westward shedding, vortex vorticity amplitude threshold for tracking, and other data treatment procedures can be found in Fine et al. (2016).

Hodge's tracking code was applied to the 2.5 years of data to determine vortex genesis locations and the subsequent circulation tracks. Genesis locations can be seen in Figure 2 for both the boreal cold and warm seasons. The boreal winter monsoon is characterized by northeasterly flow crossing the Malay Peninsula and Sumatra's northern tip (Figure 2a). Correspondingly, a high frequency of lee vortices was observed downstream of these topographic features. Two analysis boxes (SN: Sumatra North; MP: Malay Peninsula) enclose the primary regions of vortex genesis. Figure 2b shows the mean flow and genesis frequency during boreal summer, with the two primary genesis locations enclosed by boxes (SS: Sumatra South; JV: Java). The boxed regions in Figure 2 are downstream of abrupt elevation changes, indicating most of the circulations are wake vortices. The average Froude number (U/Nh where U is the speed of the oncoming flow, N is the Brunt-Väisälä frequency, and h is the mean barrier height) in the 950-850 hPa layer for easterly flow over the northern regions was 0.3, suggesting flow blocking and splitting by the mountains of Sumatra leading to wake vortex generation (Smith 1989). The Froude number for the southern regions was ~0.7, indicating a slightly weaker blocking effect at that location due to the lower average topography (Figure 1). The flow pattern over the IO exhibits a broad monsoonal seasonal reversal such that it is during the hemisphere's respective cold seasons that flow with an easterly component dominates across the island's extremities contributing to maxima in vortex genesis in the four boxed regions in Figure 2.

Tracking results for the two boxed regions near the northern end of Sumatra are shown in Figure 3. Wake vortices primarily occurred during the boreal fall and winter seasons (Figures 3a, b) when the flow across northern Sumatra was predominantly easterly (Figure 3c). Over half the vortices from region SN were shed while a far smaller percentage of the vortices were shed from region MP. Those that shed from the northerly tip of Sumatra occurred in slightly stronger low-level easterly flow than non-shed cases, which likely explains their shedding. The five TCs that occurred in the northern IO were from vortices that shed from region SN during boreal fall. The seasonal distribution of wake vortices for southern regions (Figure 4 a, b) shows wake vortices were more broadly distributed throughout the year although the majority occurred during austral winter and spring seasons. As was the case for northern Sumatra, most of the shed vortices occurred in easterly flow (Figure 4c). The eight TCs that occurred in the southern IO were during austral spring and summer seasons. In total, 309 cyclonic vortices were detected in the four regions, 103 (33%) of which were shed. Thirteen percent of the shed vortices eventually became TCs, representing 25% of the total (51) TCs occurring in the entire IO basin during the 2.5 years.

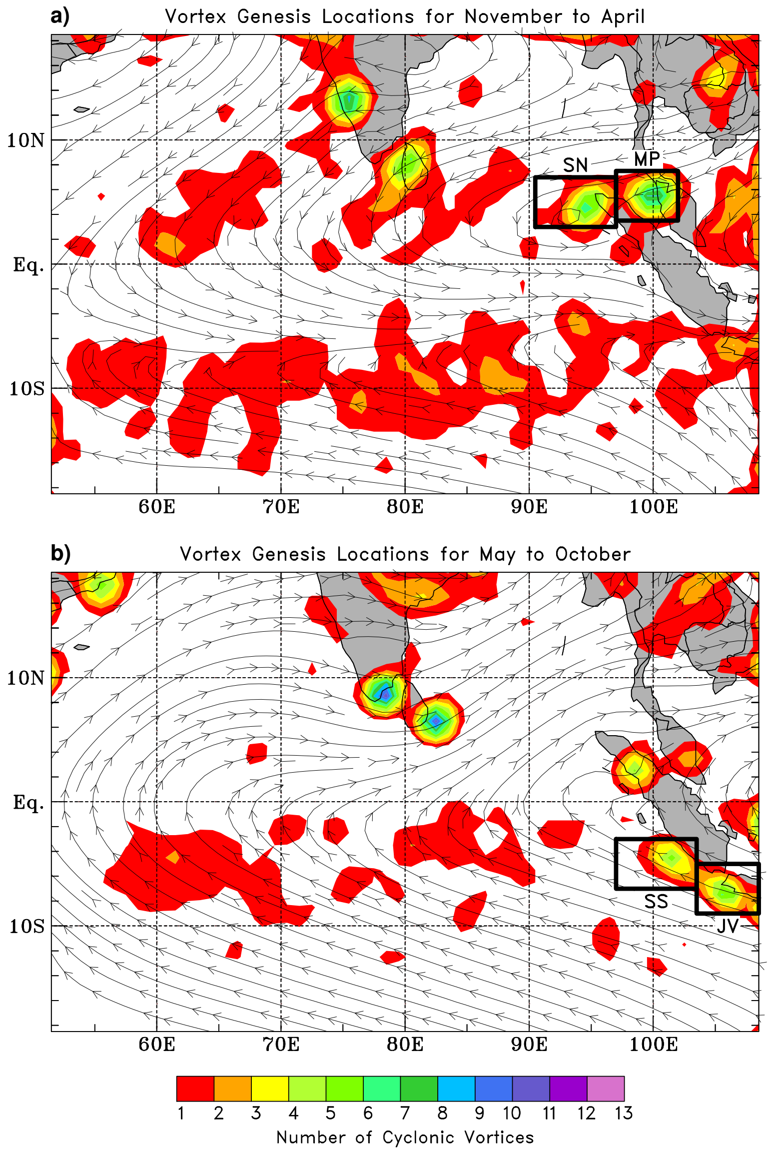

Figure 2. Frequency of cyclonic vortex genesis on a 1° grid for (a) November-April and (b) May-October periods for YOTC/DYNAMO period. Streamlines depict 925-850 hPa layer-average flows. Flows in (a) and (b) typify boreal winter and summer monsoon conditions, respectively. From Fine et al. (2016).

The tracks of shed vortices originating from the four boxed regions are shown in Figure 5. Most tracks extended westward over the IO, potentially contributing to TC genesis. Indeed, several of the tracked circulations eventually became named TCs, a few of which spanned most of the Indian Ocean. A summary depiction of the cases that ended up forming TCs is shown in Figure 6. As mentioned earlier, 13 shed vortices became named TCs. The dashed arrows depict typical low-level flow patterns associated with wake vortices that eventually became TCs. The average time from vortex genesis to named TC development being 10.1 days, indicating a relatively long gestation period for these precursor disturbances. One of the TCs (Nisha, 18-26 Nov 2008) made landfall in India and another (Ward, 29 Nov-11 Dec) made landfall in Sri Lanka.

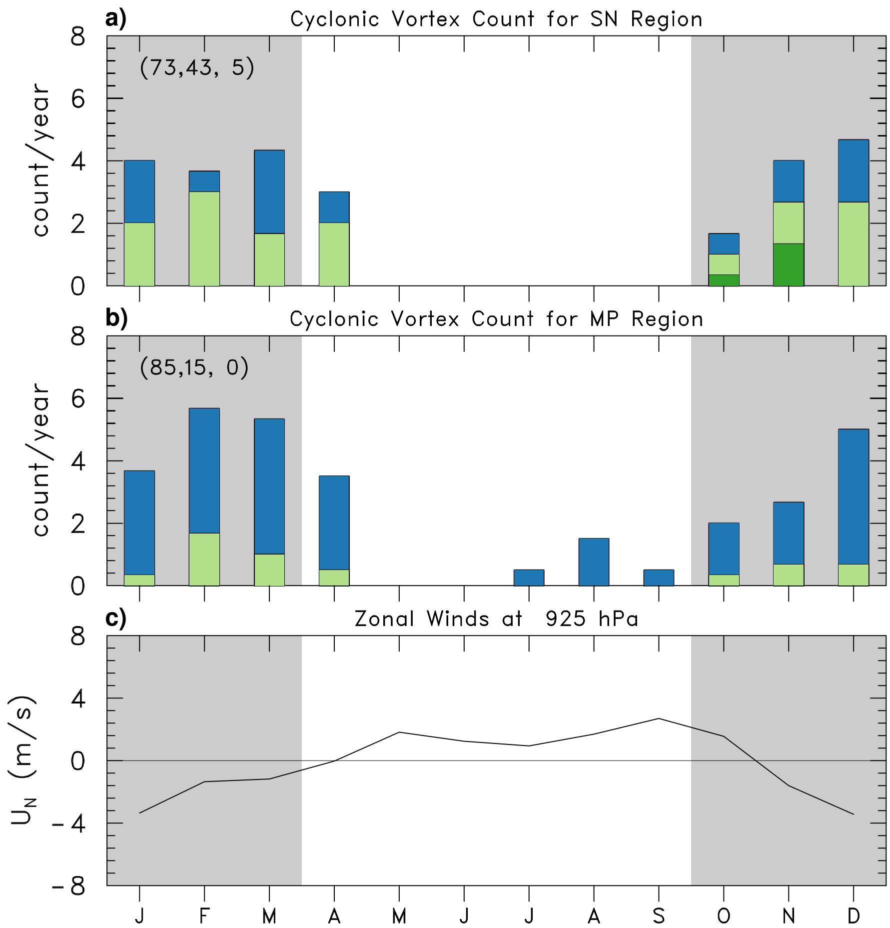

Figure 3. Monthly frequency of terrain-induced shed (top of light green bars) and non-shed (length of blue bars) cyclonic vortices for (a) Sumatra north (SN) and (b) Malay Peninsula (MP) regions. (c) Monthly mean zonal wind speed (m s^{-1}) along 100°E (line segment shown in Figure 1), indicating most cyclonic vortices in these regions occur in mean easterly flow during the boreal winter monsoon. TC events originating from terrain-induced vortices shown in dark green. Gray shading indicates period with three years of data from both YOTC and DYNAMO; unshaded period has only two years of YOTC data. Numbers in parentheses indicate total wake vortex counts, number of wake vortices that are shed, and number that became TCs, respectively. From Fine et al. (2016).

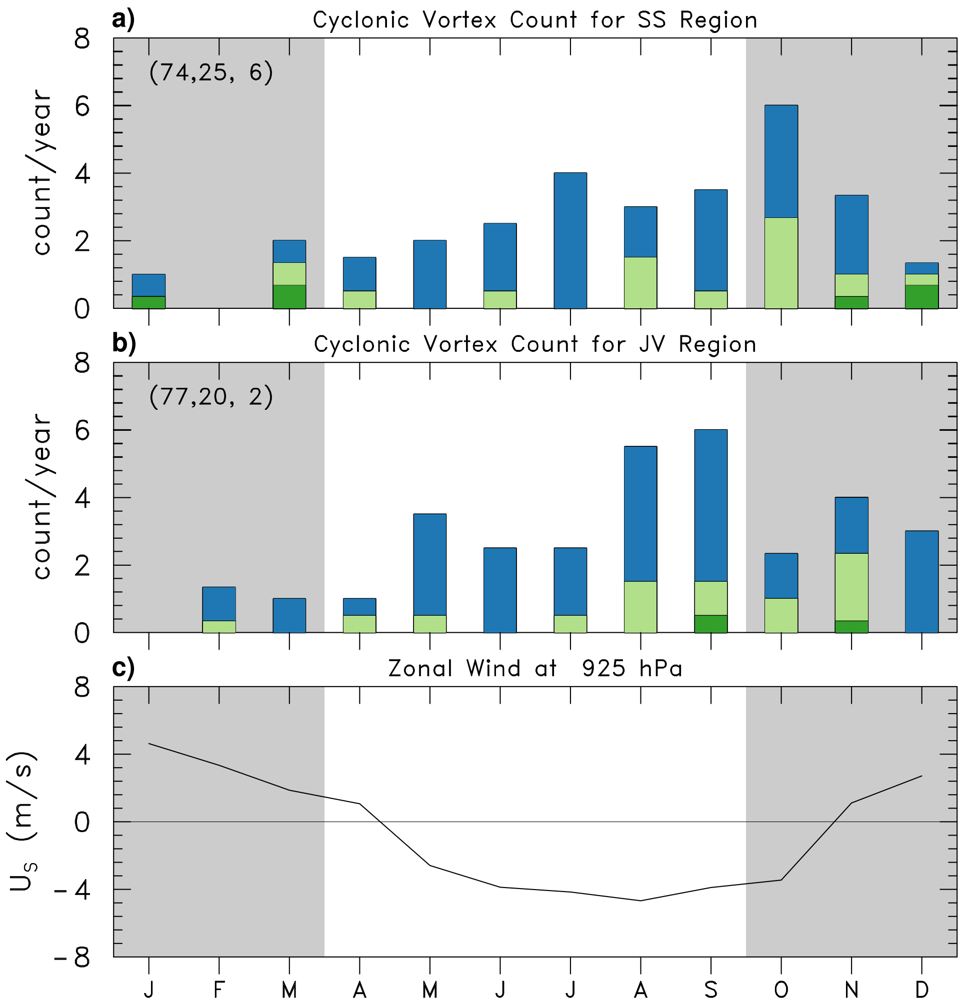

Figure 4. As in Figure 3, except for (a) Sumatra south (SS) and (b) west Java (JV) regions. (c) Monthly mean zonal wind (m s^{-1}) along 105°E (line segment shown in Figure 1), indicating cyclonic vortices in these regions can occur during both easterly and westerly mean flow. From Fine et al. (2016).

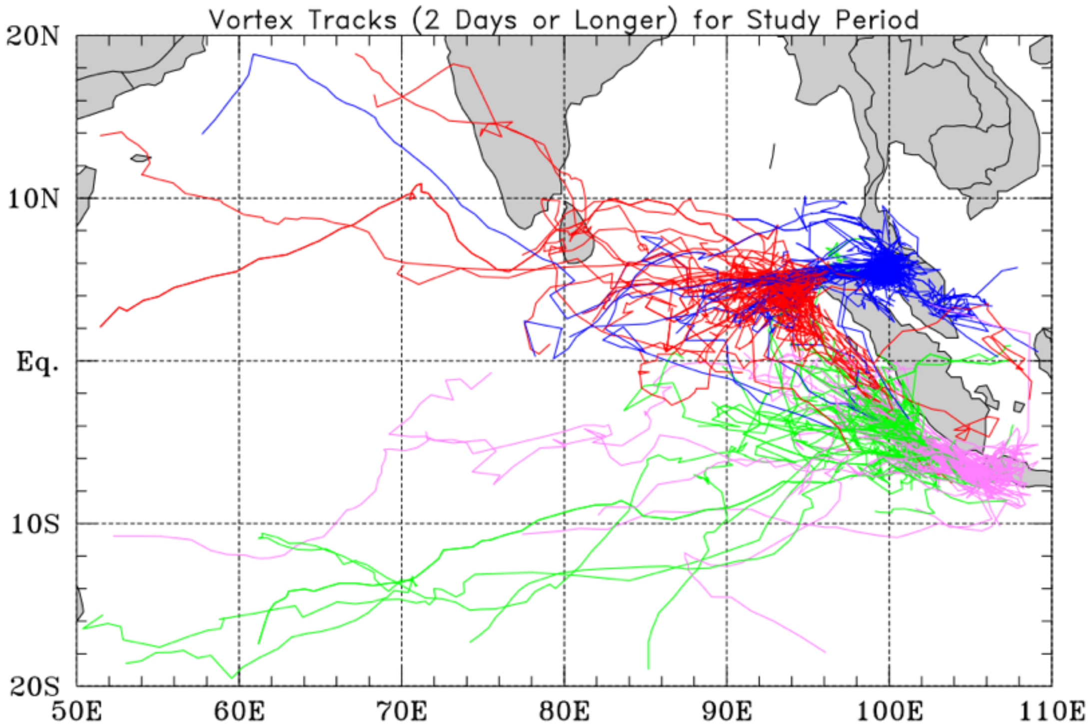

Figure 5. Tracks for cyclonic vortices that survived more than two days originating from the four analysis regions during YOTC/DYNAMO period: Sumatra north (SN, red), Malay Peninsula (MP, blue), Sumatra south (SS, green), and west Java (JV, purple). From Fine et al. (2016).

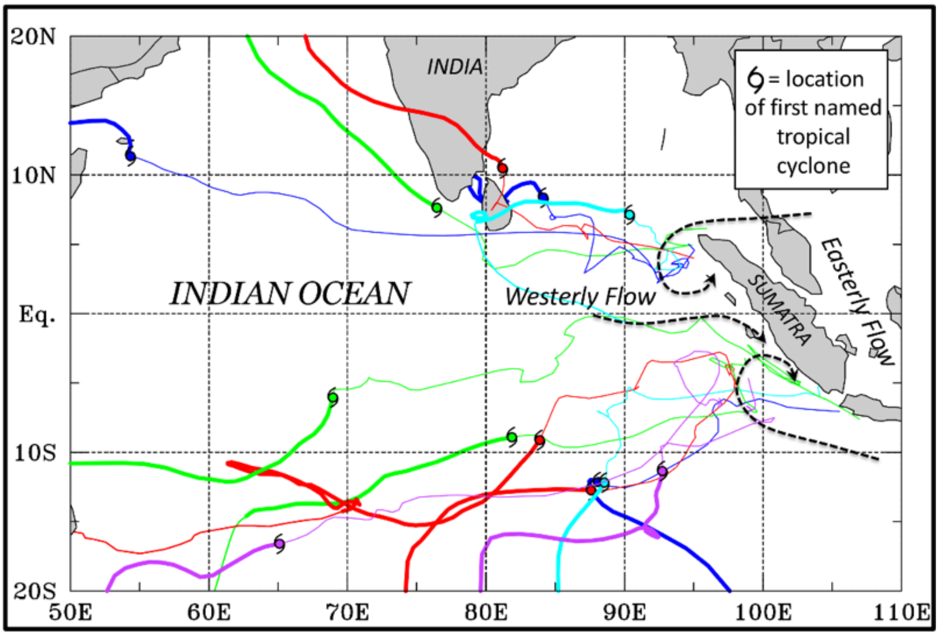

Figure 6. Tracks of the 13 shed vortices from northern and southern Sumatra that eventually formed named tropical cyclones. TC tracks are based on Joint Typhoon Warning Center (JTWC) best track data and NOAA's International Best Track Archive for Climate Stewardship (IBTrACS). Dashed arrows depict typical flow patterns associated with vortex shedding for the TC cases. One-quarter of the TCs during the DYNAMO/YOTC period originated from shed vortices.

While terrain-induced vortices were present throughout much of the year, TC genesis was confined in most of the cases (10 out of 13) to the October through December due to the weak environmental vertical wind shear as the monsoon transitioned from boreal summer to winter. In four of the cases, easterly winds prior to the onset of the MJO's active phase encountered Sumatra and produced cyclonic wake vortices that moved westward and interacted with the MJO convection before developing into tropical storms. Fine et al. (2016) showed that equatorial waves (equatorial Rossby, mixed Rossby-gravity, and Kelvin waves) also played a role in some of the TC formation cases. By way of contrast, there were some instances of *westerly* flow along the equator being blocked by Sumatra's mountains contributing to cyclonic circulations over the IO west of the island. An example of this situation is shown in Figure 7 for the seven cases of shed vortices in region SS that occurred with low-level westerly flow (U_s). The mean flow for these cases not only shows a cyclonic circulation to the west of southern Sumatra but also one west of northern Sumatra where northeasterly flow approaches the island. This flow configuration hints at the development of twin cyclones across the equator, a point that will be discussed later. As in the other cases considered in this paper, these shed vortices moved westward over the IO.

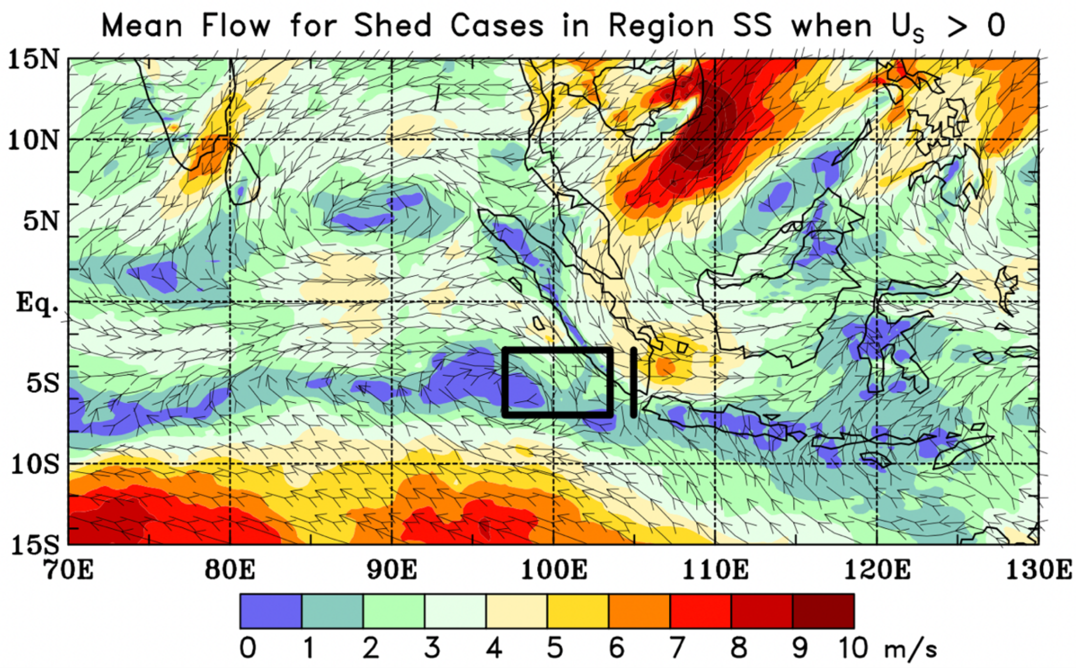

Figure 7. Mean 925-850 hPa flow over Indian Ocean basin for shed vortices from region SS (black box shown) under conditions of westerly (7 cases) flow in the analysis region. U_s is the mean zonal flow along the vertical black line segment at 105°E.

3. Extended analysis of Sumatra wake vortices (2008-2017)

Utilizing the recently available ECMWF Reanalysis 5th Generation (or ERA5) high-resolution dataset (Hersbach et al. 2020), Ciesielski and Johnson (2022) have extended the vortex tracking analyses of Fine et al. (2016) to the years 2008 to 2017. Leveraging this longer analysis period, the variability of vortex formation is considered in relationship to the MJO. The location and strength of the MJO are given by the Real-time Multivariate MJO (RMM) index developed by Wheeler and Hendon (2004). This index is based on a pair of empirical orthogonal functions (EOFs) of the combined fields of near-equatorially averaged 850-hPa zonal wind, 200-hPa zonal wind, and satellite-observed outgoing long- wave radiation (OLR) data. Daily values of the RMM index provide the amplitude and phase of the MJO.

Figure 8 shows the vortex count (based on the time of vortex formation) and zonal wind statistics relative to the phase of the MJO. Here vortex counts and winds are only considered if the MJO signal was reasonably strong, defined here as the RMM index amplitude being ≥ 1. Vortex formation (Figure 8a) is most frequent during MJO phase 1 with secondary peaks at phases 4 and 7. The maximum during phase 1 corresponds to the time when low-level easterlies are strongest over southern Sumatra (U_S), while

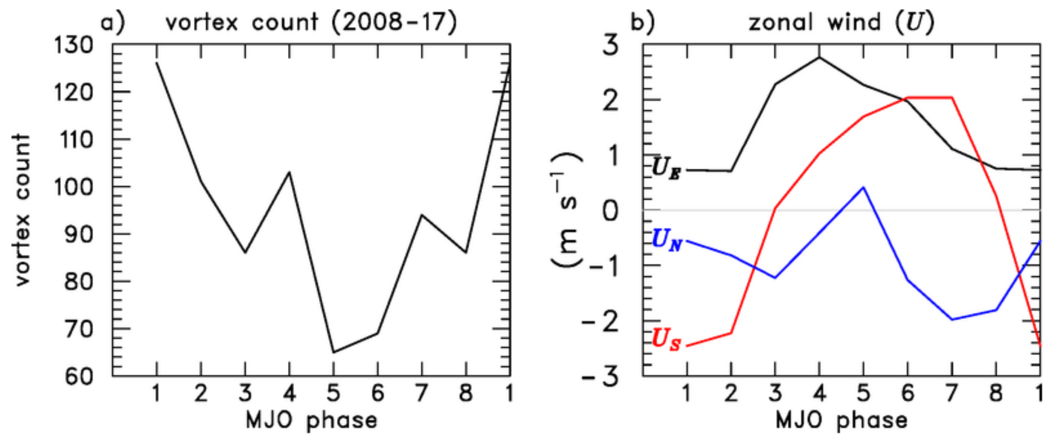

Figure 8. Statistics for the period 2008-17 as a function of MJO phase: (a) vortex count for four regions depicted in Figure 2, and (b) 925-hPa zonal winds along red line segments shown in Figure 1. Black curve represents winds averaged across the equator (U_E), blue curve over northern Sumatra (U_N), and red curve over southern Sumatra (U_S).

the secondary maximum during phase 7 is related to the peak in easterlies over northern Sumatra (U_N) (Figure 8b). Lastly, the secondary peak in vortex count during MJO phase 4 occurs when the low-level equatorial westerlies are strongest. This peak in westerlies west of Sumatra (U_E) during MJO phase 4 is consistent with the canonical structure of the MJO described in Kiladis et al. (2005), which places the low-level westerlies during this phase to the west the MJO convective center located over the Maritime Continent. The uptick in vortex formation during MJO phase 4 is most likely a combination or superposition of two effects: (1) the generation of equatorial Rossby waves to the west of the MJO convective envelope (Gill 1980) and (2) blocking and splitting of the low-level westerly flow as it encounters the steep terrain of Sumatra, which can serve to enhance counter-rotating circulations at opposite ends of the island (Smith 1989). TC initiation over the IO occurs most frequently during the convectively active MJO phase 3 (Bessafi and Wheeler 2006). Since vortex formation peaks during MJO phase 1 (or about 8 to 12 days prior to phase 3) and the average gestation period from vortex formation to TC genesis is about 10 days, then shed vortices conceivably are contributing to the IO TC initialization peak during MJO phase 3.

While the DYNAMO/YOTC and 2008-2017 studies have concentrated on the effects of topography on TC genesis, the MJO has been implicated in TC formation independent of the influence of topography. Specifically, studies have shown that a convective heat source on the equator can result twin cyclones, which have been observed in both the IO and Western Pacific (Nieto Ferriera et al. 1996). Additionally, Duvel (2015) showed that the MJO is associated with a greater frequency of TC genesis over the Southern IO by increasing both the occurrence of tropical depression initiations and the probability of depression intensification into TCs. Duvel (2015) attributed this increased frequency of development to the MJO strengthening the cyclonic meridional shear of the zonal wind in the latitudes where the TCs formed.

4. Numerical simulations of wake vortices

A better understanding of the topographic effects on TC formation over the Indian Ocean has been gained from a recent numeral modeling study (Wang et al. 2020). Three of the TC cases studied in Fine et al. (2016), Nisha (2008) in the northern IO and cross-hemispheric TC pairs Ward and Cleo (2009), were simulated using the Cloud-Resolving Storm Simulator (CReSS) having a 4-km horizontal grid. Wang et al. (2020) conducted sensitivity tests to investigate the role of topography in TC formation. It was found that all three TCs initiated at approximately the same locations and reached tropical storm status in a no-terrain simulation as in a control experiment, but the intensification was delayed without terrain. They found that the topography of Sumatra, through vertical stretching and vertical advection of vorticity, contributed to strengthening of the TCs as they moved westward over the Indian Ocean.

The simulations showed further that there are other factors involved in the development and strengthening of the wake vortices downstream of Sumatra. Migratory disturbances such as TC remnants from the western Pacific and Borneo vortices that passed over the northern Sumatra region were found to provide additional vorticity and moisture to enhance the TC genesis potential. A schematic diagram (Figure 9) summarizing their findings illustrates the typical location of a Borneo vortex or TC remnant over the South China Sea as well as twin cyclonic circulations over the IO. The TC pairs Ward and Cleo (2009) that were simulated are one of the rare examples of twin cyclones that develop in association with a surge in the equatorial westerlies and subsequent flow deflection by Sumatra (also suggested by the composite flow pattern shown in Figure 7).

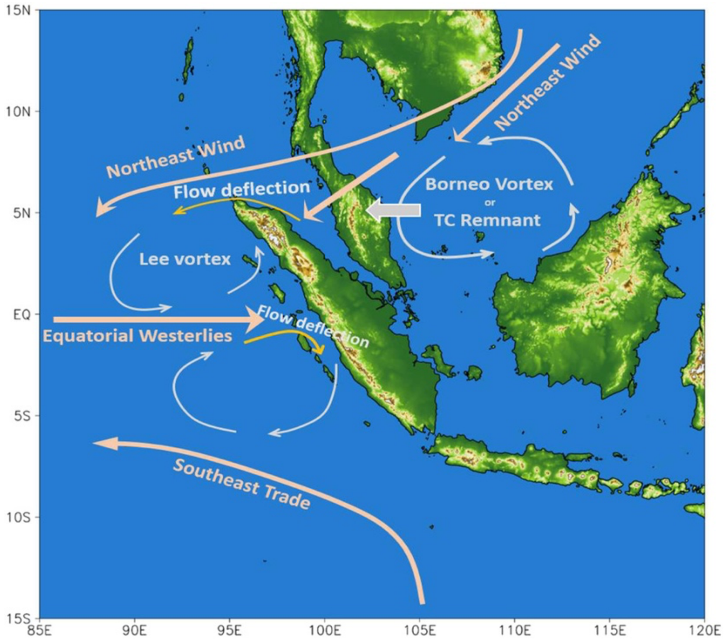

Figure 9. Synoptic conditions favorable for the formation of lee vortices to the west of Sumatra that may subsequently develop into TCs in the IO during October–December. These factors include vorticity and moisture advection from the South China Sea linked to TC remnants or Borneo vortices, prevailing northeasterly (southeasterly) winds in NH (SH), and the deflection of low-level northeasterly wind by the northern part (westerly wind by the southern part) of Sumatra for the northern (southern) vortex. From Wang et al. (2020).

5. Summary and conclusions

Recent studies have provided new insight into the role of topography in tropical cyclone (TC) formation over the Indian Ocean (IO). When easterly flow impinges on the island of Sumatra, wake vortices are found to develop at its northern and southern tips and move downstream over the IO. The vortices are counter-rotating, but since Sumatra straddles the equator, both circulations are cyclonic and thus have the potential to form TCs. Using the objective tracking code of Hodges (1995) applied to 2.5 years of DYNAMO/YOTC data, over three hundred wake vortices were identified as having been initiated at the northern and southern ends of Sumatra, one-third of which shed from the island and moved westward over the IO. Of the shed vortices, 13% developed into named TCs, accounting one-quarter of the 51 TCs over the entire IO during that period (Fine et al. 2016). The findings confirm the conjecture of Kuettner (1967) nearly five decades ago regarding the potential hydrodynamic effect of Sumatra in generating tropical cyclones over the IO.

The work of Fine et al. (2016) has been extended to a longer period (2008-2017) using ERA5 reanalysis data (Ciesielski and Johnson 2022). It shows that there is a clear relationship between shed vortex development and phases of the MJO. Namely, that the frequency of shedding peaks is maximized during phases of the MJO when there are strongest low-level easterlies across Sumatra (phase 7 for the northern end of the island and phase 1 for the southern end). There is another peak in phase 4 when strong equatorial westerlies impinge on the island as the MJO convective envelope moves over the Maritime Continent.

Numerical simulations by Wang et al. (2020) of three of the Fine et al. (2016) TC cases confirm the important role of Sumatra topography in TC genesis over the IO. However, they show that even without the terrain of Sumatra, the TCs developed, although they formed faster and were stronger when topography was included in the simulations. They further determined that there were additional circulations upstream of the island, such as TC remnants from the Western Pacific and Borneo vortices, that played an important role in the intensification of TCs over the IO.

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