

# Assessment of the Impacts of Tropical Cyclones Idai to the Western Coastal Area and Hinterlands of the South Western Indian Ocean

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## Abstract

Tropical Cyclones (TCs) are among the atmospheric events which may trigger/enhance the occurrence of disasters to the society in most world basins including the Southwestern Indian Ocean (SWIO). This study analyzed the dynamics and the impacts of the Tropical Cyclone (TC) Idai (4th-21st March, 2019) which devastated most of the SWIO countries. The study used the Reanalysis 1 products of daily zonal (u) and meridional (v) winds, Sea Surface Temperatures (SSTs), amount of Precipitable Water (PRW), and relative humidity (Rh). The dynamics and movements of Idai were analyzed using the wind circulation at 850, 700, 500 and 200 mb, where the TC dynamic variables like vertical wind shear, vorticity, and the mean zonal wind were calculated using u and v components. Using the open Grid Analysis and Display System (GrADS) software the data was processed into three-time epochs of pre, during and post; and then analyzed to feature the state of the atmosphere before (pre), during and post TC Idai using all datasets. The amount of precipitable water was used to map the rainfall on pre, during, and post Idai as well as during its landfall. The results revealed that dynamics of TC Idai was intensifying the weather (over Mozambique) and clearing the weather equatorward or southward of 12°S, with low vertical wind shear over the landfall areas (-3 to 3 m/s) and higher shear values (10 - 40 m/s) northward and southward of the Mozambican channel. Higher moisture content (80 - 90%) and higher PRW (40 - 60 mm/day) mapped during Idai over the lowland areas of Mozambique propagating westward. Higher low-level vorticity values were also mapped over the landfall areas. More results revealed that countries laying equatorward of 12°S, e.g., the northern coastal areas of Kenya (Turkana and Baringo)

and Tanzania, Idai disrupted the 2019 March to May (MAM) seasonal rainfall by inducing long dry spell which accelerated the famine over the northeastern Kenya (Turkana). Moreover, results revealed that the land falling of Idai triggered intensive flooding which affected a wide spectrum of socio-economic livelihoods including significant loss of lives, injuries, loss of material wealth, infrastructure; indeed, people were forced to leave their houses for quite a longtime; water-borne diseases like malaria, cholera among others were experienced. Furthermore, results and reports revealed that a large amount of funds were raised to combat the impacts of Idai. For instance, USAID/OFDA used about \$14,146,651 for human aid and treatment of flood-prone diseases like Cholera in Mozambique (\$13,296,651), Zimbabwe (\$100,000), and Malawi (\$280,000), respectively. Also a death toll of about 602 in Mozambique and 344 in Zimbabwe, and more than 2500 cases of injured people were reported. Conclusively the study has shown that TCs including Idai and other are among the deadliest natural phenomenon which great affects the human and his environments, thus extensive studies on TCs frequency, strength, tracks as well as their coast benefit analysis should be conducted to reduce the societal impacts of these TCs.

## **Keywords**

Tropical Cyclones, Zonal and Meridional Winds, Precipitable Water, Vertical Wind Shear, Low-Level Vorticity, Water-Borne Diseases, Deaths and Injuries

## **1. Introduction**

Normally TCs helps to moderate climate by transferring energy from warm equatorial regions to cooler higher latitudes, the combined effects of their extreme wind, precipitation, and storm surge threaten the lives of millions of people who live near the coast [1]. Among the examples of these cyclones which threatened the lives of peoples is the long-lived TC Idai (4th-16st March, 2019) which was formed on Mozambican Channel (MC), and which strengthened into moderate Tropical Storm (TS) on 9th March, 2019, and on next days it attained a rapid intensification, to intense TC, with sustained winds of 175 km/h and a central pressure of 940 mb on 11th March, 2019. Idai made multiple landfalls over the southwestern MC specifically over the low lands of Mozambique (including Beira) Figure 1, and then devastated the western coast of most areas of the SWIO countries by causing extensive flooding and a massive loss of life, facilities, and infrastructures [2] [3]. Besides, the SWIO TCs climatological records show that several TCs including Eline (2000), Dera (2001), Bondo (2006), Favio (2007) and Fantala (2014) have devastated Mozambique and Madagascar [4]-[10] and in total 50% of the TCs formed in the MC make landfall [11] [12]. TC Idai was reported to be the deadliest cyclone for the 2019/2020 TC season and was mentioned to be the worst disaster ever happened in the southern hemisphere [13] [14]. Idai persisted at the Mozambican channel for six days (as an



(a)



(b)

**Figure 1.** (a) Track of IDAI (source: GDACS, JTWC), 2 weeks rainfall accumulation (NASA-GPM), storm surge calculations (JRC) cited at <u>http://www.gdacs.org/Knowledge/models\_tc.aspx</u>), (b) TC Idai on shortly after peak intensity on 14 March (<u>https://en.wikipedia.org/wiki/Cyclone\_Idai</u>).

intense cyclone) and made landfall near Beira City, Sofala Province, in central Mozambique [15] and then tracked westerly until it dissipates (Figure 1(a)). Distribution of the impacts shows that Mozambique, Malawi and Zimbabwe were highly affected by enhanced torrential rains and flooding, whereby a death toll of about 602 in Mozambique and 344 in Zimbabwe was registered [16], and more than 1.5 million people were affected, among which 2500 people were injured; and a significant number of people were lost. Also, the flooding and strong wind due to Idai left several people homeless where about 239,700 houses in Mozambique were affected, and infrastructure (roads, bridges among others) was severely demolished, to an extent that the international community remarked this event as a massive disaster in Mozambique and Zimbabwe. This catastrophic event costs the international community (USAID/OFDA) about \$14,146,651 for human aid and treatment of flood-prone diseases like Cholera in Mozambique (\$13,296,651) Zimbabwe (\$100,000) and Malawi (\$280,000), respectively [16]. Extensive impact analysis has been documented in Zimbabwe and Mozambique, but either little or none has been documented on the northern coastal areas of Tanzania and Kenya. Thus, this study aimed at assessing dynamics associated with TC Idai and its social impacts to the western coastal area of the SWIO countries (Tanzania and Kenya in particular), by using the observations, remotely sensed and analysis products of zonal and meridional winds and model assimilations. Indeed, this study and others will deeply help the policy and decision makers' coastal managers, disaster and risk management departments in the western side of the SWIO to develop good emergency responses programs, resilience and adapting strategies towards reducing the impacts of tropical cyclones in the region and their respective management areas.

## 2. Data and Methods

Based on the fact that TCs are synoptic large scale phenomenon which affects large area, and since TC Idai started as a tropical disturbance extended to the extra tropical or mid latitude regions, this study covers a region bounded by 5° -40°S and 28° - 80°E. This area was selected to cover all areas where TC Idai resulted into significant impact. As for datasets, the study used the daily mean Reanalysis 1 data to examine dynamics of TC Idai which brought the devastating impacts. These datasets includes the daily zonal (u) and meridional (v) winds at 850, 700, 500, and 200 mb, respectively. The u, v winds data has a spatial resolution of  $2.5^{\circ} \times 2.5^{\circ}$  and a temporal resolution of 1974 to date [17] [18]. The multi level relative humidity and surface specific humidity datasets with spatial resolutions of  $2.5^{\circ} \times 2.5^{\circ}$  and temporal resolution which covers the two months of March and April, 2019 [17] was also used. Other datasets include the amount of precipitable water (here after **PRW**). Moreover, the daily mean extended reconstructed sea surface temperature anomaly (SST<sub>A</sub>) with spatial resolution of 0.25°  $\times$  0.25° and a temporal resolution of two months and the total cloud cover was also used. It should be noted that TC Idai lived for about 17 - 18 days, hence, this study used the 25th February to 31st March, 2019 datasets to analyse the Idai dynamics . The u and v wind vectors at 850 and 200 mb were used to derive the environmental vertical wind shear (200 - 850 mb) the parameter which explained why the Idai tracked southwestward instead of northwestward, while u and v winds at 500 and 700 mb were used to derive the zonal mean steering winds (m/s) and vectors. Besides, the vertical vorticity of the Idai was also calculated to see how Idai was decaying or strengthening with time. The study used three time epochs of pre, during and posts Idai to analyze its genesis development and decay. The comparisons between the produced maps indicating the moisture content at 850 - 700 mb, PRW and the amount of rainfall were then compared for the pre, during and post time epochs. For clear understanding of the development and decay of TCs/TSs with time and it is inversely related to vertical uplifting of moisture during the TC/TS development and decay phase, the environmental vertical wind shear between 200 and 850 mb (hereafter  $EVWS_{852}$ ) was calculated. The studies including [19] [20] has shown that the lower the EVWS<sub>852</sub> the more intense the TCs become. Thus, the EVWS<sub>852</sub> between the three time epochs was calculated using the [21] and [22] relation given by:

$$EVWS_{852} = \sqrt{(U_{200} - U_{850}) * (U_{200} - U_{850}) + (V_{200} - V_{850}) * (V_{200} - V_{850})}$$
(1)

where  $U_{200}$ ,  $U_{850}$ ,  $V_{200}$  and  $V_{850}$  are the zonal and meridional wind at 200 and 850 mb, respectively. Indeed, the zonal mean steering winds between 700 to 500 mb for the three time epochs (hereafter  $U_{75}$ ) was calculated by averaging at each grid point zonal (u) winds at each level as given by Equation (2):

$$U_{75} = \left(U_{700} + U_{500}\right)/2 \tag{2}$$

where  $U_{700}$  and  $U_{500}$  are the zonal winds at 700 and 500 mb, respectively. The  $U_{75}$  component was calculated to seen whether the extent to which mean steering levels behaves for the three selected time epochs of Idai. The sign convention for mean zonal winds in equation 2 indicate that, positive sign (+) are westerly (from west to east) and negative sign (-) indicate the easterlies (from east to west). Lastly the low level cyclonic vorticity at 850 mb (**LLRV**<sub>850</sub>) for the mentioned three time epochs was computed using a centered finite-difference scheme which is clearly explained by [23] [24].

As for a simple and clear understanding of the algorithm used in this paper, **Figure 2** provides a concise sketch which clearly explains the methodological approach used.

## **3. Results**

## **3.1. The Wind Vector Circulations**

The results of the wind vector circulations at pressure levels of 850, mean (700 - 500) and 200 mb for the three epochs of pre, during, and post TC Idai presented in **Figure 3(a)** reveals that the mean pre Idai wind circulation was dominated by weak depression over the northeastern Madagascar which induced strong easterly over the northern tip of Madagascar with reduced strength as they approach



Figure 2. Schematic diagram/flow chart of the procedures used to study TC Idai, its dynamic and impacts.

the northern MC and northern coastal areas of Mozambique. The East African (EA) coast (e.g. coastal Tanzania and Kenya) was under the influence of weak south easterlies which resulted into linear convergence over this coast, while strong easterly to south easterly was experienced over the entire coastal and hinterlands of Kenva, the phenomenon which tried to decline the weather over Kenva and southern Somali. Also during Idai especially on landfall days (9-13th March, 2019) the 850 mb wind circulation Figure 3(b) attained a strong circulation over the cyclone center (Southern MC) with strong north easterlies from Somali coast and great horn of Africa rushing to the cyclone, whereas the hinterlands and coast areas of Kenya and Tanzania was characterized by strong north easterlies which were rushing to the cyclone area, and hence affect the countries laying equator ward of 12°S e.g. the northern coastal areas of Kenya (Turkana and Baringo) and Tanzania. This wind circulation shows that TC Idai disrupted the MAM 2019 seasonal rainfall by inducing long dry spell which accelerated the famine over the north eastern Kenya (Turkana) as well as severely disorganize the MAM 2019 early onset seasonal rainfall by sucking the moisture towards the deep pressure of TC Idai.

The Idai cyclonic circulation was enhanced by anticyclone circulation (high pressure) located at 35°S and 35° - 40°E resulting into its long staying at MC. On the other hand, the 850 mb wind circulations during Idai over the southwestern to western area of Tanzania and its neighboring countries (Rwanada Burundi and Congo) was linearly converging with very light winds. As for the post Idai condition, the 850 mb wind circulation **Figure 3(c)** revealed that on 17<sup>th</sup> March, 2019 another TS Savannah crossed over SWIO basin, and shortly reach its peak intensity as intense TC, whereas on 19<sup>th</sup> March, 2019 TC Savannah transitioned into a post-tropical cyclone, with southwestward tracking and steered eastward on 20<sup>th</sup> March, 2019, before turning westward on 21<sup>st</sup> March, 2019. The existing





**Figure 3.** The average 850 mb ((a) - (c)); 500 mb ((d) - (f)), and 200 mb ((g) - (i)) wind circulations on pre ( $28^{th}$  Feb- $3^{rd}$  March, 2019); during ( $10^{th}$ - $13^{th}$  March, 2019) and post ( $22^{rd}$ - $23^{rd}$  March, 2019) tropical cyclone Idai.

of this short lived TC resumed the weather patterns over most coastal and hinterland areas EA (Kenya and Tanzania being examples) by inducing the weak and linearly convergent easterly from the Indian ocean to the coastal areas.

As for the pre, during and post Idai conditions for 500 mb wind circulations, results revealed that 5 days average wind circulation before Idai Figure 3(d) had light easterlies at western coastal areas of SWIO (Kenya, Tanzania and Mozambique) with light clockwise circulation at the Mozambican channel and southeastern Madagascar. The condition which supports what was happening at 850 mb. Similar results hold for the 500 mb wind circulation during Idai Figure 3(e). As

for the post Idai, the average 500 mb wind circulation was having nearly the same orientation as in Figure 3(d) and Figure 3(e) but with higher wind strength. Similar results holds for 200 mb wind circulation presented in Figure 3(g)-(i), where on pre Idai the wind circulation at 200 mb was having weak easterly orientation at the coastal area of Tanzania and Kenya and north easterly at the MC (cyclone area) and strong north westerly flow at southern parts of Madagascar (40°S), as for the wind circulations during Idai Figure 3(h) revealed strong easterly at the EA coast and weak circulation at the center of TC Idai, where as the cyclonic circulation at the southern Madagascar has progressed forward and its area was covered by anti cyclonic circulation of Idai. While for the post Idai, the 200 mb wind circulation Figure 3(i) has quite different wind orientation from that of pre and during Idai conditions, where the wind at this epoch was strong at the cyclone areas, and weaker northeasterly at coastal Tanzania and Kenya. Moreover, Figure 3(i) mapped the weak anticyclone circulation indicating the formation of new TC Savannah (which either had no, or very little impact to the SWIO countries) at the northeast Madagascar after TC Idai. In general Figure 3 revealed the situation of the upper level wind circulations pertained on pre, during and post Idai conditions.

#### 3.2. The Mean Sea Level Pressure

The results of the analysis of the Mean Sea level Pressure (MSLP) condition for the three epochs presented in Figure 4 revealed that prior to the onset of TC Idai Figure 4(a), the EA coastal areas and Mozambique were under the influence of 1012 mb low pressure trough with center of 1010 mb at the border between Mozambique and Tanzania (i.e. at Mtwara), also another 1010 mb contour located at north eastern Madagascar was progressing towards the EA coastal waters, while the high pressure ridge located at southeastern Madagascar was progressing westward. These low and high pressure cells progressions was indicating that any further increase in atmospheric instability may deepen the pressure, and hence trigger the formation of TC. During the occurrence of Idai (Figure 4(b)) the tropical EA countries bounded by 5° - 20°S was under the influence of low pressure systems with distributed cells of low pressure centers at Zimbabwe and Malawi as well as at the MC where the eye of Idai was existing. Also the high pressure cell which was located at southeastern Mozambican channel was shifted further southeastward. As for the post Idai the results presented in Figure 4(c) show that new TC Savannah was initiated with center of 1010 mb at NE Madagascar, while inducing low pressure trough to most coastal and hinterland areas of EA. Further results in Figure 4(c) reveals nearly the same condition like Figure 4(a) for the EA coastal and hinterland areas. Though the EA countries were under the influence of low pressure system, but the orientation of Idai's wind circulation was declining the rainfall over these areas based on the fact that TC sucking effect redirects the moist winds towards the cyclonic circulation of the TC Idai, thus leaving the mentioned areas very dry.

Av slp pre 28th Feb-3rd March, 2019 pre TC Idai



Figure 4. The average mean sea level pressure (slp) on pre (28<sup>th</sup> Feb-3<sup>rd</sup> March, 2019); during (10<sup>th</sup>-13<sup>th</sup> March, 2019) and post (22<sup>nd</sup>-23<sup>rd</sup> March, 2019) TC Indai.

## 3.3. The Sea Surface Temperature Anomaly (SST<sub>A</sub>)

The results of the analysis of the mean  $SST_A$  for the three epochs of pre, during and post Idai presented in **Figure 5** shows that before the onset of the TC Idai (*i.e.*, pre Idai) **Figure 5(a)**, the mean  $SST_A$  over the EA coastal waters was higher ranging from 0°C - 3°C while at the border between Tanzania and Mozambique, and at central MC the areas which were experiencing low pressure (**Figure 4(a)**)



**Figure 5.** The spatial distribution of the mean SST anomaly on pre (28<sup>th</sup> Feb-3<sup>rd</sup> March, 2019); during (10<sup>th</sup>-13<sup>th</sup> March, 2019) and post (22<sup>nd</sup>-23<sup>rd</sup> March, 2019) TC Indai.

the mean SST<sub>A</sub> was slight lower ranged from 0°C to -1°C, and at southern MC and eastern side of Madagascar the mean SST anomaly ranged from 0°C to 3°C except at the northern tip of Madagascar where the mean SST<sub>A</sub> was low (ranged from 0°C to -1°C). The pre Idai mean SST<sub>A</sub> spatial distribution over the SWIO was in a condition necessary for the TC occurrence. During TC Idai the mean SST<sub>A</sub> over the EA coastal waters and the northern MC was reduced up to range of -1°C to 1°C (**Figure 5(b**)), due to boundary layer mixing, and the variations of subsurface oceanic stratification, the condition which modulate the amplitude of TCs-induced cooling as noted by [25], and which in turn enhanced the decline of MAM seasonal rainfall and extending of the seasonal dry spells over the EA coastal strip. Moreover, SST<sub>A</sub> over the southern MC and at the Bengali bay (where Idai made its first land fall) was reduced to range from 0°C to -3°C; the state which could be explained by the boundary layer mixing of ocean water (i.e. upwelling where deep water are raised up and surface water sinks down) which was further accelerated to upwelling as noted by Kai, (2018) and Similarly, [26] who noted that year-to-year thermocline depth variability in the southwest tropical Indian Ocean was associated with changes in TC activity. On the other hand, the existence of the positive phase of subtropical Indian Ocean Dipole (SIOD) which is bounded by 55 - 65°E, 37 - 27°S west and 90 - 100°E, 28 - 18°S east, and characterized by warm SSTA in the southwestern part *i.e.*, south of Madagascar and cold SST<sub>A</sub> in the eastern part of Australia (Bahera and Yamagata, 2001; Ash and Matyas (2010); Suzuki et al, 2004) and as well as the northward pushing of warms SST anomaly at the southern MC due to induced low pressure cell associated with light winds [27] [28] [29]. Figure 5(a) and Figure 5(b) were among the factors which enhanced the strength of the Idai over the MC. As for the post Idai conditions, the higher mean SST anomaly over eastern and northeastern Madagascar as well over EA coastal waters (Figure 5(c)) which is supported by Figure 3(c) and Figure 4(c)) supports the presence of short lived TC Savanah, and the existence of low SST<sub>A</sub> over the Mozambican channel Figure 5(c) as well as higher vertical wind shear at the northern part of the channel were among the conditions which prevented Savanah to track over the channel.

#### 3.4. Perceptible Water (PRW) and Relative Humidity (Rh)

The results of the analysis of spatial distribution of the amount of PRW and relative humidity over the countries directly or indirectly affected by Idai on its pre, during and post conditions are presented in Figure 6, for PRW and Figure 7 for Relative humidity (Rh) at 850 and 700 mb, respectively. The spatial distribution of the amount of PRW at the atmosphere before the onset of the TC Idai presented in Figure 6(a) shows that northern Mozambican channel and EA coastal waters had higher amount of PRW ranged from 45 mm/day to more than 51 mm/day as supported by [30] [31] and [32] that globally and central Indian Ocean in particular, PRW values average ranges from 40 - 50 mm over regions where TCs forms. Furthermore, Figure 6(a) shows that the northern coastal areas of Tanzania and Kenya was mapped by moderate amount of 35 - 42 mm/day, while the hinterlands of Mozambique and Malawi were mapped by an amount ranged from 39 - 40 mm/day, indicating that prior to Idai the atmosphere over the most affected areas had low amount of PRW *i.e.* precipitation was not highly or likely expected over these areas, but over the ocean (MC) the condition was very convincing for the TC to trigger. Moreover, the very low amount of PRW ranged from 21 - 30 mm/day in Kenya and northeastern highlands of Tanzania (Kilimanjaro and Arusha areas) could explain the existing drier and drought conditions in most parts of Kenya in an extent that the occurrence of Idai enhanced the rainfall decline in Kenya and some parts of Tanzania. The mean spatial distribution of PRW during the Idai land fall Figure 6(b) reveals the existence of the southward shift of the peak mean PRW and the reduction in



average precipitable water pre TC Idai (28 Feb-3 Mar, 2019)

(a)



**Figure 6.** The mean spatial distribution of the amount of PRW on pre (28<sup>th</sup> Feb-3<sup>rd</sup> March, 2019); during (10<sup>th</sup>-13<sup>th</sup> March, 2019) and post (22<sup>nd</sup>-23<sup>rd</sup> March, 2019) for TC Idai.

PRW over the northern coastal areas, while hinterland areas of Mozambique Malawi and Zimbabwe were having significant increase in PRW, also the eastern part of Madagascar had significant changes in PRW. Significant changes in PRW were observed on pre and during Idai conditions over the Tanzanian southeastern highlands and southern parts of Kenya. The increase in PRW over the central Mozambican channel could be explained as the basis for the increases rainfall activities over Mozambique, Malawi and Zimbabwe and hence results to the devastating events of floods and other storm related issues as noted by [13] [14] and [15]. The spatial distribution of the PRW on post Idai condition presented in **Figure 6(c)** reveals the onset of the new TC savannah which had less impact to the western MC countries, but it seems to resume the seasonal rainfall activities.

ties over the EA coastal areas (which had low PRW ranged from 30 - 39 mm/day) while the northeastern highlands of Tanzania and southern to central parts of Kenya being affected by low PRW ranged from 18 - 26 mm/day. Further results show that over eastern Madagascar the influence of TC Savannah has induced higher PRW ranged from 42 - 51 mm and this could be explained by the increase in SST<sub>A</sub> (Figure 5(c)) which promote higher evaporation rates, and hence contribute to the increased precipitable water amount as supported by [31] and [33].

The spatial distribution of Rh at 850 and 700 mb for the pre, during and post Idai conditions presented in Figure 7 reveled that before the onset of Idai the vertical spatial distribution of the moisture content at 850 and 700 mb Figure 7(a) and Figure 7(b) had limited moisture content ranged from 30% - 60% at EA coastal areas, and this moisture content was decreasing northward of the coastal Tanzania towards Kenyan coast which had being mapped with very low moisture content ranged from 20% - 40%, the feature which is more pronounced in Figure 7(b) (at 700 mb). Moreover, Figure 7(a) and Figure 7(b) mapped the northern Mozambican Channel, northern Mozambique, Malawi and western Tanzania with high moisture content ranged from 70% - 90% indicating that the atmosphere at these areas was moist enough to allow the TC development. As for the moisture distribution during Idai Figure 7(c) and Figure 7(d)) revealed that the EA coast was characterized by declined moisture content indicating that the dry spell which was marked during the Idai was among other things caused by this decline of moisture and the rushing of 850 mb winds to the cyclone center (Figure 3(b)) which results the cyclonic flow at 500 and 200 mb Figure 3(c) and Figure 3(d)). Likewise, Figure 7(c) and Figure 7(d) were favoring the MC, Mozambique, Malawi, Zimbabwe and nearly entire western Tanzania with the exception of the coastal line which has low moisture content. This indicate that extreme rainfall events observed in Mozambique, Malawi and Zimbabwe which results into flooding, land sliding among others, was associated with the existing of high moisture content which was induced by the sucking effect of Idai. As for the post Idai conditions Figure 7(e) and Figure 7(f) revealed that though there was a short lived TC Savannah at the northeastern Madagascar but the vertical moisture distribution from 850 - 700 mb was extremely limited at the EA coastal line with the highest moisture declined observed at 700 mb (Figure 7(f)). The existing band of high moisture at 850 m (Figure 5(e)) in areas of northwestern Mozambique, Malawi and western Tanzania could be the one responsible for enhancing the high rainfall which in turn enhancing the wide flooding, and creating worse conditions for the rescue teams to reach the highly Idai effect in areas of Mozambique, Malawi and Zimbabwe as reported by [34] cited by

http://www.usaid.gov/what-we-do/working-crises-and-conflict/responding-time s-crisis/where-we-work.

As for the total cloud distribution over the Idai affected areas, results presented in Figure 8 revealed that on pre Idai conditions (Figure 8(a)) coastal Tanzania, Kenya, Somali, southern Mozambique, Zimbabwe and Zambia had



**Figure 7.** The mean spatial distribution Rh on pre (28<sup>th</sup> Feb-3<sup>rd</sup> March, 2019); during (10<sup>th</sup>-13<sup>th</sup> March, 2019) and post (22<sup>nd</sup>-23<sup>rd</sup> March, 2019) TC Indai where a c and e represents the 850 mb and b, d and f represents 700 mb.



Av total cloud 10-13 March, 2019 during TC Idai



**Figure 8.** The mean spatial distribution total cloud cover on (a) pre Idai (28<sup>th</sup> Feb-3<sup>rd</sup> March, 2019); (b) during (10<sup>th</sup>-13<sup>th</sup> March, 2019) and (c) post Idai (22<sup>nd</sup>-23<sup>rd</sup> March, 2019).

very low amount of total cloud cover ranges from 10% - 40%, while south to northwestern Tanzania, Eastern Congo, Northern Mozambique among others had significant (high) amount of cloud cover ranged from 60% - 90% indicating the overcast conditions, the situation which resulted in heavy rainfall in most of the domain areas, and declined rainfall over the northern coastal areas including Dar es Salam, Zanzibar, Tanga and entire countries of Kenya and Somali. Additionally, the declined total cloud cover during the pre Idai induced clear conditions over areas of southern Mozambique, Zambia, and Zimbabwe among others. Besides, **Figure 8(b)** presents the average total cloud cover condition during Idai on 22<sup>nd</sup> to 24<sup>th</sup> March, 2019, where less cloud condition was shown over the entire coastal Tanzania, Kenya and Somali. This condition is in good agreement with **Figure 3(b)** where 850 mb winds over these areas were rushing towards the

Av total cloud post 22-24 March, 2019 during TC Idai

cyclone areas (*i.e.* Mozambican Channel). However, most areas of southern to southwestern Tanzania, Mozambique, Malawi and Zambia among others were having significant amount of clouds. As for the post Idai condition, **Figure 8(c)** show an existence of great band of total cloud cover over eastern to southeastern Madagascar, which extend northwards to coastal water of EA countries. This situation is well agreed by **Figure 3(c)** indicating the existence of short lived tropical cyclone Savannah, which tried to resume the declined wet conditions over EA, as well as enhancing the wet conditions over Mozambique and its neighborhood areas.

#### 3.5. The Vertical Wind Shear

The results of the spatial distribution of  $EVWS_{852}$  presented in Figure 9(a) revealed that pre Idai conditions along the coastal Tanzania and EA Coastal Current (EACC) areas was increasing with highest of 15 m·s<sup>-1</sup>, the value which is not conducive for both TC development as well as intensity *i.e.* large levels of EVWS<sub>852</sub> produce a sizable ventilation and will destruct the TC in short time [35] [36] [37], while at northeastern Madagascar (i.e. at 50 - 80°E and 8 - 12°S) and northern MC the EVWS<sub>852</sub> was small (*i.e.*  $\leq 8 \text{ ms}^{-1}$ ). This EVWS<sub>852</sub> of 8 m·s<sup>-1</sup> and less favors the formation and development of TC as supported by [9] [10] [36]. As for the results of EVWS<sub>852</sub> distribution during cyclone Idai presented in Figure 9(b) revealed a 6 m·s<sup>-1</sup> contour bounded over northern Madagascar, northern MC as well as Mozambique, Malawi, Zambia and Zimbabwe. The area where Idai was centered and where it made its landfall (i.e. the intense storm made landfall in Beira, Mozambique) was bounded by 3 m·s<sup>-1</sup> indicating that at those areas TC Idai was very intense. These results are in agreement with [9] [36] [38] that EVWS<sub>852</sub> is one of the most prominently disputed in the TC intensity and small EVWS<sub>852</sub> values enhance stronger TCs. Indeed, Idai could not have heavy devastating impacts at coastal Tanzania at Dar es Salaam, Lindi and Mtwara areas because the EVWS<sub>852</sub> was increasing equator ward of 12°S (*i.e.* it was 9 m·s<sup>-1</sup> at EACC and coastal areas of Tanzania) resulting in decreasing of its strength (Figure 9(b)), while areas which had very small EVWS<sub>852</sub> was highly affected by heavy rains and floods. The EVWS<sub>852</sub> distribution on post Idai presented in Figure 9(c) shows that lower values of about 6 m·s<sup>-1</sup> centered at northeastern Madagascar (over areas where short lived TCs savannah and Joaninha was tracking), also the 6  $m \cdot s^{-1}$ EVWS<sub>852</sub> troughed over the EACC areas and at coastal Tanzania, the phenomenon which resumed and enhanced the MAM rainfall activities over the coastal Tanzania as supported by Figure 7(d) and Figure 8(c) and Frank and Ritchie, (2001) that at small shear, rainfall and cloud water at most levels, are formed.

#### 3.6. The Zonal Mean Horizontal Winds and Their Vectors

The results of the spatial distribution of mean zonal winds  $U_{75}$  for the three time epochs presented in Figure 10 reveals that, mean zonal winds on pre Idai (Figure 10(a)) was propagating easterly northward of 20°S with increasing



**Figure 9.** The mean spatial distribution of the environmental vertical wind shear on (a) pre Idai (28<sup>th</sup> Feb-3<sup>rd</sup> March, 2019); (b) during (10<sup>th</sup>-13<sup>th</sup> March, 2019) and (c) post Idai (22<sup>nd</sup>-23<sup>rd</sup> March, 2019).



**Figure 10.** The mean spatial distribution of the zonal mean wind (at 700 - 500 mb), and the mean wind circulation at the same level for the time epochs of (a) pre Idai (28<sup>th</sup> Feb-3<sup>rd</sup> March, 2019); (b) during (10<sup>th</sup>-13<sup>th</sup> March, 2019) and (c) post Idai (22<sup>nd</sup>-23<sup>rd</sup> March, 2019). Similar situation holds for the mean wind vectors of (d)-(f).

speed from -2 to -8 m/s at the center of the disturbance, while coastal Tanzania and MC was mapped by 0 - 4 m/s. This indicates that the weak and unstable disturbance (e.g. depression) was moving from east towards west and then centered at northeastern Madagascar. As for the southward of 20°S (Figure 10(a)) the area was dominated by increasing westerly flow with its strength ranged from 0 - 28 m/s indicating an upper level ridge extending southwards of the Madagascar and MC. The mean zonal winds during Idai (Figure 10(b)) shows that areas bounded by equator to 30°S was dominated by weak zonal mean flow characterized by both pockets of westerly and easterly especially over areas where Idai had made landfall. Further results in Figure 10(b) reveals that at the landfall areas zonal wind flow was weak easterly indicating heavy deposition of moisture content resulting into flooding. Indeed, Figure 10(b) revealed a changing orientation (track of the Idai) due to changing zonal wind direction at MC from westerly ( $\leq 3$  m/s indicating a southwesterly flow) to easterly ( $\leq 3$  m/s indicating a northeasterly flow). The northern Madagascar and coastal EA was bounded by easterly flow of  $\geq 3$  m/s indicating clearing weather conditions. The spatial distribution of the mean zonal wind flow for post Idai (Figure 10(c)) had easterly flow of -3 m/s at the center of short lived tropical cyclone Savannah. The increasing of the zonal wind speed (southward of Madagascar) and changing its direction from east to west as well as increasing of vertical wind shear both northward and southward of the center of the savannah (Figure 9(c)) could be among reasons of its early dissipation.

Also Savannah could not have southwestward track because it was surrounded by a ridge on its east and west direction (*i.e.* the winds were opposing its motion, and the shear was disturbing its vertical extent by the ventilation effect). As for the analysis of the mean zonal wind vectors at steering level, the results presented in Figures 10(d)-(f) shows that pre Idai (Figure 10(d)) zonal wind vectors were purely easterly over Mozambique, northern Madagascar and over EACC areas, with the exception of coastal areas of Kenya and Tanzania the winds were changing from northerly (Kenya, and Somali coast) and northeasterly parallel to the coast (at coastal Tanzania). Moreover, Figure 10(d) shows a linear convergent of winds near over EACC areas resulting into moisture advection to coastal Tanzania and Mozambique. The results in Figure 10(d) indicate that irrespective of Idai, Mozambique and southern to southwestern Tanzania were having favorable conditions for precipitation as supported by Figure 8(a). The mean zonal wind vectors distribution during Idai (Figure 10(e)) reveals a pure easterly at the EACC areas and coastal Tanzania, and a cyclonic circulation at the Mozambican channel at areas where Idai made a landfall. This result also reveals that Idai had great vertical extent from surface to 500 mb which was enhanced by weak vertical shear (Figure 9(b)). Indeed, Figure 10(e) show a series of westward flow of low and high pressure cells at 25 - 35°S this could be among the reason which led Idai to have long time land falling at Mozambique and nearby countries like Zimbabwe and Malawi (i.e. its southward flow was denied by anticyclone circulation centered southern Madagascar. Figure 10(f) reveals the post Idai conditions, where new short lived cyclone Savannah was propagating southwestward with good northeasterly to easterly over the Tanzania coastal line and hinterland areas. This condition resumed the decline MAM 2019 rainfall over the coastal areas of Kenya and Tanzania during Idai. Though Idai dissipated but the rainfall condition over Mozambique and its neighbors was still affecting the Idai flood victims as supported by weak cyclonic flow over Mozambican channel (**Figure 10(e)**).

#### 3.7. Vortcity Changes during TC Idai

The low level vertical vorticity (LLV<sub>85</sub>) in the cyclone environment is represented either by a uniform horizontal shear, a uniform solid-body rotation, or a combination of both [23] [39]. Also studies suggest the convection in developing TCs, is dominated by intense updrafts and comparatively weak downdrafts (e.g. reference [40]). For instance, wind shear threshold ranged from 12.5 to 25 m·s<sup>-1</sup> *i.e.* shear threshold is unlikely for TC formation [41]. The distribution of the LLV<sub>85</sub> during the pre Idai **Figure 11(a)** reveals a negative vorticity (a counter-clockwise



**Figure 11.** The mean spatial distribution of the LLV85 for (a) pre Idai; (b) during; and (c) post Idai; where (d) and (e) are the vertical structure of the vorticity at  $45^{\circ}$ E (pre Idai) and  $56^{\circ}$ E (post Idai).

spin) of about  $9 \times 10^{-6}$ /s at the northern Madagascar and the entire strip from the southern Madagascar via Mozambique to southwestern Tanzania. Also the entire area which has high climatology of TCs tracks was under the influence of negative LLRV<sub>85</sub>. These results indicate that the area was under the influence of decreasing vertical wind shear which is among the necessary conditions for TCs genesis and development as supported by [41], and [42]. Besides, Figure 11(a) shows that for the pre Idai condition the entire coastal Tanzania and northeastern highlands of Tanzania was under the influence of positive vorticity of about  $5 \times 10^{-6}$ . As for the distribution of LLRV<sub>85</sub> Figure 11(b) shows that negative LLRV<sub>85</sub> was mapped on center of the landfall area (coastal Mozambique *i.e.* Beira where Idai made a landfall near Beira, Category 2 storm with winds exceeding 105 mph on 14th to 15th March, 2019 with heavy rainfall and flood on Mozambique Malawi and Zimbabwe and nearby countries like southern western Tanzania) and the southwestern Madagascar which the two were in a position to support each other. Also during Idai life the negative LLRV<sub>85</sub> was mapped at north eastern Madagascar indicating the possibility of having the development of other TCs. Indeed, Malawi and southwestern and central Tanzania was under the influence of negative LLRV<sub>85</sub> indicating that the wide distribution of the cyclonic impacts of the Idai during its Landfall. As for the post Idai results presented in Figure 11(c) reveals the negative spinning centered at northeastern Madagascar at the area where the short lived TC Savannah was centered. On the other hand Figure 11(c) show that more affected areas of Mozambique Zambia and Malawi and most parts of Tanzania was now under the influence of zero spin.

The vertical profile of vorticity at 45°E (the landfall longitude of TC Idai) and 56°E (center of TC Savanah) presented in Figure 11(d) and Figure 11(e) revealed a positive vertical spinning of vorticity (Figure 11(d)) from low level to upper level was observed at a latitude range of 10 - 30°S with vertical increased values of vorticity indicating that the impact of Idai fall on the defined latitude range of 10 - 30°S. Also Figure 11(d) shows that equator ward of Idai (5°S to 0) was not having strong spinning indicating stable conditions. In Figure 8(e) results revealed a dipole vertical spinning (i.e. negative or anticlockwise; at low level and positive or clockwise at higher level), with latitude range of 20 to 5S being dominated by this spin. These results indicate the existing of negative vertical shear above the boundary layer, which led the vorticity dipole reverses in sign with height as supported by [41]. Also study results is in agreement with Figure 7(c) where at 56°E the area is dominated by weak vertical shear indicating the strengthening of the storm Savannah. Also Figure 7(c) shows the shear was degreasing northward of latitude 10°S. Indeed, results in Figure 7(c) and Figure 8(e) explain as to what the rainfall resumed at northern coastal areas of Tanzania and Kenya.

## 4. Rainfall Outcome of the Tropical Cyclone Idai

The results of the strength of the rainfall during TC Idai over the mentioned domain using the precipitable water data is presented in Figure 12. Results in

**Figure 12(a)** shows the mean precipitable water distribution during 10<sup>th</sup>-12<sup>th</sup> (*i.e.* before landfall), where MC and coastal areas of Mozambique was mapped with higher rates of more than 50 mm/day, while Malawi. Southern areas of Tanzania and hinterlands of Mozambique were mapped with PRW of 40 - 45 mm/day. As during landfall low **Figure 12(b)** revealed that low lands of Mozambique were marked with heavy PRW rates of more than 50 mm/day, while southern Tanzania, Malawi and Zimbabwe were having PRW rates ranged from



**Figure 12.** Mean precipitable water for different time periods during the landfall of TC Idai March, 2019, where (a) is the mean for  $10^{th}-12^{th}$  *i.e.* before landfall; (b) is the mean for  $13^{th}$  to  $15^{th}$  during landfall; (c) is the mean for  $15^{th}$  to  $17^{th}$  the peak landfall, and (d) is the mean for  $18^{th}-20^{th}$  post landfall and starting of TC Kenneth.

30 - 45 mm/day indicating that Mozambique was more affected by heavy precipitation and floods. As TC Idai tracks southwestward and intensifying its landfall to further interior, then heavy precipitation affected Southern Mozambique and Zimbabwe as shown in Figure 12(c) with high PRW rated at more than 50 mm/day, with the rest of Mozambique and some parts of Zimbabwe having higher PWR rated at 35 - 40 mm/day. Furthermore, the distribution of PRW shows that during 18th-20th March, 2019, instead of getting relief, due to weakening of Idai (16th March, 2020) the condition became more worse because of the strengthening of short lived TC Savannah (18th-20th March, 2019) which intensified and devastated the entire region (Malawi, Zimbabwe, and Mozambique including southern Tanzania) Figure 12(d). Also Figure 12(d) revealed that the entire Mozambique and southern Malawi had higher PRW rates at of more than 50 mm/day indicating that the occurrence of Savannah accelerated the floods due to landfall of Idai and hence affecting the socio-economics, and livelihood status of the three neighboring countries of Mozambique Zimbabwe and Malawi. Besides, results revealed that the occurrence of Savannah reduced the effect of Idai over the Tanzania, Kenya and Uganda (cleared or dried the weather condition) due to turning of 850 mb winds from northeasterly to northerly and to southeasterly (Figure 3(b) and Figure 3(c)).

## 5. The Societal Implications of the TC Idai

The southern African region was severely devastated by cyclone Idai which greatly affected Mozambique, Malawi and Zimbabwe in early to mid March 2019, leaving over 1000 people dead and almost 3 million people being affected. The forecaster warns that locations from Lindi, Tanzania to Pemba in Mozambique may experience the worst of the storm (weather forecaster accuweather). The outcome of the forecast revealed a massive flooding associated to Idai, strong winds and torrential rains which left the west coast southern Africa (Mozambique, Malawi and Zimbabwe (*i.e.* at Chimanimani and Chipinge)) and hinterland areas in flimsy and inundated state due to catastrophic damage. Based on the effects posed by this storm United Nations Office for Coordination and Human Affair [15] estimated that about 1.6 million people were affected in the mentioned three countries. Further analysis revealed that more than 77,000 people were displaced and at least 602 and 344 people were killed in Mozambique and Zimbabwe, respectively. Also the report revealed that about 239,700 houses were damaged in Mozambique and more than 59,100 individuals across Buhera, Chimanmani, Chipinge, and Mutare districts in Zimbabwe. Moreover, communicable diseases including cholera and malaria were reported. According to Mozambican government 4,032 case of cholera were reported and nearly 8900 malaria cases were reported in Beira, Buzi, Dondo, and Nhamantanda [16]. Furthermore, the oral Cholera Vaccination (OCV) campaign vaccined 802,347 people (96% of the target) [15] As for the food security, the Mozambican government estimated that at least 715,378 hectares (including 1.77 million acres of crops [16] of agricultural land were damaged, affecting 500,000 producing families. indeed [16] reported that the flooding and winds related to TC Idai severely damaged water and sanitation systems in Zimbabwe, such that United Nations High Commissioner for Refugees (UNHCR) reported a shortage of safe drinking water in Chipinge district's Tongogara refugee camp, where more than 13,000 refugees and asylum seekers [16]. As for Malawi heavy rains and flooding linked to TC Idai killed 60 people, displaced nearly 87,000 people and affected nearly 870,000 persons in 15 districts (Malawi government), where the most affected areas are southern Malawi in districts of Chichawa, Nsanje, Phalombe, and Zomba. On summary the study results has revealed that TC Idai has severely devastated, the southern African community in the countries Mozambique, Malawi and Zimbabwe, and call the attention for international funders, and humanitarian activists including the USAID, CARE among others to intervene the situation, where a total of \$58,518,212 from different missions were used as humanitarian funding for TC Idai and floods response. On the other hand the occurrence of TC Idai disrupts the MAM 2019 seasonal rainfall over the coastal and hinterland areas of Kenva, Tanzania and Somali, but the occurrence of short lived tropical cyclone Savannah redirected he 850 mb wind orientation an resumed the normality of MAM 2019 rainfalls in EA countries (coastal Kenya Tanzania and Somali).

### 6. Discussions and Conclusions

Tropical cyclones are among natural phenomena that result in devastating situations, which in turn affect the societies leaving either nearby or along the world tropical cyclone basins. The SWIO basin has been experienced worse and more devastating conditions during the occurrences of TCs such as Bondo 1996, Elline 2000, Fantatla 2016, Fobane (2014) among others. The 2018/2019 SWIO TC season has been among the worse seasons in the history of TCs in this basin. The occurrence of three consecutive TCs of Idai (4-16th March, 2019), Savannah (18-20th March, 2019) and Kenneth (21st-29th April, 2019) has been among the issues of world concern due to damages associated with these TCs over Mozambique (four provinces of Sofala, Manica, Zambezia and Tete were severely damaged), Zimbabwe, and Malawi as well as the countries lying equatorward of 12°S (such as Tanzania, Kenya Uganda and Somalia). The frequent episodes of floods droughts facing Mozambique and nearby countries could be explained as the growing reality of the negative impact of climate change as noted by [43]. Based on the impacts of the strongest TCs in the SWIO, and which made landfall in Mozambique, TC Idai (2019) was the second in the record after TC (Elline, 2000) which induced the biggest floods causing the death of 700 people and affecting more than 2 million people, and economic damages estimated to 600 million USD [44]. The study has devoted to analyzing the dynamics of the TC Idai which caused the devastating events of heavy rainfall, floods and strong winds which resulted in the marked catastrophic moments over the stated domain. The presented results and the reports have agreed that nearly all necessary conditions for the TCs genesis and development were in a state to allow the formation and development of the TC Idai. For instance, wind vectors (Figure 3), MSLP (Figure 4), SSTs (Figure 5), PRW (Figure 6) among others all were in agreement to support the TC Idai development and intensification. Moreover, apart from causing catastrophic damages to most SWIO countries including Mozambique, Zambia and Malawi, but also TC Idai declined the MAM 2019 weather over the coastal strip of EA (Kenya, Tanzania, Somali among others) resulting in enhanced dry conditions over Kenya, the phenomenon which is well agreed by [9] that when TCs are tracking on MC the weather in most areas of northern coastal Tanzania, the coastal strip of Kenya and Somali among others is declined.

Based on the presented results and discussions, the study came up with the following conclusions:

1) TCs are among the climate events which results in the catastrophic environment over most areas, hence extensive studies on TCs characteristic and its landfall behaviors especially over low lands of Mozambique should be well researched to reduce the vulnerability and the impacts;

2) TCs landfall events has been several time forecasted over the Tanzanian coast (e.g. Fantala, Keneth, Jobo among others), but unfortunately, the forecasts went wrong, so extensive studies should be conducted to explain why TCs do not normally make land fall to the coastal strip of Tanzania especially the northern coast;

3) Extensive studies should be conducted to understand why when TCs are tracking over the MC the coastal strip of Tanzania and Kenya become dry;

4) The need to improve the infrastructures to minimize the impacts of the frequent landing cyclones over the MC and neighborhood areas.

## **Conflicts of Interest**

The authors declare no conflicts of interest regarding the publication of this paper.

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