European Commission

JRC TECHNICAL REPORTS

Tropical Cyclone ENAWO
Post-Event Report

Madagascar, March 2017

TC-2017-000023-MDG

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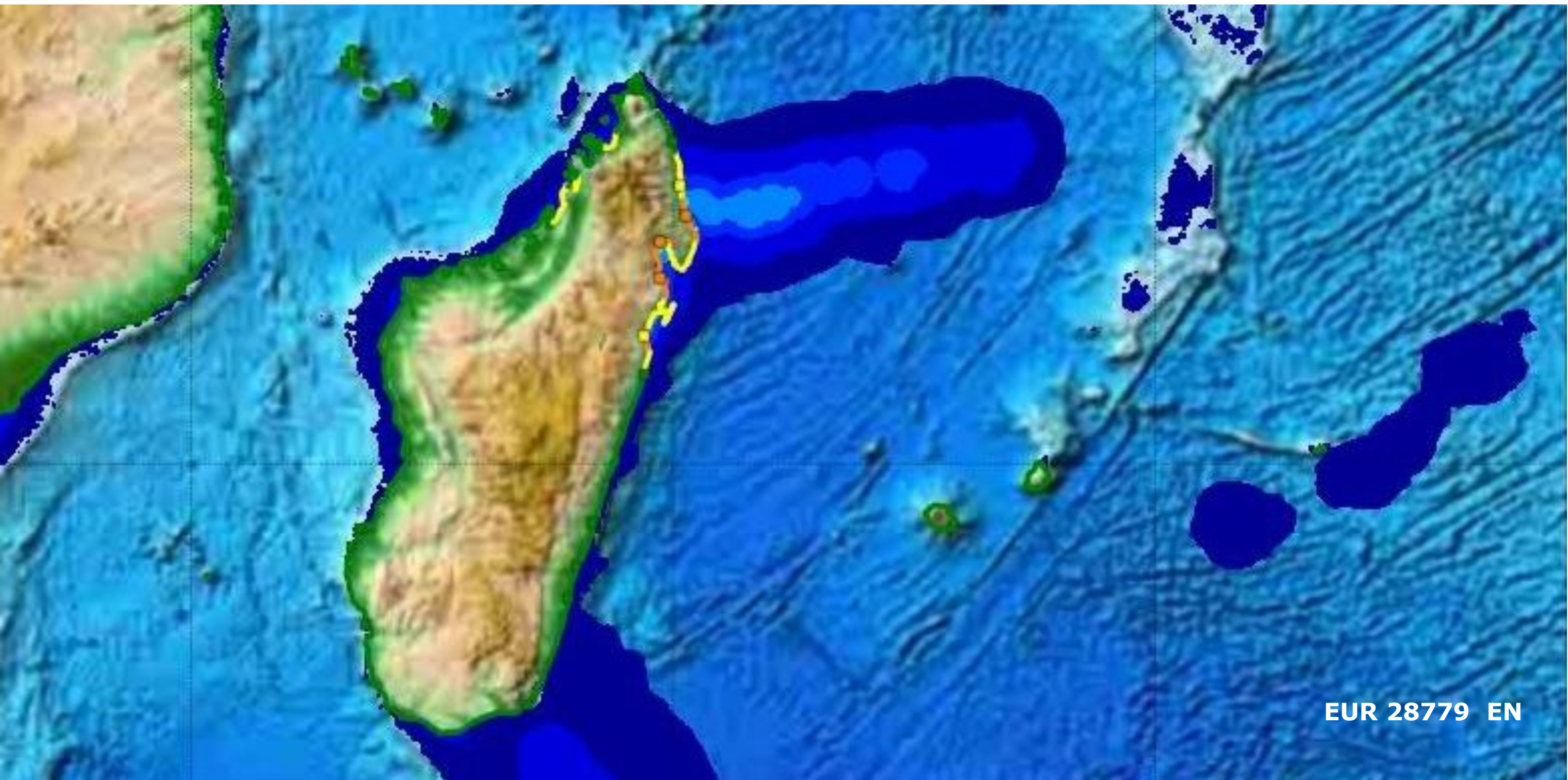
2017



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Contents

Abstract

Tropical Cyclones (TCs) are among the most damaging events. They affect the population with three dangerous effects: strong wind, heavy rain and storm surge. JRC has developed a system used in Global Disaster Alert and Coordination System (GDACS) that includes the analysis of all these effects for every TC occurring worldwide to assess the overall impact.

This document is the first POST-EVENT Report, which is a new type of report produced by the JRC after a major event aimed to report the real status of the impact that occurred, based on media reports, onsite analyses, and satellite images.

The event analysed in this report is the intense TC ENAWO, that made landfall in north-eastern Madagascar on 7 March 2017, killing more than 80 people and causing extensive damage, especially in Sava and Analanjirofo regions. Authorities issued a "declaration of national emergency" and formally requested international assistance on 14 March.

GDACS issued the first RED alert (for high winds) in Madagascar on 3 March. The Emergency Response Coordination Centre (ERCC) of DG ECHO activated ARISTOTLE on 5 March and the Copernicus Emergency Management Service (EMS) on 7 March.

The responses of the alert and information systems are analysed and the results are compared with the damage reported by national authorities and satellite images analysis.

In order to improve the current early warning system and impact estimations, JRC is implementing a new method to evaluate the areas potentially most affected by a TC, using new datasets and classifications. The results are also included in the report.

1 Introduction

Tropical Cyclones (TCs) are among the most dangerous natural disasters. They affect the population with three destructive effects (strong wind, heavy rain and storm surge) and every year they cause extensive damage and deaths in several countries around the world, especially along the coastal areas. In order to estimate the area and the population affected by a TC, all three types of physical impact must be taken into account.

Global Disaster Alert and Coordination System (GDACS, www.gdacs.org) includes the analysis of all these effects for every TC occurring worldwide. GDACS is a cooperation framework between the European Commission and the United Nations Office for the Coordination of Humanitarian Affairs (UN-OCHA). It provides alerts and preliminary impact estimations of the natural disasters around the world, like earthquakes, tsunamis, tropical cyclones and floods. Its alerts are primarily aimed at the international humanitarian community and reflect the possibility of a need of international assistance. It is also a support tool in case of emergency, providing real-time access to web-based disaster information systems and related coordination tool. For this system, the JRC set up an automatic routine that includes the TC bulletins produced by the National Oceanic and Atmospheric Administration (NOAA) and the Joint Typhoon Warning Center (JTWC) into a single database, covering all TC basins. Moreover, JRC has developed a specific storm surge calculation system, introducing the atmospheric forcing in the JRC's HyFlux2 code and using as input the TC bulletins. Recently, JRC has developed a new storm surge system that uses as input different atmospheric inputs (see Technical Annex).

The JRC's tools developed for the analysis of the TCs are used in early warning systems like GDACS, since the alerts can be issued before the event and the areas potentially most affected could be identified. This information allows to define the cases in which the International Assistance is expected to be required, as well as to determine the areas of interest for the activation of COPERNICUS Emergency Management Service (EMS).

The results of these activities on TCs modelling are also used to provide specific support (e.g. reports, maps, flash) to the Emergency Response Coordination Centre (ERCC) of DG ECHO (see http://erccportal.jrc.ec.europa.eu/).

In February 2017, the new pilot project named All Risk Integrated System TOwards Trans-boundary hoListic Early-warning (ARISTOTLE) set-up by DG ECHO with funds from the European Parliament in 2016, started the production of a multi-risk report within few hours from the activation. Earthquakes, Tsunami, Volcanic eruption and Severe Weather events, including Tropical Cyclone are the events considered.

This document is the first POST-EVENT Report, which is a new type of report produced by the JRC after a major event aimed to report the real status of the impact that occurred, based on media reports, onsite analyses, and satellite images. It includes also a scientific analysis of the responses of the alert and information warning systems, like GDACS.

The event analysed in this POST-EVENT Report is TC ENAWO (GLIDE number: TC-2017-000023-MDG) that hit Madagascar on 7 March 2017 as an intense TC, killing more than 80 people and causing extensive damage, especially in Sava and Analanjirofo regions. Authorities issued a "declaration of national emergency" and formally requested international assistance on 14 March.

GDACS issued the first RED alert (for high winds) in Madagascar on 3 March and an Orange Alert for the Storm Surge impact on 4 March. ERCC of DG ECHO activated ARISTOTLE on 5 March and Copernicus EMS on 7 March. The responses of GDACS and ARISTOTLE are analysed and the results are compared with the damage reported by national authorities and using satellite remote sensing data (e.g. Copernicus EMS).

In order to improve the current GDACS system, JRC is currently developing and implementing several new tools for the analysis of the TC impacts and evaluate their potential risks. The first preliminary results of the new methodology are presented in this report.

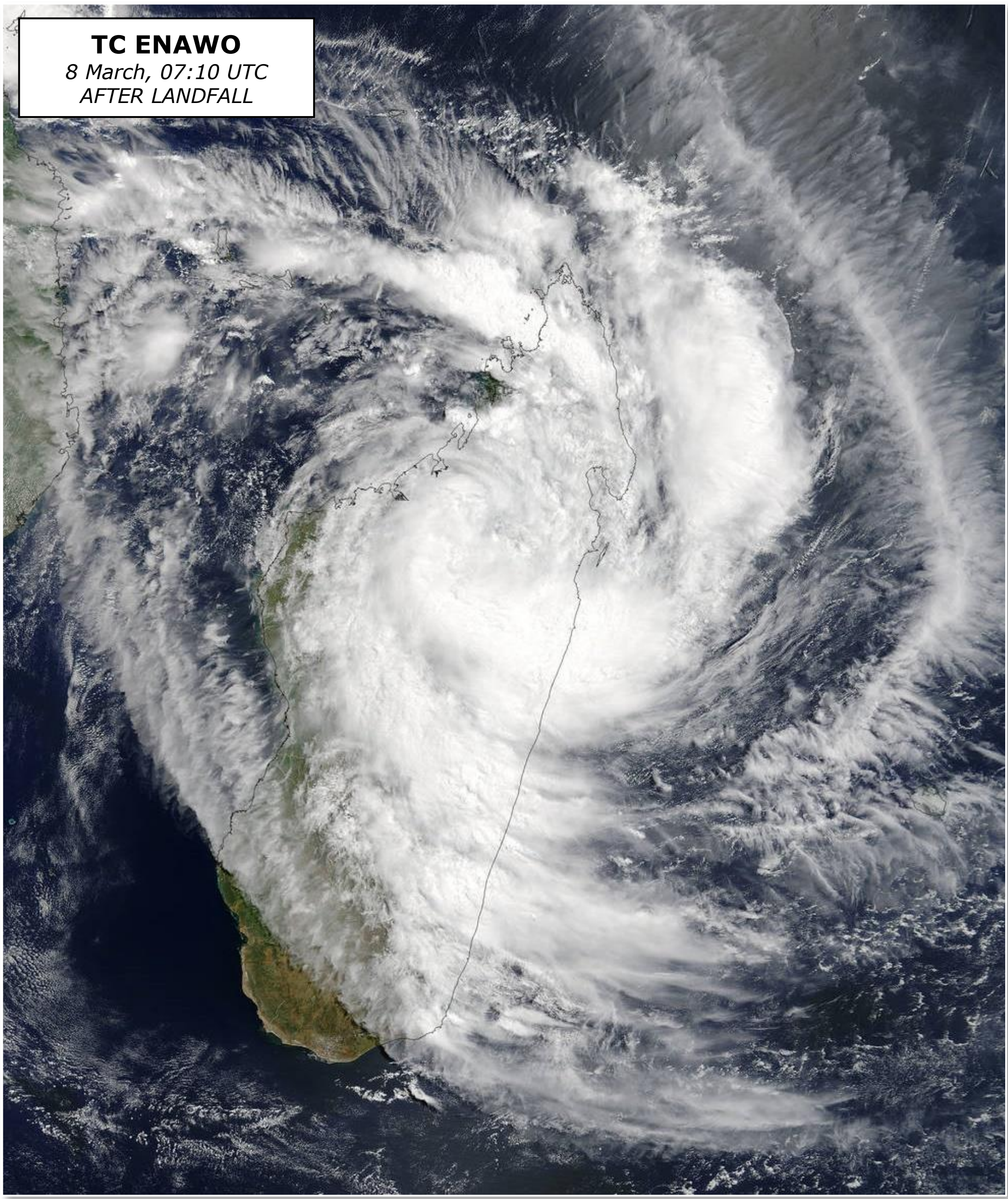


Figure 1 *– TC ENAWO - NASA's Terra satellite, as of 8 March, 07:10 UTC (source: NASA Goddard MODIS Rapid Response Team: https://www.nasa.gov/feature/goddard/2017/enawo-southern-indian-ocean).*

2 Situation Assessment

2.1 Tropical Cyclone ENAWO

Tropical Cyclone ENAWO formed on 3 March over the Southern Indian Ocean and moved W-SW toward the north-eastern coast of Madagascar, increasing its strength and reaching 1-min sustained winds of 230 km/h (equivalent to a Category 4 in the Saffir-Simpson Hurricane wind Scale , SSHS) before the landfall (see TC ENAWO track in **Figure 2**).

TC ENAWO made landfall along the coast of Sava region (north-eastern Madagascar), between the cities of Sambava and Antalaha in the morning of 7 March (09:30-09:45 UTC) with maximum sustained winds of 210-230 km/h. Strong winds, heavy rainfall and storm surge especially affected the districts of Antalaha (Sava region) and Maroantsetra (Analanjirofo region), see **Figure 2**.

After the landfall, it moved SW-S over central and southern Madagascar, weakening into a Tropical Depression, but still damaging infrastructures, causing floods and landslides in several areas of the country (see Section 2.2).

Late on 9 March, it emerged again into the southern Indian Ocean and started strengthening again, moving away from the southern coasts of Madagascar.

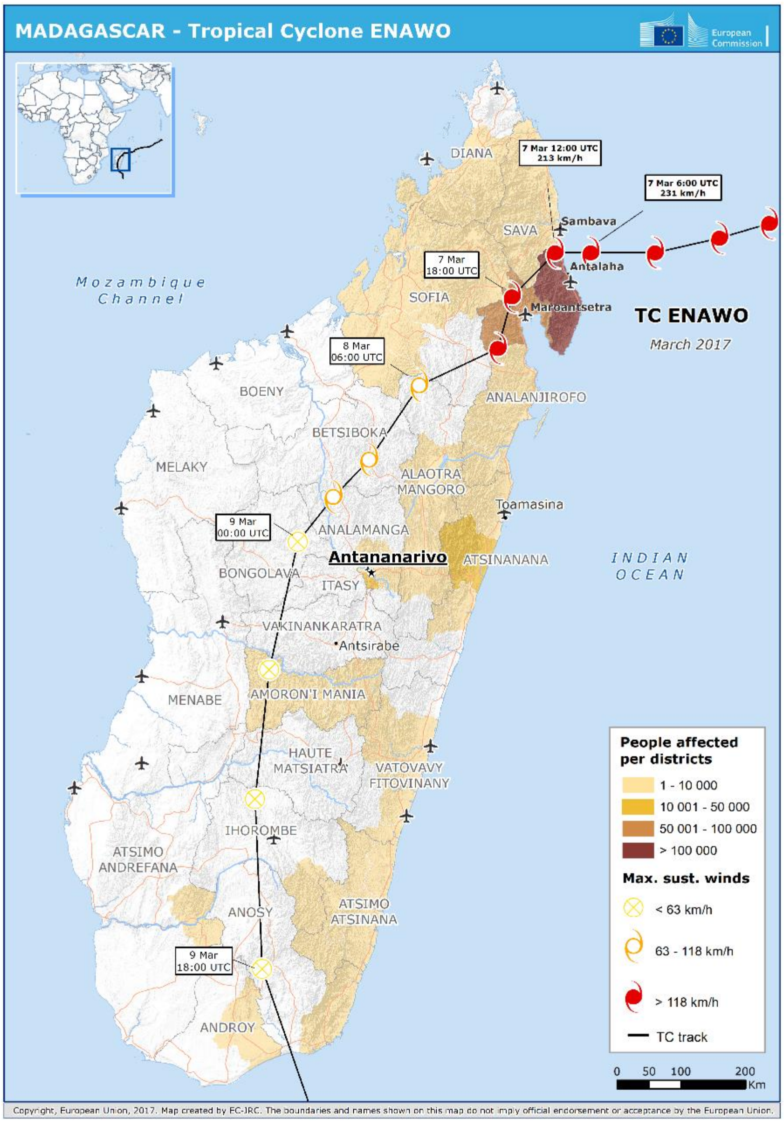


Figure 2 - *Track of TC ENAWO and population affected per districts (data sources: JTWC, BNGRC)*

2.1.1 Measurements

2.1.1.1 Wind

Multiplatform Tropical Cyclone Surface Winds Analysis (MTCSWA)

The surface winds obtained (3h before / 3h after landfall) using the satellite product of NOAA - National Environmental Satellite Data and Information Service (NESDIS) *Multiplatform Tropical Cyclone Surface Winds Analysis (MTCSWA)*[1] are shown below. According to this data, 3h before the landfall TC EANWO had max. sustained winds of 219 km/h (equivalent to a Category 4 in the SSHS).

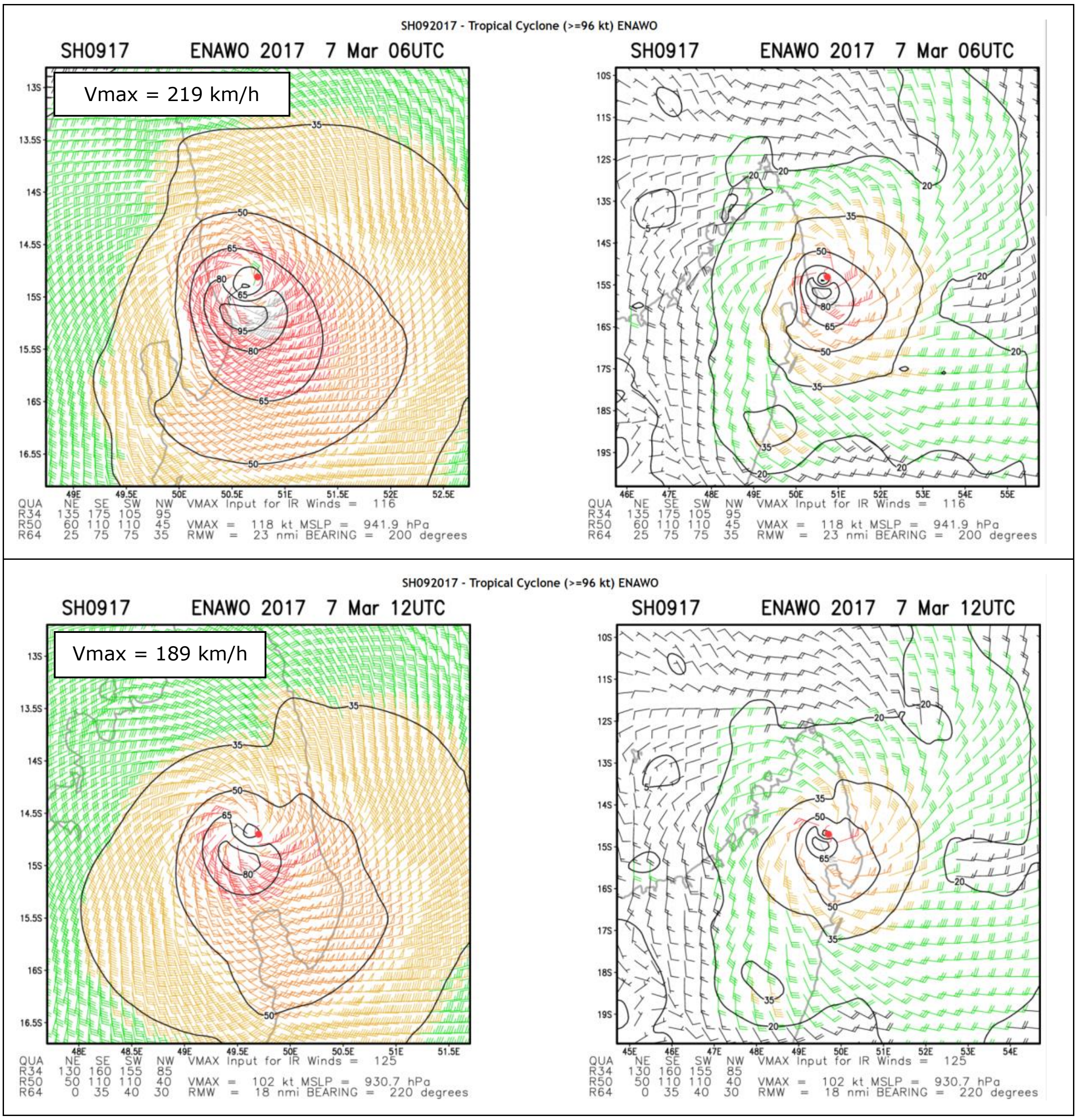


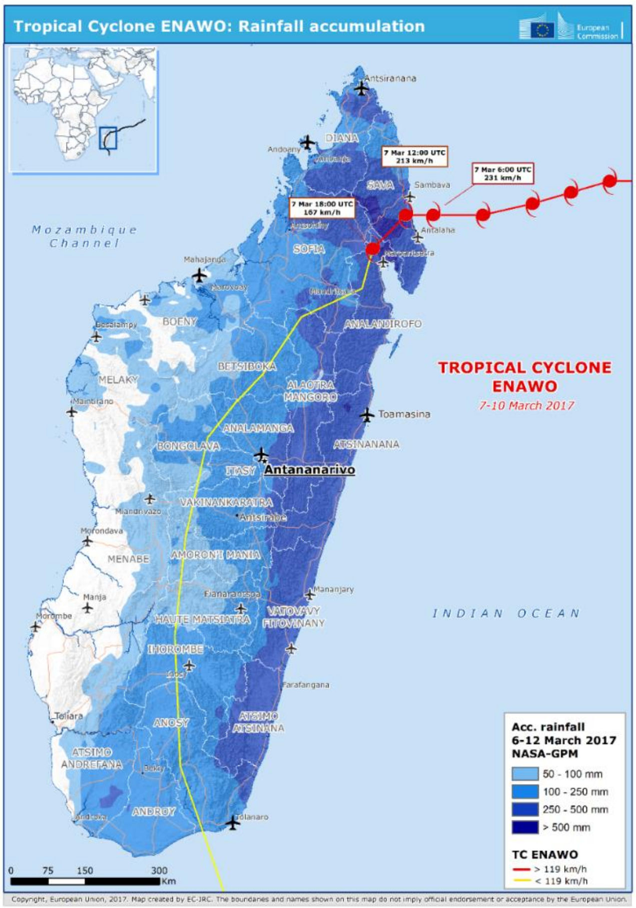
Figure 3 *– NOAA-MTCSWA winds for TC ENAWO on 7 March 06:00 UTC (above) and on 7 March 12:00 UTC (below) (source: NOAA-NESDIS)*

[1] More information on this product are available at: http://www.ssd.noaa.gov/PS/TROP/MTCSWA_UM.pdf

2.1.1.2 Rainfall

NASA-Global Precipitation Measurement (GPM) and METAR

The accumulation rainfall obtained using the satellite product of NASA-GPM (Global Precipitation Measurement[2]) are shown below. More than 500 mm of rainfall affected some areas of SAVA and northern ANALANJIROFO regions during the passage of ENAWO.
The rainfall measured (METAR[3] data) are shown in the tables below.
The average monthly rainfall of March in the area of Analaha and Maorantsetra is nearly 300 mm (data source: World Bank[4]). More information on the average monthly rainfall mean is in Annex 6, while the comparisons between the rainfall produced by TC ENAWO and the monthly average of March is shown on the next page.



24h rainfall accumulation 6 Mar 06:00 – 7 Mar 06:00	
Sambava	104 mm
Antsirabato	71 mm
Toamasina	48 mm
St. Marie	37 mm
24h rainfall accumulation 7 Mar 06:00 – 8 Mar 06:00	
Sambava	215 mm
Ambohitsilaozana	99 mm
Toamasina	97 mm
Mananjary	39 mm
Antananarivo/Ivato	56 mm
St. Marie	128 mm
Fascene (Nossi-Be)	102 mm
Antsohihy	102 mm
24h rainfall accumulation 8 Mar 06:00 – 9 Mar 06:00	
Antsohihy	104 mm
Mananjary	237 mm
Fianarantsoa	137 mm
Antananarivo/Ivato	100 mm
Besalampy	94 mm
Fascene (Nossi-Be)	70 mm

Figure 4 – *Figure: Accumulation rainfall 6-12 March 2017 (data source: NASA-GPM)*
Table: Rainfall measured (METAR)

[2] NASA-GPM (Global Precipitation Measurement): https://www.nasa.gov/mission_pages/GPM/main/index.html
[3] NOAA NNDC Climate Data Online:
https://www7.ncdc.noaa.gov/CDO/cdopoemain.cmd?datasetabbv=DS3505&countryabbv=&georegionabbv=&resolution=40
[4] http://sdwebx.worldbank.org/climateportal/index.cfm?page=country_historical_climate&ThisCCode=MDG

NASA-GPM vs monthly average

The total rainfall accumulation produced by TC ENAWO obtained using the data of NASA-GPM has been compared with the average rainfall of March obtained using the climate data of WorldClim 2.0[5] (see Fick and Hijmans, 2017) to identify the areas most affected by heavy rainfall. The results are presented in **Figure 5**: the area where the rainfall produced by TC ENAWO is higher than the monthly average is shown in blue.

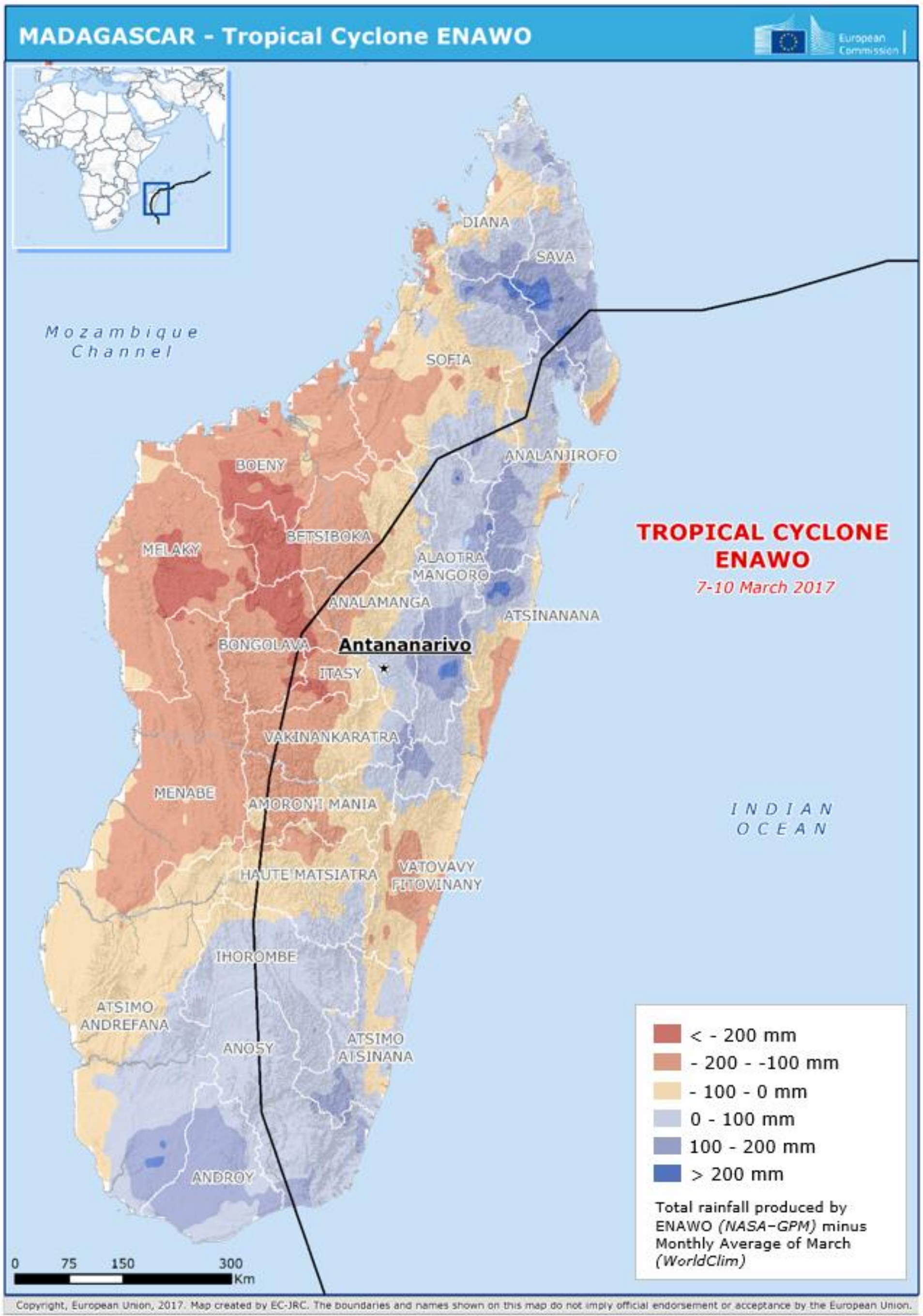


***Figure 5 –** Difference between the total rainfall accumulation produced by TC ENAWO (NASA-GPM) and the average monthly rainfall mean of March using the climate data of WorldClim 2.0 (see Fick and Hijmans, 2017).*

[5] See Fick and Hijmans, 2017. http://worldclim.org/version2

2.1.1.3 Storm Surge

In order to evaluate the JRC storm surge calculations, the only tide gauge available in the area is located in Toamasina in Antisanana region, approx. 370 km south of Antalaha (landfall area). The signal detected by this instrument is shown in the figure below.

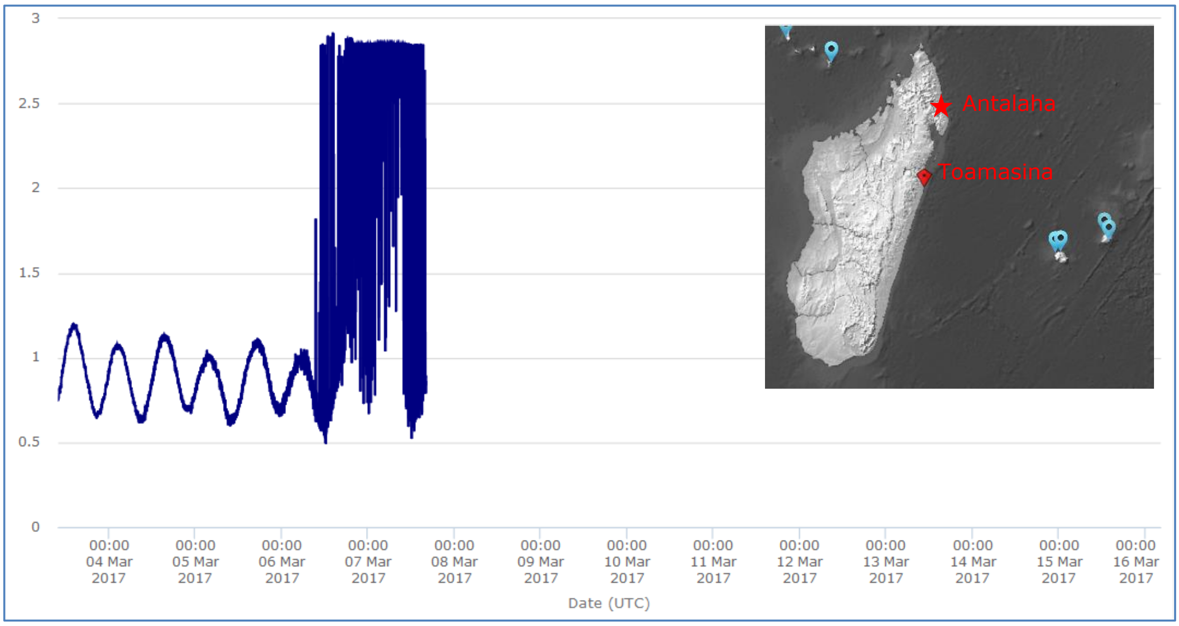


***Figure 6 -** Sea level measured in Toamasina during the passage of TC ENAWO*

(see http://webcritech.jrc.ec.europa.eu/SeaLevelsDb/Home/TideChartPro/1588)

As can be seen in this figure, the instrument was working well until the arrive of TC ENAWO on 7 March. At that time the signal started oscillanting and then it stopped.

The measurement of this instrument was used by the JRC in 2012 to validate the results for TC GIOVANNA. During this analysis the JRC detected the same problem, that was due to the presence of a barbed wire located under the device. A brief description of of this problem is reported in Annex 6, while more information can be found in Probst et al (2012).

Therefore the measurements of this tide gauge can not be used for the validation. However from this figure it is possible to see the passage of ENAWO, that occurred during the strong oscillations visible on the **Figure 6**.

2.2 Humanitarian Impact

Tropical Cyclone ENAWO made landfall over Antalaha district (northeastern Madagascar) on 7 March, then it moved southwards across central and southern areas of the country. It caused damage and deaths in several regions of Madagascar, especially in the north-eastern and eastern areas of the country. The districts of Antalaha (Sava region) and Maroantsetra (Analanjirofo region) are the districts most affected, with 15 municipalities (out of 31) severely affected (see UN-BNGRC Situation Report nr. 5).

As of 17 March, the Government's Office for disaster and risk management (BNGRC - *Bureau National de Gestion des Risques et Catastrophe*) reported 434 000 people affected with 58 districts out of 119 reporting damages, nearly 250 000 temporarily displaced and 81 dead. According to the UN-BNGRC Situation Report nr. 5 (14 April 2017), the estimation of economic losses conducted by the CPGU (*Cellule de Prevention et de Gestion des Urgences*) and the World Bank was: $400 million (corresponding to about 4% of annual GDP of Madagascar).

On 14 March, national authorities issued a "declaration of national emergency" and requested assistance from national and international partners.

The damage due to TC ENAWO will be analysed, using Sendai Targets and related Indicator, in Section 4.2.

2.2.1 Affected population

During its passage at least 81 people were killed, and over 430 000 people were affected. The latest figures available for each regions (as of March 2017[6]) are shown in the Table below, while the total number of people affected per regions and districts, as well as the number of deaths are shown in Figure 18. The percentage of people affected and displaced per region (pop. of *Office National pour l'Environnement*", see Annex 4), are shown below.

Region	Dead	Missing	Injured	Displaced	Pop affected	% affected	% displaced
ALAOTRA MANGORO	17	2	2	6 789	10 964	1 %	0.6 %
AMORON I MANIA	2	-	-	1 203	2 041	0.3 %	0.2 %
ANALAMANGA	5	-	6	28 783	32 983	1 %	0.8 %
ANALANJIROFO	**7**	1	6	62 621	**66 784**	**6 %**	**6 %**
ANDROY	-	-	-	-	2 130	0.3 %	-
ANOSY	-	-	-	392	392	0.1 %	0.1 %
ATSIMO ANDREFANA	-	-	-	95	95	< 0.1 %	< 0.1 %
ATSIMO ATSINANANA	3	12	-	8 297	10 004	1 %	< 0.1 %
ATSINANANA	34	1	46	19 432	28 358	2 %	2 %
DIANA	1	-	2	-	2 559	0.3 %	0.3 %
IHOROMBE	-	-	-	63	63	< 0.1 %	< 0.1 %
SAVA	**6**	**1**	**184**	**114 500**	**236 456**	**23 %**	**11 %**
SOFIA	5	-	4	62	27 046	2 %	< 0.1 %
VATOVAVY FITOVINANY	1	1	3	4 982	14 110	1 %	0.3 %
Total	**81**	**18**	**253**	**247 219**	**433 985**	**2 %**	**1 %**

Table 1 - Impact TC ENAWO: Dead, people missing, people displaced, people affected, % people affected / total people in the regions, % people displaced / total people in the regions. (Source: BNGRC, as of 17 March 2017[6])

[6] *BNGRC (source: IOM Report - Annexes, http://www.globaldtm.info/madagascar/)*

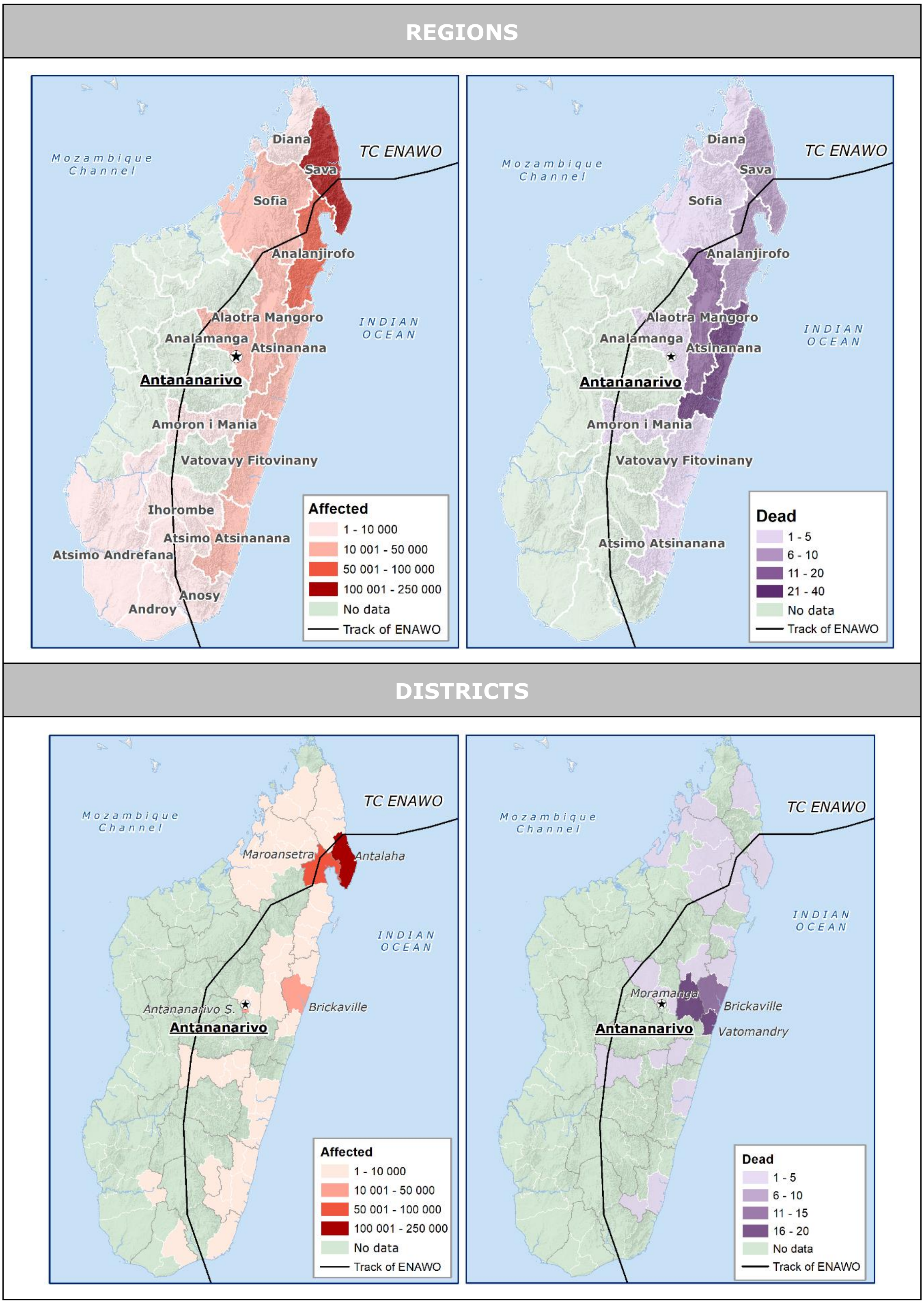


Figure 7 – *TOP: Affected people (left) and deaths (right) per regions*
BOTTOM: Population affected (left) and number of deaths per districts (right).
As of 17 March 2017

As shown in **Figure 7** the regions with the highest number of people affected are **Sava** and **Analanjirofo**. Analysing the number of people affected in the districts of these two regions, the districts most affected are:

- **Antalaha (Sava)**: 92 % of people affected
- **Maroantsetra (Analanjirofo):** 25 % of people affected

However, analysing the number of deaths, the highest values are in:

- ATSINANANA: 17 in Vatomandry, 15 in Brickaville, 1 in Toamasina, 1 in Marolambo.
- ALAOTRA MANGORO: 16 in Moramanga, 1 Ambatondrazaka.

Several people in the area of Brickaville died due to landslides and floods.

The highest number of the people injured was in Sava region, where the landfall occurred.

Most Affected Regions			
Region	**Population**	**Pop. Affected**	**% affected**
SAVA	**1 034 599**	**236 456**	**23 %**
Andapa	200 296	5 861	2.9 %
Antalaha	**244 174**	**224 571**	**92 %**
Sambava	321 059	450	0.1 %
Vohémar	269 070	5 574	2.1 %
ANALANJIROFO	**1 091 901**	**66 784**	**6 %**
Maroantsetra	**233 091**	**58 401**	**25 %**
Mananara N.	179 262	2 348	1.3 %
Soanierana-Ivongo	143 515	429	0.3 %
St. Marie	28 003	311	1.1 %
Fénérive Est	325 308	2 095	0.6 %
Vavatenina	182 722	3 200	1.8 %
TOTAL	**2.1 million**	303 240	-

Table 2 - *Impact of ENAWO in the two most affected regions*

(source: BNGRC, as of 17 March 2017)

2.2.2 Damaged houses

The number of houses destroyed, flooded and unroofed for each region and district according to the official report of BNGRC number 4 of 13 March 2017[7] are shown in the figures below. The regions most affected by floods and damaging winds are SAVA and ANALANJIROFO. However also other two regions, ATSINANANA (Brickaville district) and ANALAMANGA (Antananarivo), results particularly affected by floods.

Region	Destroyed	Flooded	Unroofed
ALAOTRA MANGORO	71	644	-
AMORON I MANIA	15	-	21
ANALAMANGA	**142**	**3 153**	**2**
ANALANJIROFO	**1 845**	**3 131**	**1 598**
ANOSY	-	106	-
ATSIMO ANDREFANA	17	-	-
ATSIMO ATSINANANA	52	640	4
ATSINANANA	**764**	**5 229**	**600**
DIANA	14	452	13
IHOROMBE	11	-	-
SAVA	**34 894**	**5 287**	**34 420**
SOFIA	22	122	3
VATOVAVY FITOVINANY	141	526	106
Total	**37 988**	**19 290**	**36 767**

Table 3 *– Impact of TC ENAWO: Houses destroyed, flooded, unroofed (as of 13 March 2017)*

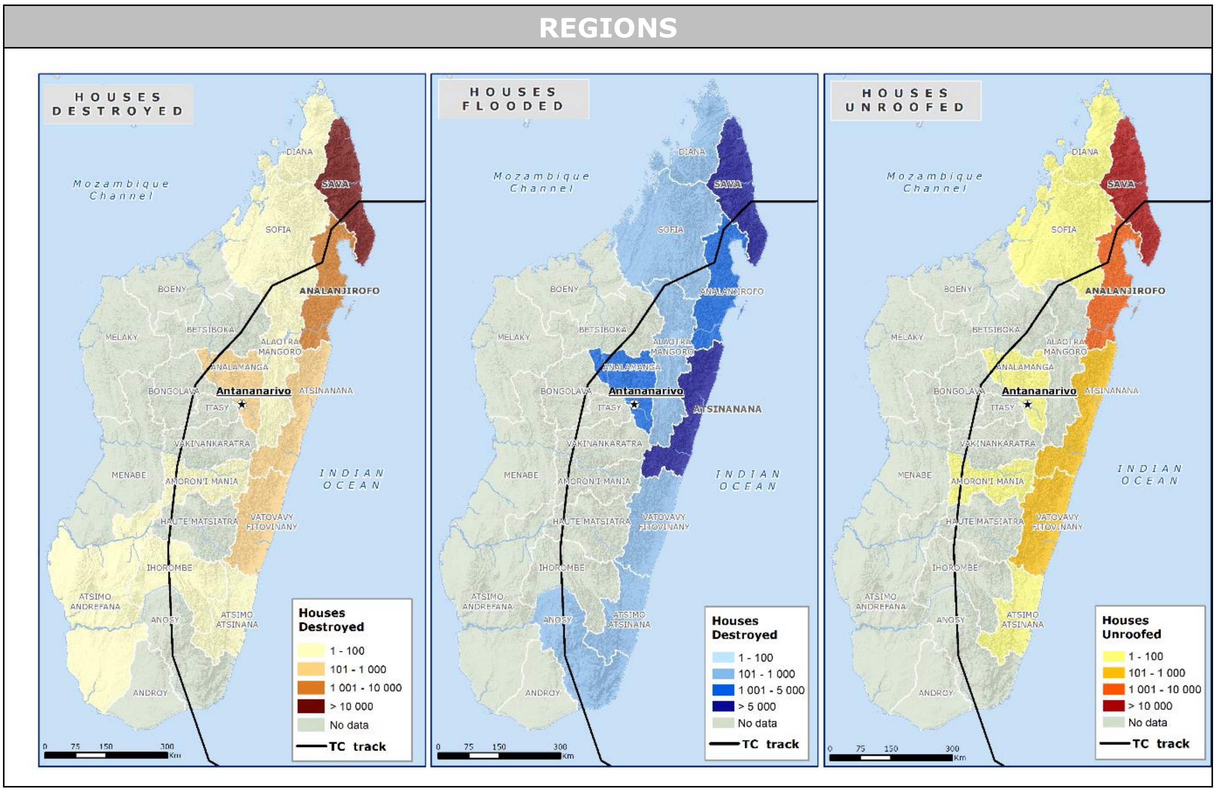


Figure 8 *- Impact of TC ENAWO: houses destroyed (left), flooded (middle) and unroofed (right) per regions*

[7] BNGRC report: http://www.bngrc-mid.mg/index.php?option=com_content&view=article&id=7&Itemid=112

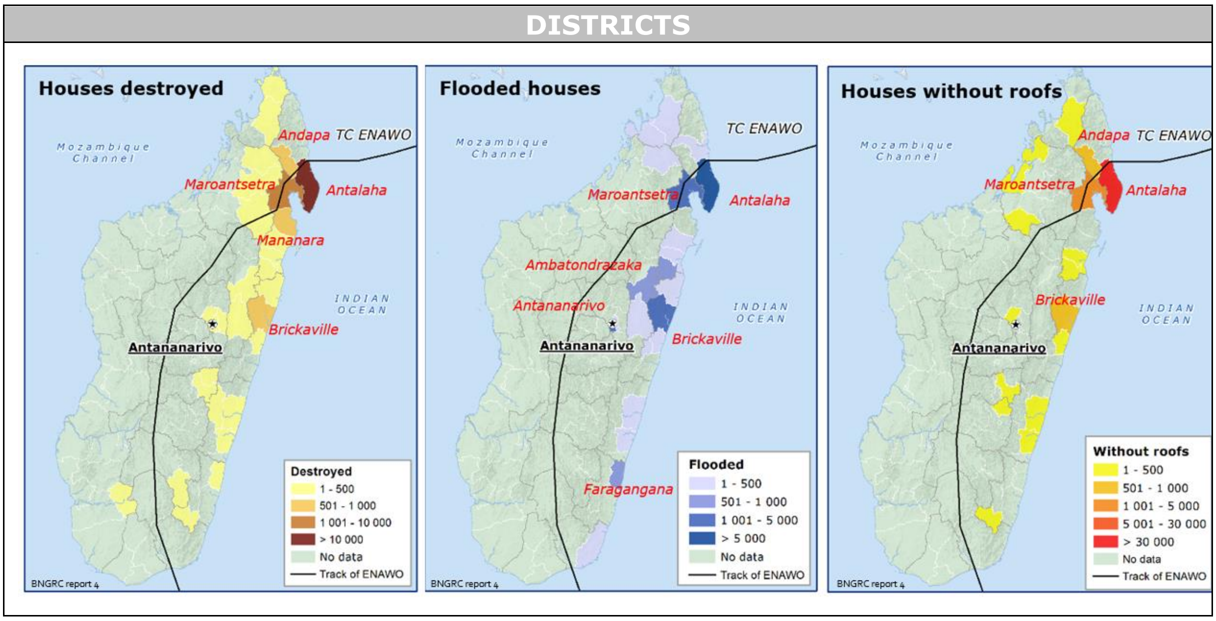


Figure 9 - *Impact of TC ENAWO: houses destroyed (left), flooded (middle) and unroofed (right) per districts (as of BNGRC report nr. 4 of 13 March 2017)*

NOTE:
The area of Maroantsetra has been particularly affected by floods (see Figure below). According to media[8], a dam burst around the city of Ambinanitelo and caused floods in the city itself and in the surrounding areas, including Maroantsetra.

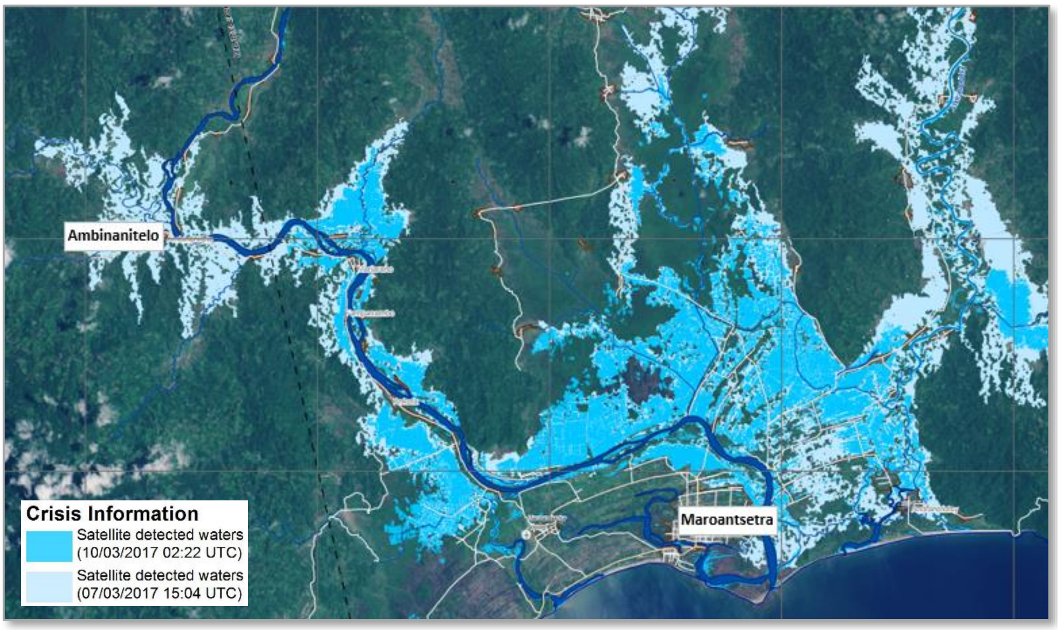


Figure 10 - *Floods in Maroantsetra*
(source: Copernicus EMS © 2017, [EMSR197] Maroantsetra; Delineation Map)

[8] https://blogdemadagascar.com/photos-inondations-a-maroantsetra-apres-le-passage-du-cyclone-enawo/, http://www.orange.mg/actualite/rupture-barrage-dambinanitelo-maroantsetra-sous-eaux

2.3 Humanitarian Response

European Commission

- The European Commission released emergency assistance of €1 million to help Madagascar deal with the consequences of TC ENAWO. Several European Commission humanitarian partners activated the mechanism for rapid response which allowed them to immediately address the effects of these disasters (see ECHO FACTSHEET, Southern Africa & Indian Ocean - April 2017).
- DG ECHO partners operating in cyclone affected areas activated the crisis modifier integrated in their current DG ECHO funded actions, allowing them to provide immediate response (see ECHO Daily Flash 17 March 2017, see ERCC portal). DG ECHO supported by the Danish, German and Norwegian Red Cross Societies to support the Malagasy Red Cross Society (MRCS) mobilized 24 National Disaster Response Team (NDRT) and 120 Branch Disaster Response Team (BDRT) members, as well as 889 volunteers on the ground to raise awareness ahead of the cyclone and conduct rapid assessments in six regions (see UN - BNGRC Situation Report 5)
- Emergency Response Coordination Centre (ERCC) of DG ECHO activated ARISTOTLE on 5 March and two reports were produced (5 and 7 March).

Joint Research Centre

- As part of the Administrative Arrangement with DG ECHO, the JRC produced 5 daily maps published on the ERCC Portal (http://erccportal.jrc.ec.europa.eu/maps) and distributed to all Member States. JRC also provided updated information on TC ENAWO in its ECHO Daily Flash reports, available at http://erccportal.jrc.ec.europa.eu/ECHO-Flash.
- The Copernicus EMS was activated by ERCC on 7 March and produced a significant number of satellite image based maps on the extent of the damage caused by TC ENAWO, also at the request of authorities.

Local and national response

- The government's office for disaster and risk management (BNGRC *Bureau National de Gestion des Risques et Catastrophe*) is responsible for disaster management and response in Madagascar.
- Red alerts were issued in several regions, including Sava and Analanjirofo before the arrive of TC ENAWO. BNGRC send a number of teams to the affected areas (Antalaha, Analanjirofo, and Sofia) to support local authorities and to train rescue workers. Tents, beds, survival kits and food were provided. BNGRC evacuated affected populations, relief items were pre-positioned and supplies were distributed to affected populations. The Malagasy Red Cross Society mobilised volunteers in the affected areas (see ACAPS report).
- On 10 March, the President of Madagascar, accompanied by the Prime Minister and many Government officials, visited several areas affected by ENAWO, underscoring the engagement of national authorities in leading and coordinating the response. (see Flash Appeal, March 2017).
- Relief items were pre-positioned in 15 districts ahead of Cyclone Enawo's arrival to respond to food security, education, health, nutrition, shelter, water and sanitation, and protection needs. Additional supplies started to be deployed to Sava and Analanjirofo regions on 10 March (see ECHO Crisis Flash nr 2, 17 March 2017)
- The Government of Madagascar declared a national emergency situation on 14 March and launched an appeal for international assistance. Response activities initiated by the Government and humanitarian partners, using in-country supplies.

International Response

- A UNDAC (UN Disaster Assessment and Coordination) team was deployed to support the BNGRC and humanitarian partners in information management, assessments and coordination arrived in Madagascar on 8 March. International Federation of Red Cross (IFRC) sent a FACT (Field Assessment and Coordination Team) team to support the Malagasy Red Cross. Other humanitarian organizations were also strengthening and/or establishing their in-country presence (see Flash Appeal, March 2017).
- From 9 to 10 March, the United Nations Resident Coordinator and members of the Humanitarian Country Team (HCT) conducted an overflight of the cyclone-affected areas in Sava and Analanjirofo regions.
- UN agencies have mobilised the emergency cash grant system.
- On 23 March the Government of Madagascar, the United Nations and other humanitarian partners jointly launched the Madagascar Cyclone Enawo Flash Appeal, calling for just over US$ 20 million to assist 250 000 of the most vulnerable people affected by the storm with life-saving assistance and protection for the next three months.
- The UN Under-Secretary-General and Emergency Relief Coordinator (USG/ERC) and the Malagasy Permanent Representation at the UN re-launched the Flash Appeal on ENAWO on 28 March in New York, with the participation of the Malagasy Prime Minister, various Ministers and the UN Resident Coordinator for Madagascar via videoconference.

2.4 Historical events in the area

TCs season

Madagascar is affected by Tropical Cyclones during the Indian Ocean TC season that officially is: **from mid-Nov to mid-Apr** (see Annex 5).

Historical TCs in Madagascar

The impact (dead and number of people affected) over the period 1990-2016 included in EMDAT-CRED is shown in **Figure 11**. TC ENAWO is also included in the figure and it is shown in RED. As can be seen, the most damaging TC (highest number of deaths and people affected) over the last years was:

TC GAFILO in 2004: it made landfall in Sava Region, near Antalaha, as an intense TC (equivalent to a Cat 4 in the SSHS). It killed more than 360 people (> 100 due to a shipwreck) and affected nearly 1 million people. It hit Madagascar only one month after TC ELITA. Therefore the damage from TC GAFILO became more severe. The Government of Madagascar **declared an emergency and appealed for international assistance** on 8 March 2004.

Moreover, TCs IVAN and FAME affected more than 239 000 people in Madagascar in 2008. A **Madagascar Flash Appeal** was launched on 3 March 2008 to support Government efforts to respond to the immediate and early recovery needs of over 239 000 people in urgent need of assistance (source: FAO[9]).

The TCs included in the Figure below made landfall in different areas of Madagascar. A more detailed analysis on the NE Madagascar (area of the landfall of ENAWO) is shown on the next page.

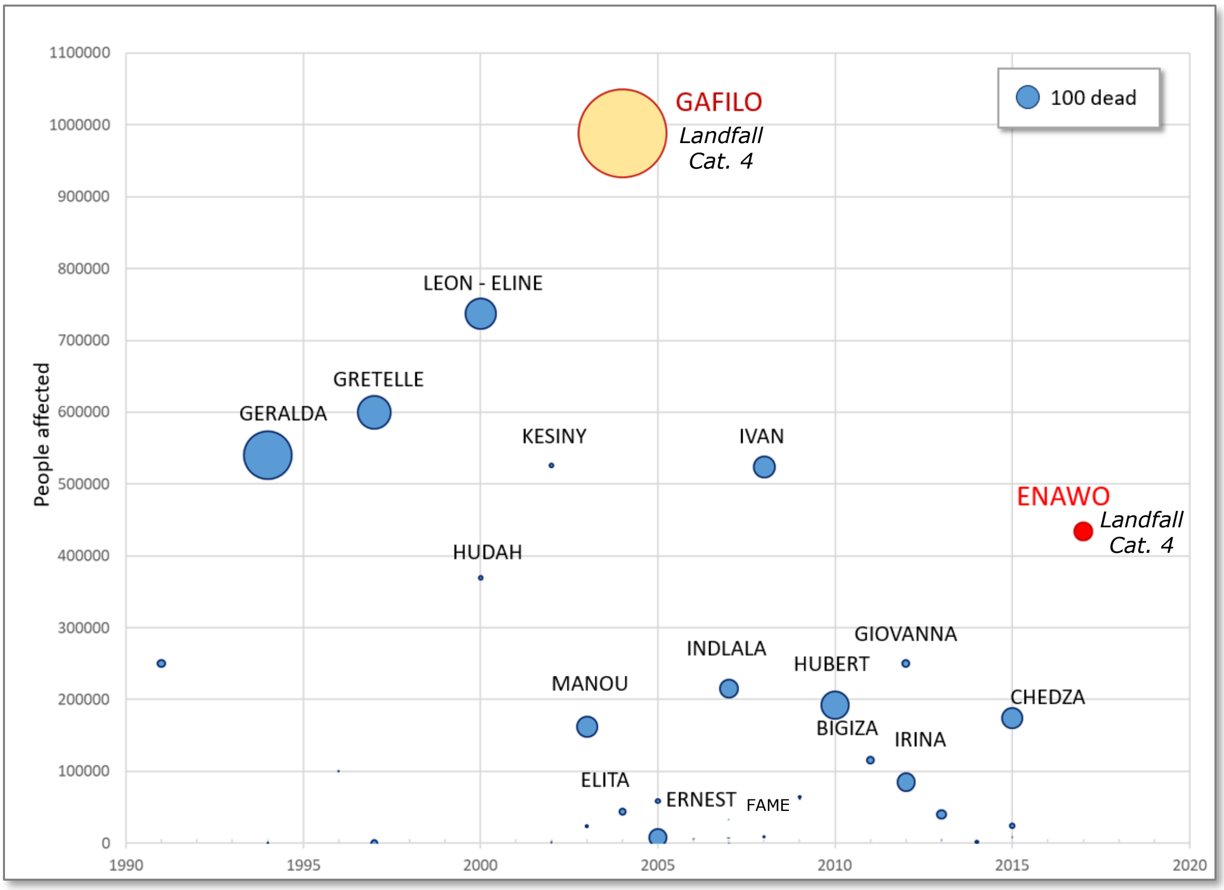


***Figure 11** - TC Impact (people affected and deaths) in Madagascar over the period 1990-2017. Data source: EMDAT – CRED*

[9] http://www.fao.org/emergencies/appeals/detail/en/c/168107/

Landfall Area

The most significant TCs since 2000 in NE Madagascar are shown in the Table below and in **Figure 12**.

NAME	YEAR	EQUIVALENT SSHS LANDFALL	POP. AFFECTED	DEAD *(CRED)*
HUDAH	2000	Cat 4	370 000	23
HARY	2002	Cat 5	-	1
GAFILO	2004	Cat 4	990 000	363
INDLALA	2007	Cat 3	215 000	80
JAYA	2007	Cat 1	-	3
IVAN	2008	Cat 4	524 000	93
JADE	2009	Cat 1	65 000	15
BINGIZA	2011	Cat 2	115 000	35
ENAWO	2017	Cat 4	434 000	81

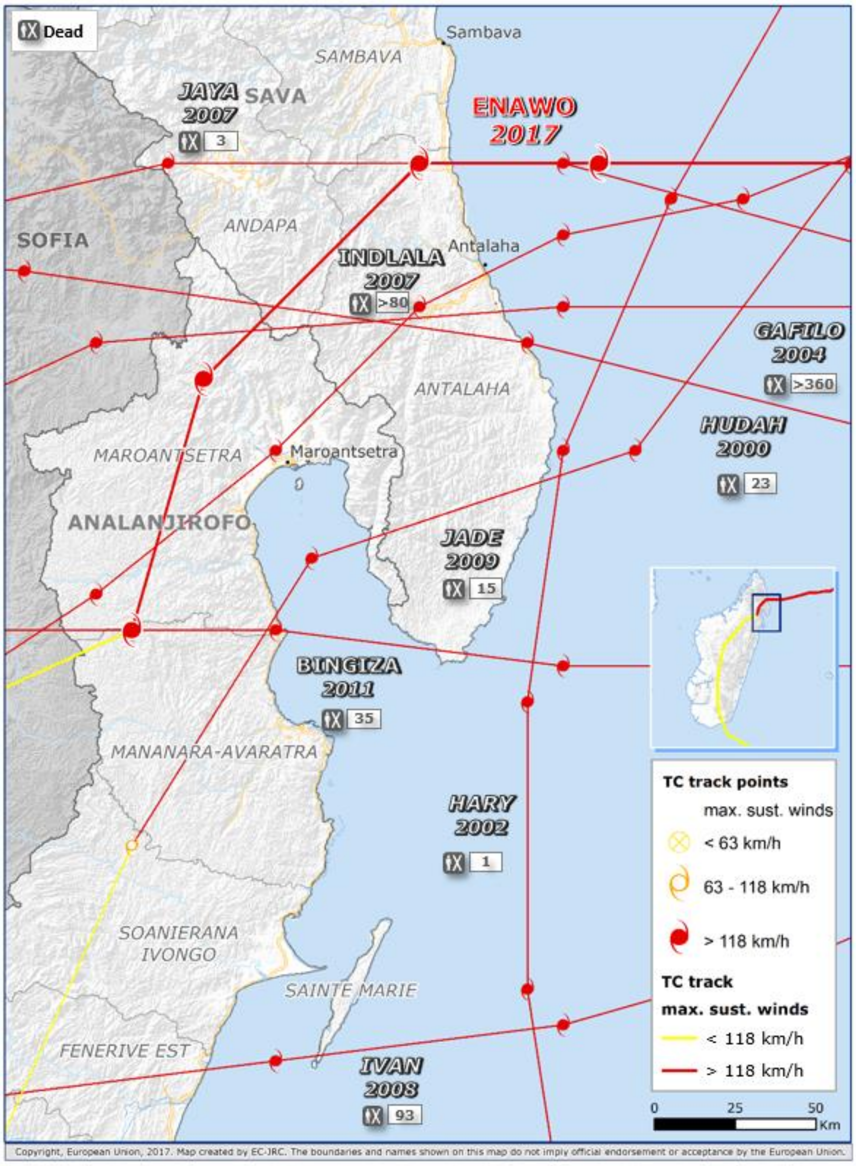


***Figure 12** – Significant TCs in the area over 2000-2017.*
(sources: GDACS, JTWC, EMDAT-CRED)

3 Pre-event: *Impact estimation*

3.1. Overview

Several data sources are available to obtain the TC information: TC bulletins, Numerical Weather Forecasts (e.g. global scale, regional scale specific for the TCs) and Satellite data, see Annex 2.

The most important sources of TC information are the TC bulletins provided by the Regional Specialized Meteorological Centres (RSMCs) and the Tropical Cyclone Warning Centres (TCWCs). These centres have the regional responsibility to forecast and monitor each area of TC formation. Every 6-12 hours the TC warning centres publish a TC bulletin, including several TC information, which vary from centre to centre.

For Madagascar, the RSMC responsible of the south-western Indian Ocean TC basin is Meteo France La Reunion (http://www.meteofrance.re/).

In addition to these centers other organizations, as the Joint Typhoon Warning Center (JTWC), provide TC information.

The JRC set up an automatic routine that includes the TC bulletins produced by the National Oceanic and Atmospheric Administration (NOAA) and JTWC into a single database, covering all TC basins (see http://portal.gdacs.org/Models). This system is currently used in GDACS.

A brief description of the data and models used by the JRC are presented in Annex 2, while more information can be found in the WMO - Global Guide to Tropical Cyclone Forecasting, 2017.

In this report only the results of following systems are presented:

Section 3.2	National Meteorological Service (NMS) of Madagascar
Section 3.3	Regional Specialized Meteorological Centre (RSMC): *Meteo France La Reunion*
Section 3.4	GDACS *(based on JTWC forecasts)*
Section 3.5	ARISTOTLE *(based on RSMC forecasts)*

Table 4 *- Systems analysed in this report.*

3.2. National Meteorological Service

The National Meteorological Service[10] of Madagascar (MMS) is:

- *"Direction Generale de la Meteorologie"*: http://www.meteomadagascar.mg/

The MMS has four different types of alerts as shown in the figure below:

GREEN ALERT	YELLOW ALERT	RED ALERT	BLUE ALERT
Alerte Verte **Signification** **5 à 2 jours avant la catastrophe** Il existe un cyclone dans les parages, mais la menace pour la localité est encore vague et imprécise **Soyez attentif** La station météorologique est en état d'alerte et les autorités locales sont informées **Actions à entreprendre** › Hisser le drapeau CYCLONE › Ecouter régulièrement et attentivement les informations concernant la météo à la radio et à la télévision › Renforcer portes et fenêtres › Avoir un stock suffisant de bougies et de piles électriques › Garder les médicaments et les papiers dans un endroit sec	**Alerte Jaune** **Signification** **48h à 24h avant l'impact** Le cyclone menace la localité mais le danger n'est pas immédiat. **Dans les prochaines heures, Soyez très vigilant** › Les autorités locales prennent toutes les dispositions qu'elles jugent utiles. › Mettez vous à l'abri, tenez-vous informés. › L'Avis de menace peut être très court ou même ne pas exister. **Actions à entreprendre** › Ecouter en permanence les informations radiophoniques et télévisées › Abandonner les maisons situées au bord de l'eau › Rejoindre un endroit sûr, si l'habitation ne l'est pas › Faire une provision suffisante pour quelques jours › Cesser toutes activités maritimes › Stocker de l'eau potable › Mettre dans un endroit sûr le bétail › Ramener les pirogues vers la terre ferme et bien les amarrer	**Alerte Rouge** **Signification** **12h avant l'impact** Le cyclone menace à brève échéance la localité et ses effets constituent un danger pour la population. **Phénomène prévu dans l'immédiat ou en cours** Restez à l'abri de votre habitation, ne circulez pas, tenez-vous informés. **Une vigilance absolue s'impose** Tenez-vous régulièrement au courant de l'évolution météorologique et conformez-vous scrupuleusement aux conseils ou consignes émis par les Autorités Locaux. **Actions à entreprendre** › Cesser toute activité › Se tenir toujours au courant des dernières informations météorologiques › Couper le courant électrique › Etre vigilent et ne pas sortir › Prendre garde au calme apparent lors du passage de l'œil du cyclone › Rester à l'intérieur d'un bâtiment sûr	**Alerte Bleue** **Signification** **Phénomène s'éloignant ou se comblant. Mais il reste des résidus de phénomènes, des dangers persistent localement** Fortes pluies, crues, mer grosse et vents violents sont encore possibles. Les secours s'activent, les services réparent. Evitez les déplacements, tenez-vous informés. **Pas de vigilance particulière** Attention, cela ne veut pas dire qu'il fait beau : un ciel couvert et faiblement pluvieux, des petites averses sont classés en alerte bleue. L'alerte bleue peut ne pas exister. **Actions à entreprendre** › Continuez à écouter les informations radio pour tous les avis et communiqués officiels › Attendez d'avoir été officiellement prévenus que les alertes sont levées avant de sortir › Ne vous approchez pas des fils tombés à terre, des bâtiments et des arbres endommagés, ni des cours d'eau en crue › Facilitez l'accès des secours › Traitez l'eau du robinet
Avis d'avertissement	*Avis de menace*	*Avis de danger imminent*	*Vigilance post aléas*

***Table 5 -** Alert types for TCs (National Meteorological Service of Madagascar)*

For TC ENAWO, the MMS placed the coastal areas from the northeast to the eastern parts of the country, including Antalaha and Maroantsetra districts, on

- 3-4 March: Green Alert
- 5-6 March: Yellow Alerts
- 7-8 March: Red Alerts

Red alerts for central and southern regions were also issued on 7 - 9 March.

The time-evolution of the alerts is shown in the next figures.

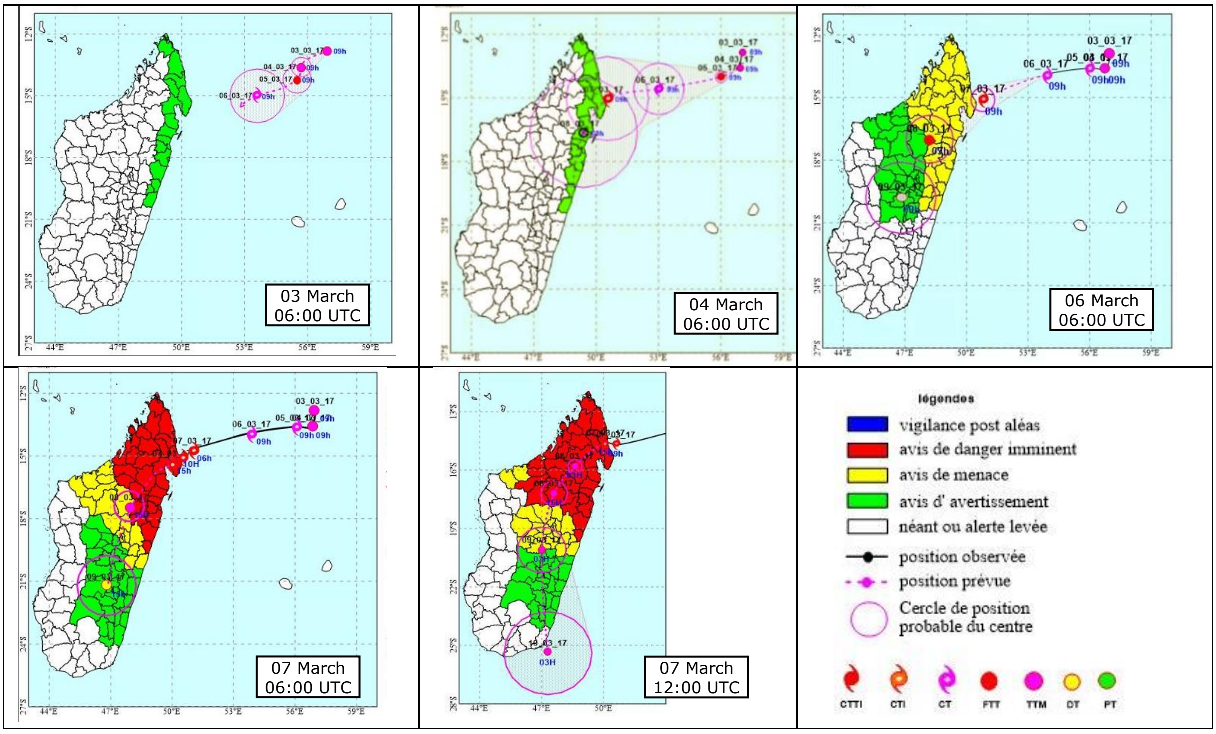


Figure 13 - Forecast TC ENAWO and Alerts (Meteo Madagascar)

[10] List of all national meteorological services is available at https://www.wmo.int/cpdb/, https://public.wmo.int/en/about-us/members or https://worldweather.wmo.int/en/members.html

3.3. Regional Specialized Meteorological Centre

The Regional Specialized Meteorological Centre (RSMC) responsible for the south-western Indian Ocean TC basin is

- Meteo France La Reunion: http://www.meteofrance.re/

For TC ENAWO, the RSMC La Reunion:

- issued the first bulletin for ENAWO on **3 March 2017 morning**
- identified the **landfall** in SAVA region the first time on **3 March evening**
- identified the **intensity** (Intense Tropical Cyclone, 10-min averaged winds[11]: 166 - 212 km/h) on **3 March evening**.

Track and Intensity

The track of the following bulletins are shown in **Figure 14**. The maximum winds (10 min average) estimated in each bulletin are shown in **Figure 15**, while the storm surge estimations in **Table 7**.

RSMC La Reunion *(TC bulletins included in Figure 14)*	
3 March 06:00 UTC	4 days before landfall
3 March 12:00 UTC	**Landfall / Intensity area identified the first time**
4 March 12:00 UTC	3 days before landfall
5 March 12:00 UTC	2 days before landfall
6 March 12:00 UTC	1 day before landfall
7 March 12:00 UTC	First bulletin after landfall
11 March 06:00 UTC	Last bulletin

Table 6 - *List of Forecasted maps included in Figure 14*

Last information on TC ENAWO is available at:

http://www.meteofrance.re/cyclone/activite-cyclonique-en-cours/dirre/ENAWO

[11] Vmax of JTWC: 1-min sustained, Meteo France La Reunion: 10 min averaged.
The conversion factors are shown in the table below (source WMO).

$Vmax_{600}=K\ Vmax_{60}$	At-Sea	Off-Sea	Off-land	In-Land
K	0.93	0.90	0.87	0.84

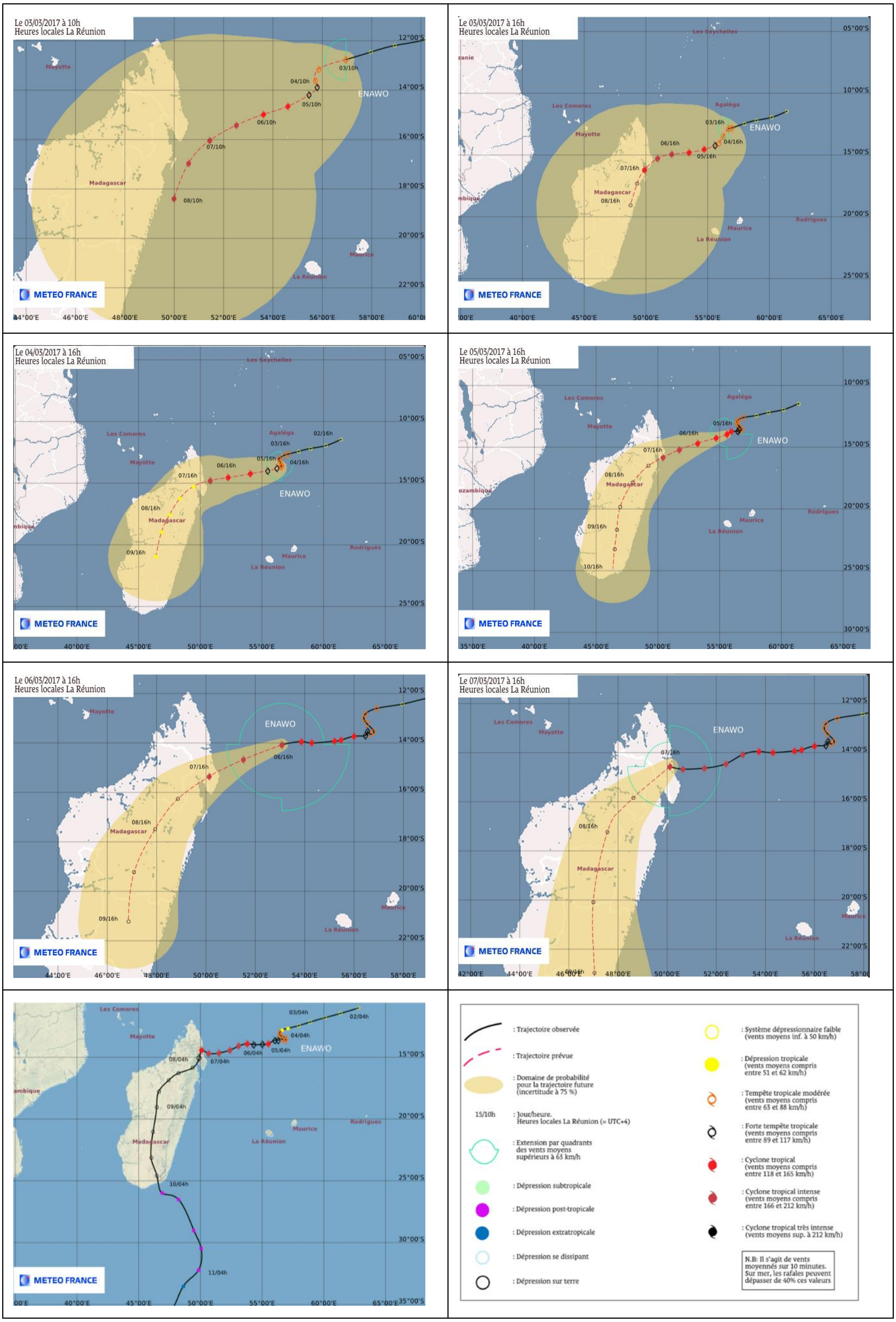


Figure 14 *- TC ENAWO track/intensity (source: RSMC La Reunion Meteo France)*

Winds

The 10-min averaged winds estimated in each bulletin are shown in the Figure below.

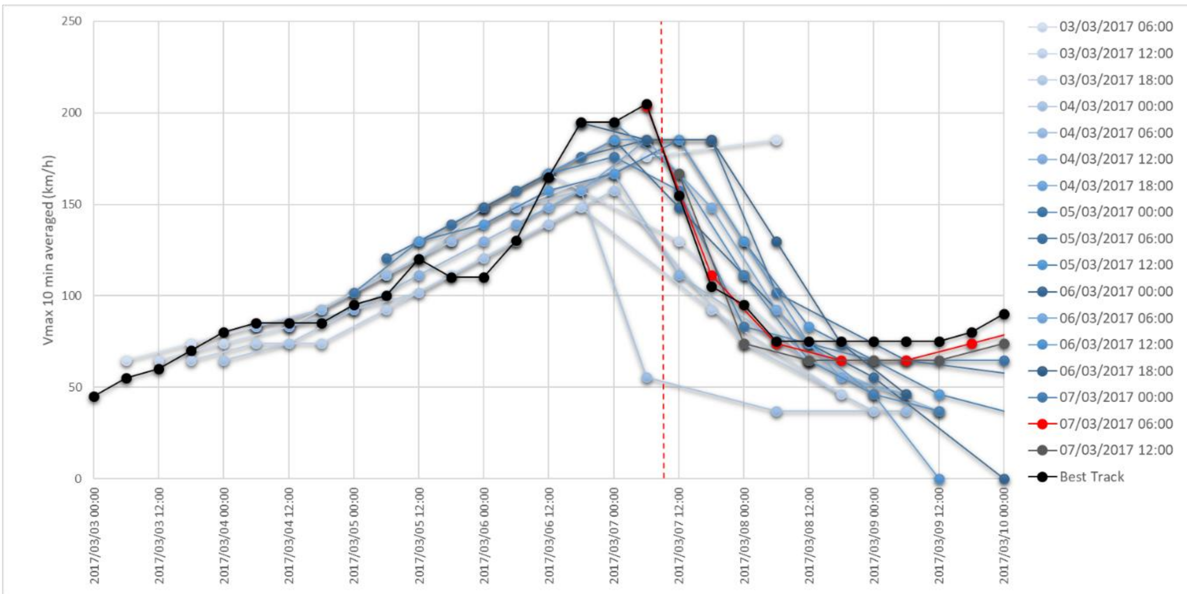


Figure 15 – *RSMC La Reunion- Meteo France Forecasts: maximum winds (10min averaged) for each TC bulletin. Red track line: last bulletin before the landfall. Grey track line: first bulletin after the landfall. Black line: Best Track Meteo France. Red dotted line: Landfall time.*

Storm Surge

RSMC La Reunion included in the bulletins the following storm surge estimations:

DATE	STORM SURGE ESTIMATIONS
6 March 06:00 UTC	**ANTONGIL BAY** IS MORE LIKELY TO UNDERGO SIGNIFICANT STORM SURGE. IT IS EXPECTED TO REACH **3-4 METERS** NEAR **MAROANTSETRA** BUT ONLY **1 METER** SOUTH OF **ANTALAHA**.
6 March 12:00 UTC	**ANTONGIL BAY** IS MORE LIKELY TO UNDERGO SIGNIFICANT STORM SURGE. IT IS EXPECTED TO REACH **3-4 METERS** NEAR **MAROANTSETRA** BUT CLOSER TO **1 METER** SOUTH OF **ANTALAHA** AND NEAR **ANTANAMBE**
6 March 18:00 UTC	**ANTONGIL BAY** IS MORE LIKELY TO UNDERGO SIGNIFICANT STORM SURGE. IT IS EXPECTED TO REACH **3-4 METERS** NEAR MAROANTSETRA BUT CLOSER TO **1 METER** SOUTH OF **ANTALAHA** AND NEAR **ANTANAMBE**.
7 March 00:00 UTC	**ANTONGIL BAY** IS MORE LIKELY TO UNDERGO SIGNIFICANT STORM SURGE. IT IS EXPECTED TO REACH **3-4 METERS** NEAR **MAROANTSETRA** BUT CLOSER TO **1 METER** SOUTH OF **ANTALAHA** AND NEAR **ANTANAMBE**.
7 March 06:00 UTC	WITH A REAL TRACK FURTHER NORTH THAN EXPECTED, THE STORM SURGE IN THE **ANTONGIL BAY** SHOULD BE LESS THAN EXPECTED. IT IS NOW EXPECTED TO REACH **1-2 METERS** NEAR **MAROANTSETRA**. AT **ANTALAHA** WITH A BATHYMETRY LESS CONDUCIVE FOR STRONG STORM SURGE EVENT, EXPECTED STORM SURGE VALUE IS WITHIN THE SAME RANGE (BEWARE THAT THIS VALUE DOES NOT TAKE INTO ACCOUNT THE TIDE AND THE WAVE SET UP).

Table 7 - *Storm surge estimations (RSMC La Reunion - Meteo France)*

3.4. GDACS

JRC is responsible for the operation of Global Disaster Alert and Coordination System (GDACS), that plays a major role in alerting the international community to humanitarian emergencies during natural disasters. The alerts of GDACS (Green, Orange, Red) are elaborated based on the severity of the event, the population involved and the vulnerability of the countries (see www.gdacs.org). GDACS also sends e-mail and SMS alerts to subscribed recipients. GDACS includes the analysis of all three TC effects (wind, rain, storm surge) for every TC occurring worldwide, using several different data sources.

The description of the GDACS alert system for the TC can be found in Annex 1, while an overview on the TC data sources used is presented in Annex 2.

3.4.1. Overview

GDACS issued the first **RED alert** (for high winds[12]) in Madagascar on **3 March** and an **Orange Alert** for the Storm Surge impact on 4 March. The region of the landfall area, SAVA Region, was identified on 4 March. The automatic GDACS report for TC ENAWO can be found at: http://www.gdacs.org/report.aspx?name=ENAWO-17.

The analysis of the GDACS alerts for winds and storm surge are presented in Section 3.4.2 and the following bulletins are analysed more in detail.

GDACS *(Bulletin Nr.)*	Date
3	4 Mar 06:00 UTC (Three days before the landfall)
5	5 Mar 06:00 UTC (Two days before the landfall)
7	6 Mar 06:00 UTC (One day before the landfall)
9	7 Mar 06:00 UTC (Few hours before the landfall)
10	7 Mar 18:00 UTC (First advisory available after the landfall)

Table 8 - *TC bulletins analysed in detail in the next Sections.*

TC Data source: For the TCs developed in the TC basin of SW Indian Ocean, like TC ENAWO, GDACS uses the forecast of the JTWC. The forecasted track of all the JTWC advisories are shown in Figure 4, while the track of the Regional Specialized Meteorological Centre (RSMC) Meteo France La Reunion is in Section 3.1. JTWC issued a Tropical Cyclone Formation Alert on 2 March and the first TC Warning NR 1 on 3 March at 09:00 UTC for TROPICAL CYCLONE 09S (NINE).

[12] OVERALL GDACS alert: it is based only on the Wind impact and not also on the rainfall and storm surge effects.

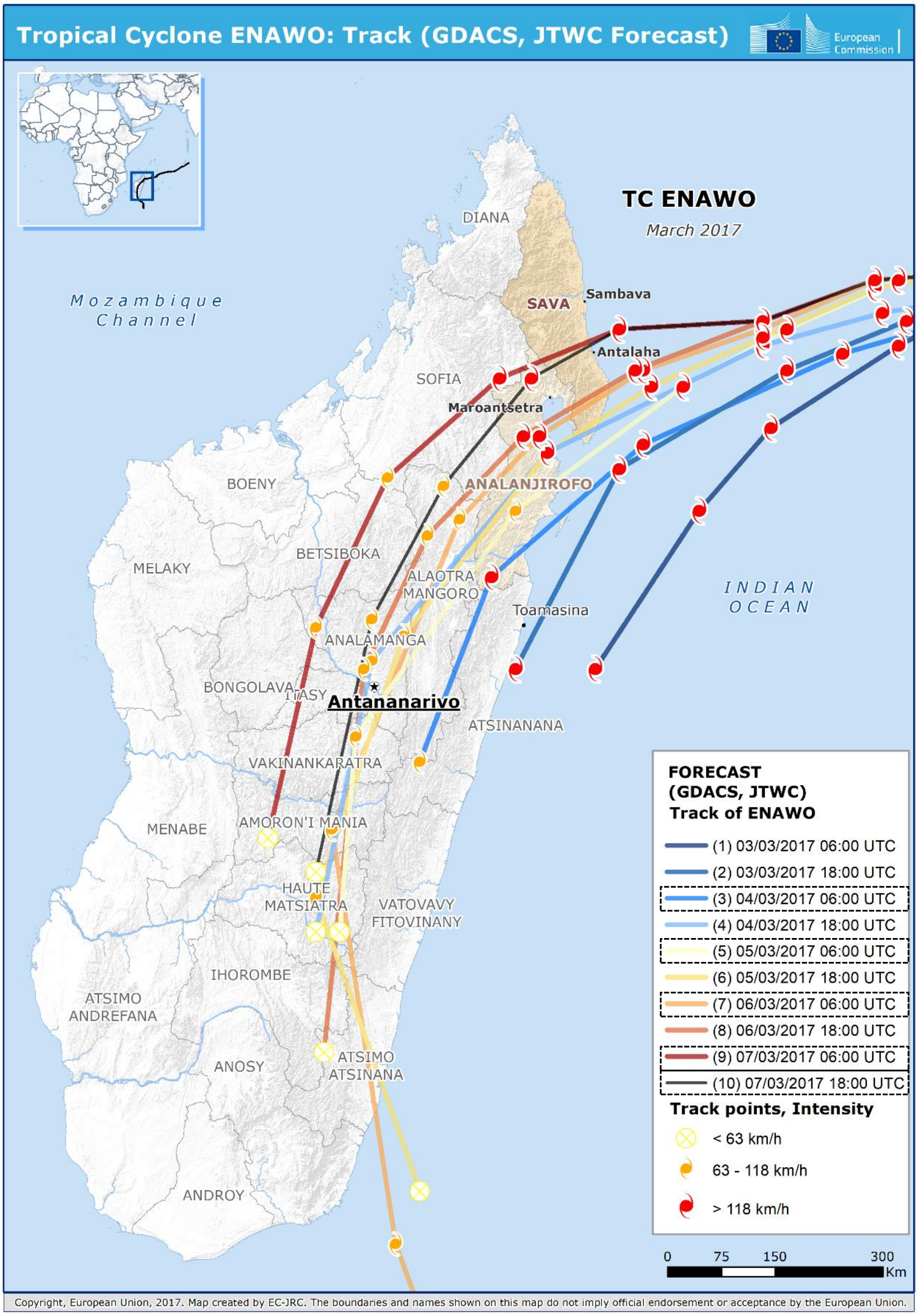


Figure 16 - *GDACS Track of TC ENAWO (Forecast JTWC)*

3.4.2. Wind Alert (Overall Alert)

GDACS has issued the first **RED alert** (for High winds) in Madagascar on 3 March at 18:00 UTC and it has maintained this alert level until the landfall, except for the bulletin 7 issued on 6 Mar at 06:00 UTC, when the alert level was reduced to Orange due to a lower forecasted intensity. All the alerts issued by GDACS for this event are shown in **Table 9**.

As can be seen the alert level and population varied from bulletin to bulletin, this is due to the fact that the alert level strongly depends from the forecasted track and intensity.

The landfall area in Sava Region was identified the first time on 4 March at 18:00 UTC, while the forecast of the maximum sustained winds varied from 157 to 231 km/h.

Bulletin Number	GDACS Alert level	Bulletin Date (UTC)	Max Category forecasted (equivalent to SSHS)	Maximum sustained winds forecasted (km/h)		Number of people affected by winds > 118 km/h
				MAX	Last forecasted point before landfall	
1		03/03/2017 06:00	Category 4	231	231	0
2		03/03/2017 18:00	Category 4	222	222	2.6 million
3	(13)	04/03/2017 06:00	Category 2	157	157	1.7 million
4		04/03/2017 18:00	Category 3	204	204	5.7 million
5		05/03/2017 06:00	Category 3	185	185	240 000
6		05/03/2017 18:00	Category 3	204	204	1.2 million
7		06/03/2017 06:00	Category 2	167	167	480 000
8		06/03/2017 18:00	Category 4	231	231	1.2 million
9		07/03/2017 06:00	Category 4	231	231	2 million
10		07/03/2017 18:00	Category 2	167	-	1.7 million

Table 9 *- GDACS alerts event time line*
The alert level colour is related to population affected by high winds (> 118 km/h), vulnerability and intensity. In yellow: last bulletin before landfall, in blue: first bulletin after landfall.

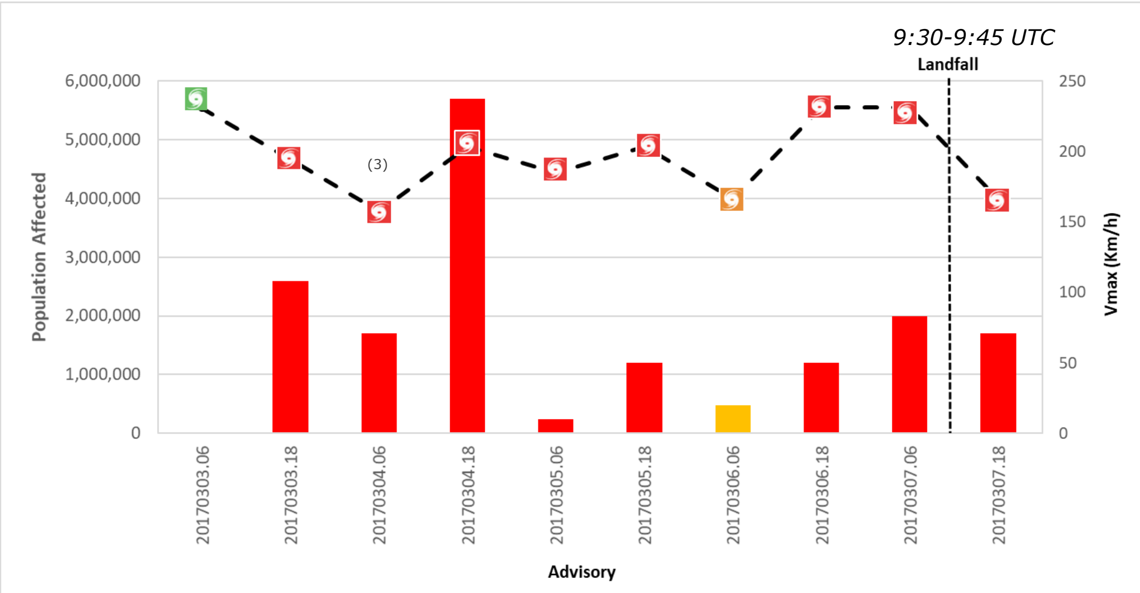


Figure 17 – *Variation of the GDACS alert levels for TC ENAWO for each TC bulletin. The bars represent the population affected, the line represents the variations of the Vmax for the last forecasted point before the landfall for each TC bulletin.*

[13] This GDACS alert was issued on 4 March using LandScan™ 2013 for the population. This alert has been recently revised using a new version of LandScan ™ and now it is a GDACS orange alert (see Technical Annex).

Three days BEFORE the landfall (4 March, 06:00 UTC)

The GDACS alert level for winds using the data of the advisory 3 was **RED**[14]**.**

As shown in the figure below, according to this data the maximum sustained winds forecasted was 204 km/h.

According to this forecast, there were nearly 2 million people possibly affected by winds of more than 120 km/h (i.e. Hurricane -force winds). The GDACS impact estimation of this advisory and the Event time line are shown below.

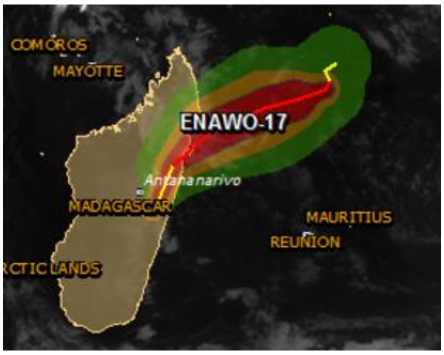


Figure 18 - *GDACS track and wind-buffers for Adv. 3. (green: 64-92 km/h, orange: 93-118 km/h, red: > 118 km/h)*

Event time line

The storm evolution is shown in the table below. Alert levels and population estimates are related to the area from a point to the next.

Advisory	Alert color	Date (UTC)	Category	Wind speed	Wind gusts	Population affected by cyclone winds (>120km/h)	Location (lat, lon)
1	green	03 Mar 2017 06:00	Tropical storm	**65 km/h** (40 mph)	km/h (mph)	no people	-12.7, 56.8
2	green	03 Mar 2017 18:00	Tropical storm	**83 km/h** (52 mph)	km/h (mph)	no people	-13.1, 56.3
3	green	04 Mar 2017 06:00	Tropical storm	**102 km/h** (63 mph)	km/h (mph)	no people	-13.6, 56.5
3	green	04 Mar 2017 18:00	Category 1	**120 km/h** (75 mph)	km/h (mph)	no people	-14, 56.3
3	green	05 Mar 2017 06:00	Category 1	**139 km/h** (86 mph)	km/h (mph)	no people	-14.2, 55.7
3	green	05 Mar 2017 18:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	no people	-14.5, 54.8
3	orange	06 Mar 2017 06:00	Category 3	**204 km/h** (126 mph)	km/h (mph)	43000 people	-14.9, 53.4
3	red	07 Mar 2017 06:00	Category 2	**157 km/h** (98 mph)	km/h (mph)	1 million people	-16, 50.9
3	red	08 Mar 2017 06:00	Category 1	**120 km/h** (75 mph)	km/h (mph)	1 million people	-17.6, 49
3	green	09 Mar 2017 06:00	Tropical storm	**74 km/h** (46 mph)	km/h (mph)	no people	-19.8, 48.1

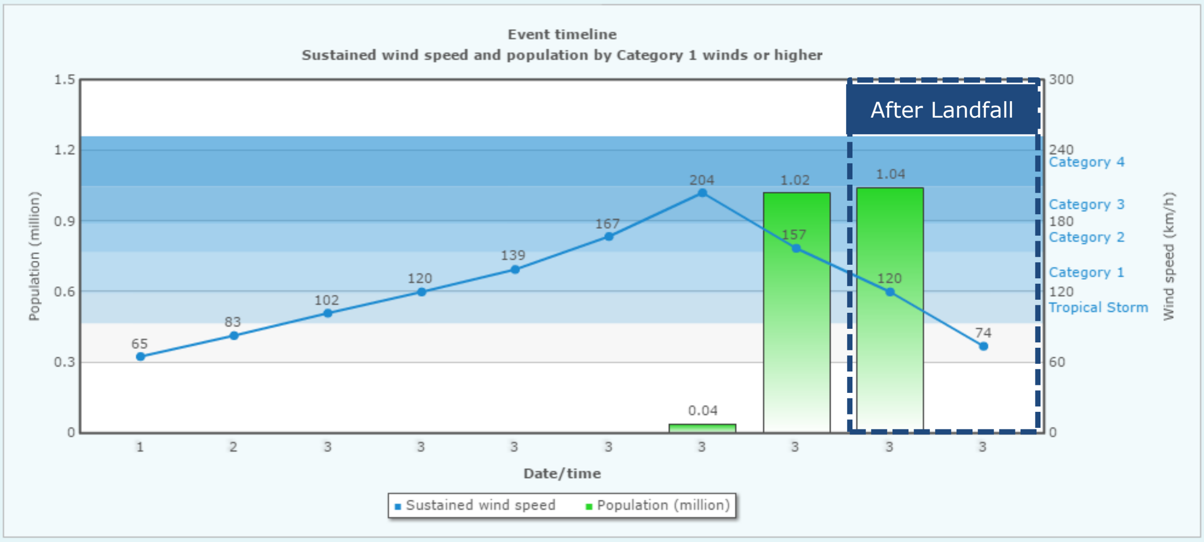


Figure 19 - *GDACS Alert for TC ENAWO - Event Time Line, according to the data of the Advisory 3, as of 4 March 06:00 UTC (three days before the landfall).*

Note: The wind speed corresponds to the maximum sustained winds at the time indicated in the column "Date", while the Category is based on the SSHS.

[14] See Footnote 13 on page 8.

Two days BEFORE the landfall (5 March, 06:00 UTC)

The GDACS alert level for winds using the data of the advisory 5 was **RED**.

As shown in the figure below, according to this data the maximum sustained winds forecasted was 204 km/h.

According to this forecast, there were 240 000 people possibly affected by winds of more than 120 km/h (i.e. Hurricane -force winds). The GDACS impact estimation of this advisory and the Event time line are shown below.

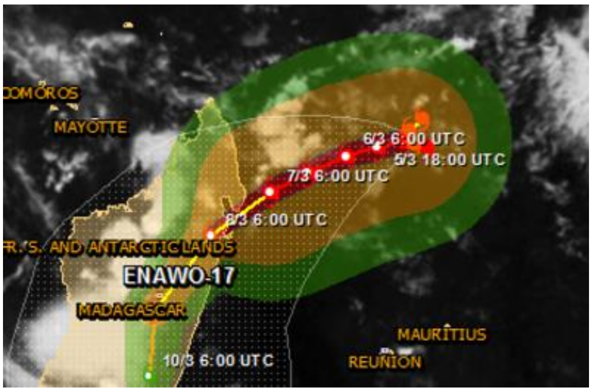


Figure 20 - *As in* ***Figure 18****, but for Adv. 5*

Event time line

The storm evolution is shown in the table below. Alert levels and population estimates are related to the area from a point to the next.

Advisory	Alert color	Date (UTC)	Category	Wind speed	Wind gusts	Population affected by cyclone winds (>120km/h)	Location (lat, lon)
1	green	03 Mar 2017 06:00	Tropical storm	**65 km/h** (40 mph)	km/h (mph)	no people	-12.7, 56.8
2	green	03 Mar 2017 18:00	Tropical storm	**83 km/h** (52 mph)	km/h (mph)	no people	-13.1, 56.3
3	green	04 Mar 2017 06:00	Tropical storm	**102 km/h** (63 mph)	km/h (mph)	no people	-13.6, 56.5
4	green	04 Mar 2017 18:00	Category 1	**120 km/h** (75 mph)	km/h (mph)	no people	-13.7, 56.9
5	green	05 Mar 2017 06:00	Category 1	**139 km/h** (86 mph)	km/h (mph)	no people	-13.5, 56.1
5	green	05 Mar 2017 18:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	no people	-13.7, 55.2
5	green	06 Mar 2017 06:00	Category 3	**185 km/h** (115 mph)	km/h (mph)	no people	-14, 54.1
5	green	06 Mar 2017 18:00	Category 3	**204 km/h** (126 mph)	km/h (mph)	no people	-14.6, 52.7
5	red	07 Mar 2017 06:00	Category 3	**185 km/h** (115 mph)	km/h (mph)	240000 people	-15.3, 51.4
5	orange	08 Mar 2017 06:00	Tropical storm	**111 km/h** (69 mph)	km/h (mph)	no people	-16.8, 49.3
5	green	09 Mar 2017 06:00	Tropical storm	**74 km/h** (46 mph)	km/h (mph)	no people	-19.5, 47.3
5	green	10 Mar 2017 06:00	Tropical depression	**56 km/h** (34 mph)	km/h (mph)	no people	-21.8, 47.1

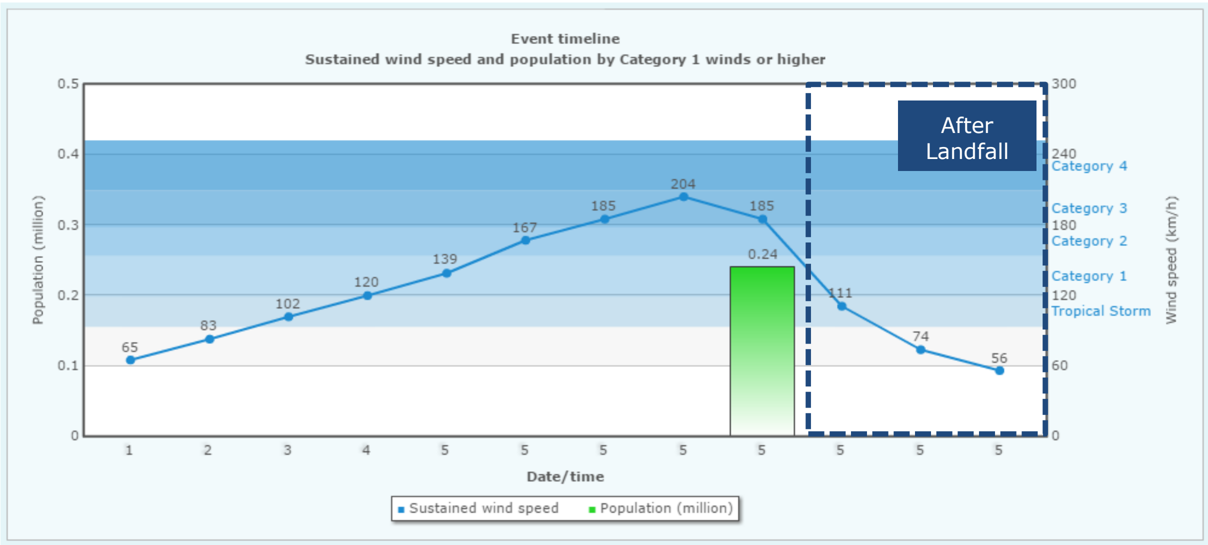


Figure 21 - *As in* ***Figure 19****, but for the Adv. 5 of 5 Mar, 06:00 UTC (two days before the landfall)*

One day BEFORE the landfall (6 March, 06:00 UTC)

The GDACS alert level for winds using the data of the advisory 7 was reduced from RED to **ORANGE** due to a lower intensity.

As shown in the figure below, according to this data the maximum sustained winds forecasted was lower compared to the previous forecast, with a maximum of 185 km/h.

According to this forecast, there were nearly 500 000 people possibly affected by winds of more than 120 km/h (i.e. Hurricane -force winds), see **Table 9**. The GDACS impact estimation of this advisory and the Event time line are shown below.

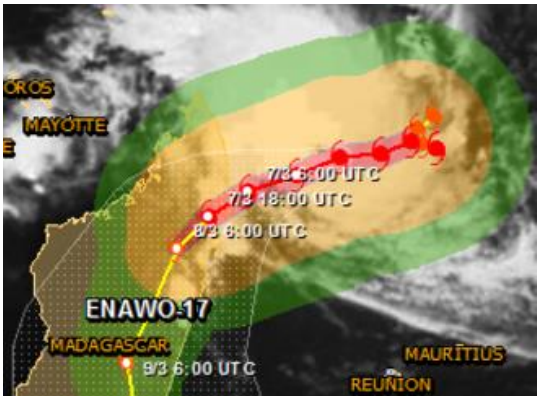


***Figure 22 -** As in **Figure 18**, but for Adv. 7*

Event time line

The storm evolution is shown in the table below. Alert levels and population estimates are related to the area from a point to the next.

Advisory	Alert color	Date (UTC)	Category	Wind speed	Wind gusts	Population affected by cyclone winds (>120km/h)	Location (lat, lon)
1		03 Mar 2017 06:00	Tropical storm	**65 km/h** (40 mph)	km/h (mph)	no people	-12.7, 56.8
2		03 Mar 2017 18:00	Tropical storm	**83 km/h** (52 mph)	km/h (mph)	no people	-13.1, 56.3
3		04 Mar 2017 06:00	Tropical storm	**102 km/h** (63 mph)	km/h (mph)	no people	-13.6, 56.5
4		04 Mar 2017 18:00	Category 1	**120 km/h** (75 mph)	km/h (mph)	no people	-13.7, 56.9
5		05 Mar 2017 06:00	Category 1	**139 km/h** (86 mph)	km/h (mph)	no people	-13.5, 56.1
6		05 Mar 2017 18:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	no people	-13.9, 55.1
7		06 Mar 2017 06:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	no people	-14, 53.8
7		06 Mar 2017 18:00	Category 3	**185 km/h** (115 mph)	km/h (mph)	no people	-14.6, 52.4
7		07 Mar 2017 06:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	320000 people	-15.1, 50.9
7		07 Mar 2017 18:00	Category 1	**130 km/h** (80 mph)	km/h (mph)	300000 people	-15.9, 49.6
7		08 Mar 2017 06:00	Tropical storm	**83 km/h** (52 mph)	km/h (mph)	no people	-16.9, 48.6
7		09 Mar 2017 06:00	Tropical storm	**65 km/h** (40 mph)	km/h (mph)	no people	-20.6, 47
7		10 Mar 2017 06:00	Tropical storm	**83 km/h** (52 mph)	km/h (mph)	no people	-25.4, 47.8
7		11 Mar 2017 06:00	Tropical storm	**65 km/h** (40 mph)	km/h (mph)	no people	-31, 50.1

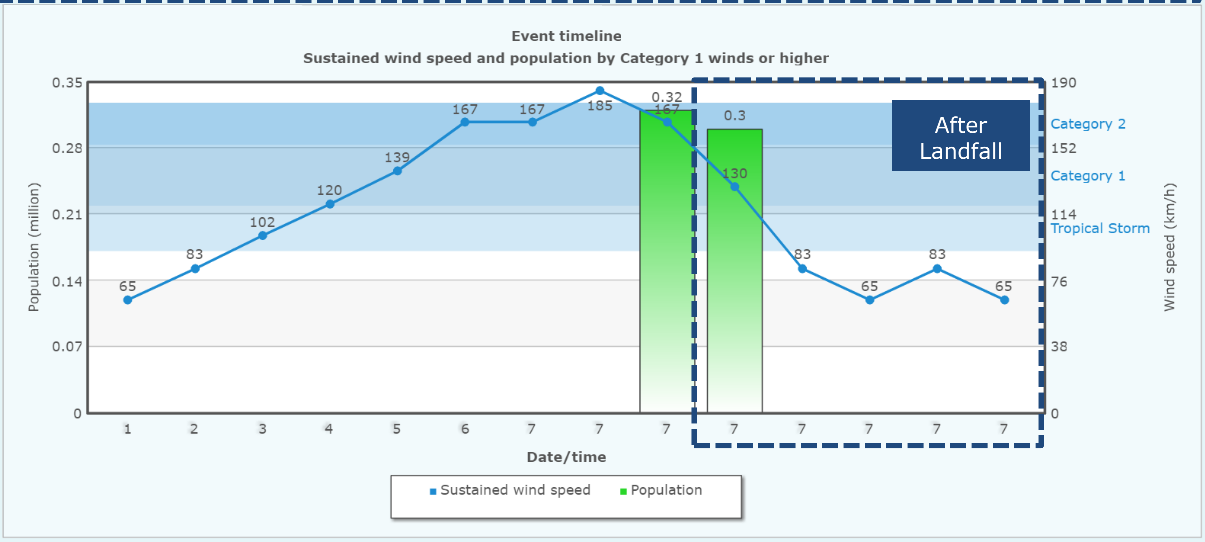


***Figure 23 -** As in **Figure 19**, but for the Adv. 7 of 6 Mar, 06:00 UTC (one day before the landfall)*

Last advisory BEFORE the landfall (7 March, 06:00 UTC)

The GDACS alert level for winds at the time of this advisory was RED, with in total over 2 million people possibly affected by winds higher than 120 km/h.

The maximum sustained winds forecasted for this advisory was 230 km/h (equivalent to a Category 4 in the SSHS) for the position just before the landfall.

The GDACS impact estimation and the Event time line for this advisory are shown in the figure below.

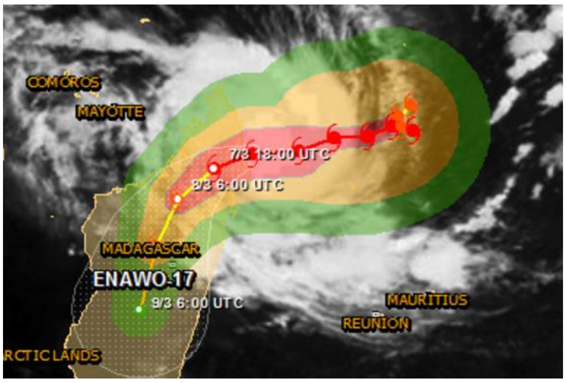


***Figure 24** - As in **Figure 18**, but for Adv. 9*

Event time line

The storm evolution is shown in the table below. Alert levels and population estimates are related to the area from a point to the next.

Advisory	Alert color	Date (UTC)	Category	Wind speed	Wind gusts	Population affected by cyclone winds (>120km/h)	Location (lat, lon)
1		03 Mar 2017 06:00	Tropical storm	**65 km/h** (40 mph)	km/h (mph)	no people	-12.7, 56.8
2		03 Mar 2017 18:00	Tropical storm	**83 km/h** (52 mph)	km/h (mph)	no people	-13.1, 56.3
3		04 Mar 2017 06:00	Tropical storm	**102 km/h** (63 mph)	km/h (mph)	no people	-13.6, 56.5
4		04 Mar 2017 18:00	Category 1	**120 km/h** (75 mph)	km/h (mph)	no people	-13.7, 56.9
5		05 Mar 2017 06:00	Category 1	**139 km/h** (86 mph)	km/h (mph)	no people	-13.5, 56.1
6		05 Mar 2017 18:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	no people	-13.9, 55.1
7		06 Mar 2017 06:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	no people	-14, 53.8
8		06 Mar 2017 18:00	Category 4	**231 km/h** (143 mph)	km/h (mph)	320000 people	-14.5, 52.4
9		07 Mar 2017 06:00	Category 4	**231 km/h** (143 mph)	km/h (mph)	1.5 million people	-14.6, 50.6
9		07 Mar 2017 18:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	1.3 million people	-15.2, 49.1
9		08 Mar 2017 06:00	Tropical storm	**111 km/h** (69 mph)	km/h (mph)	no people	-16.4, 47.7
9		08 Mar 2017 18:00	Tropical storm	**74 km/h** (46 mph)	km/h (mph)	no people	-18.2, 46.8
9		09 Mar 2017 06:00	Tropical depression	**56 km/h** (34 mph)	km/h (mph)	no people	-20.7, 46.2

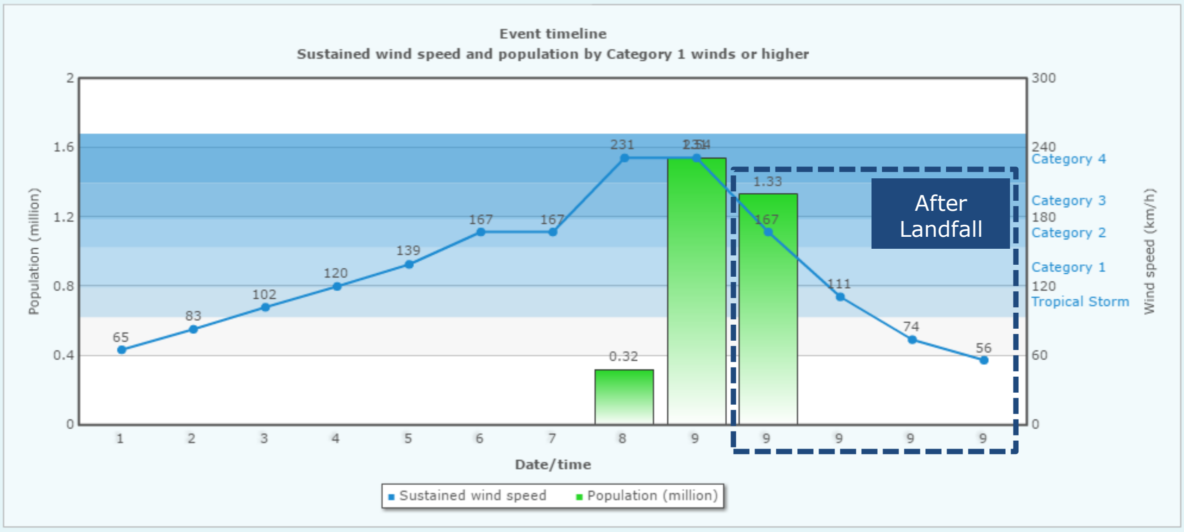


***Figure 25 –** As in **Figure 19**, but for the Adv. 9 of 7 Mar, 06:00 UTC (few hours before the landfall)*

First bulletin AFTER the landfall (7 March, 18:00 UTC)

The GDACS alert level for winds for this advisory was RED, with in total 1.7 million people (see **Table 9**) possibly affected by winds more than 120 km/h.

The maximum sustained winds forecasted for this advisory was 167 km/h (equivalent to a Category 2 in the SSHS) for the first position after the landfall.

The GDACS impact estimation and the Event time line for this advisory are shown in the figure below.

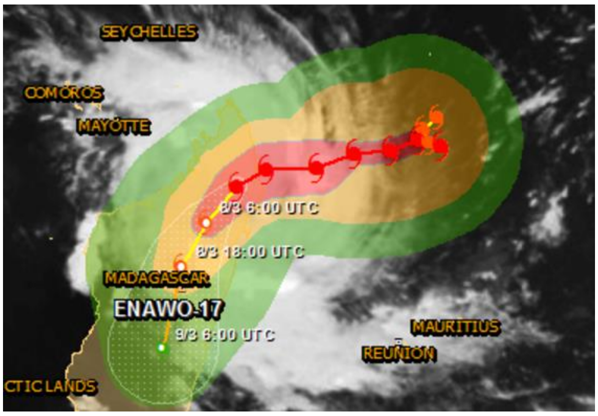


Figure 26 *- As in* ***Figure 18****, but for Adv. 10*

Event time line

The storm evolution is shown in the table below. Alert levels and population estimates are related to the area from a point to the next.

Advisory	Alert color	Date (UTC)	Category	Wind speed	Wind gusts	Population affected by cyclone winds (>120km/h)	Location (lat, lon)
1		03 Mar 2017 06:00	Tropical storm	**65 km/h** (40 mph)	km/h (mph)	no people	-12.7, 56.8
2		03 Mar 2017 18:00	Tropical storm	**83 km/h** (52 mph)	km/h (mph)	no people	-13.1, 56.3
3		04 Mar 2017 06:00	Tropical storm	**102 km/h** (63 mph)	km/h (mph)	no people	-13.6, 56.5
4		04 Mar 2017 18:00	Category 1	**120 km/h** (75 mph)	km/h (mph)	no people	-13.7, 56.9
5		05 Mar 2017 06:00	Category 1	**139 km/h** (86 mph)	km/h (mph)	no people	-13.5, 56.1
6		05 Mar 2017 18:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	no people	-13.9, 55.1
7		06 Mar 2017 06:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	no people	-14, 53.8
8		06 Mar 2017 18:00	Category 4	**231 km/h** (143 mph)	km/h (mph)	320000 people	-14.5, 52.4
9		07 Mar 2017 06:00	Category 4	**231 km/h** (143 mph)	km/h (mph)	1.5 million people	-14.6, 50.6
10		07 Mar 2017 18:00	Category 2	**167 km/h** (103 mph)	km/h (mph)	1.2 million people	-15.2, 49.5
10		08 Mar 2017 06:00	Tropical storm	**111 km/h** (69 mph)	km/h (mph)	no people	-16.5, 48.4
10		08 Mar 2017 18:00	Tropical storm	**74 km/h** (46 mph)	km/h (mph)	no people	-18.1, 47.5
10		09 Mar 2017 06:00	Tropical depression	**46 km/h** (29 mph)	km/h (mph)	no people	-21.1, 46.8

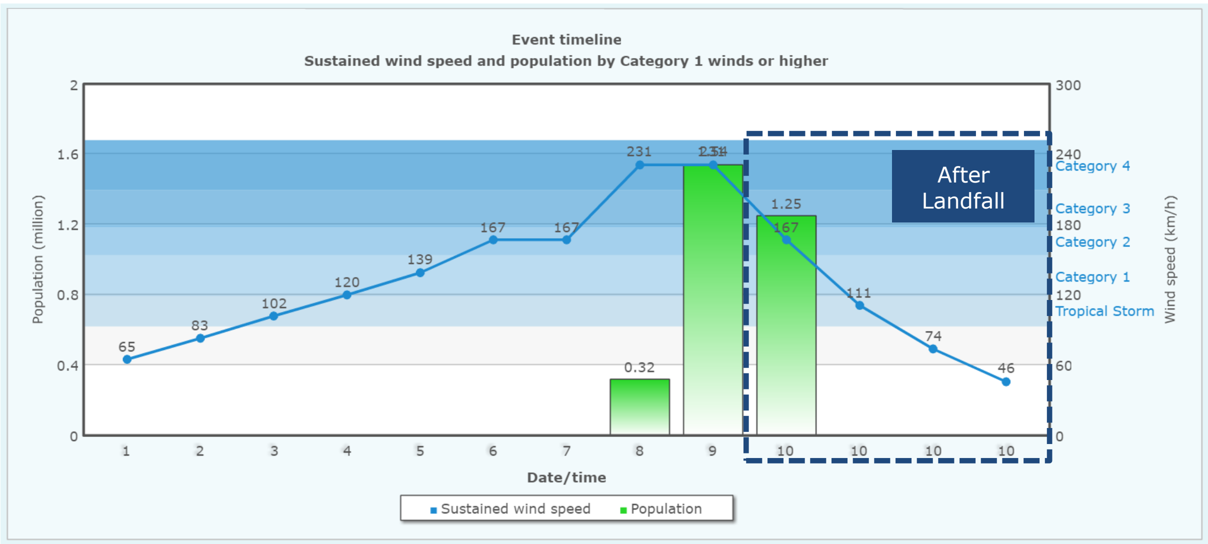


Figure 27 *- As in* ***Figure 19****, but for the Adv. 10 of 7 Mar, 18:00 UTC (after landfall)*

3.4.3. Storm surge Alert

The maximum storm surge calculated by the JRC calculations using the TC bulletins as input in the JRC HyFlux2 are shown in the figure below. As can be seen in this figure the maximum storm surge forecasted was between 0.5 and 1.4 m, and the alert level for this event varied from green to orange. It should be noted that the maximum storm surge calculated could vary significantly if the forecasted track and/or intensity change.

According to the JRC calculations, the area potentially most affected was the area along the northern coast of Helograno Antongila Bay, near **Maroantsetra**.

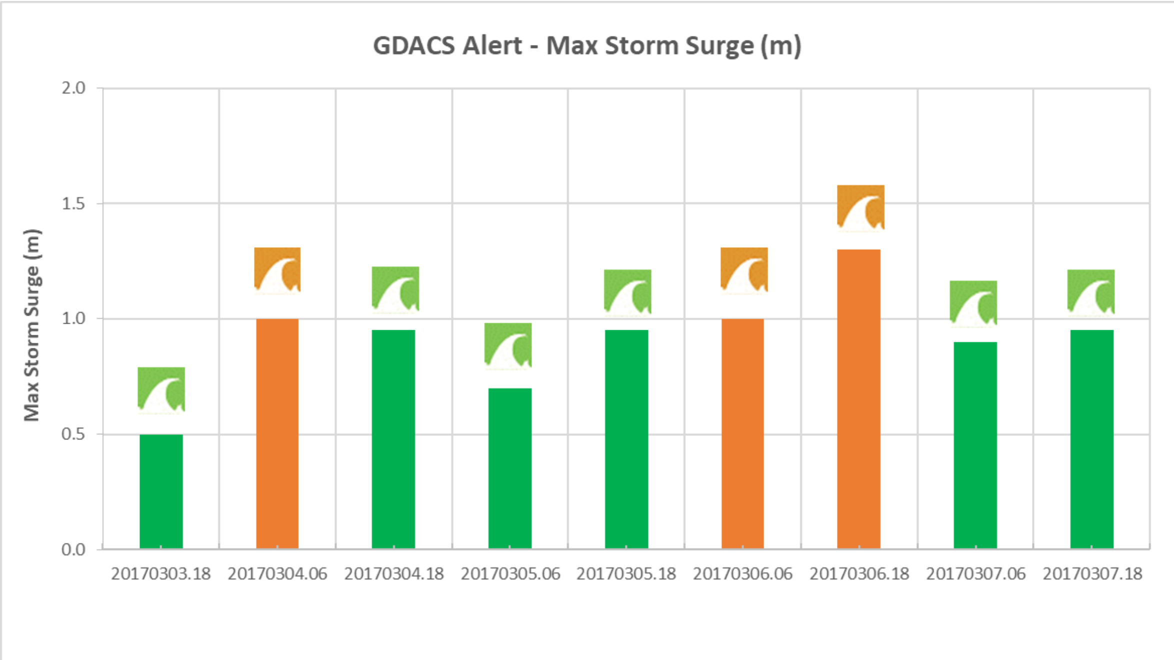


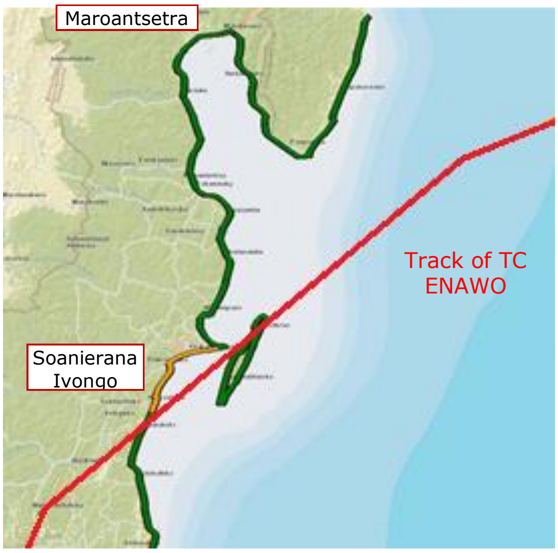
Figure 28 *– Maximum storm surge calculated for each TC bulletin.*

Note: JRC storm surge calculations don't include wave, tide and river effects. In the area of a delta river, bays, the storm surge may be higher. The torrential rains that may affect the mountains areas during the passage of a Tropical Cyclone may increase the river flow and its outflow could be blocked by the incoming storm surge. This could create floods in the surrounding areas of the cities close to a delta river.

Three days BEFORE the landfall (4 March, 06:00 UTC)

JRC calculations, using as input the data of the Advisory 3 of 4 March 06:00 UTC (three days before the landfall) estimated a possible maximum storm surge of:

- **1 m** near Soanierana Ivongo **(Analanjirofo region)**, on 7 March at 20:00 UTC.



Affected locations

Locations affected by Storm surge (15 of 76)
Calculation based on advisory number 3 of 04 Mar 2017 06:00:00.
(Simulation using 2 minute resolution)

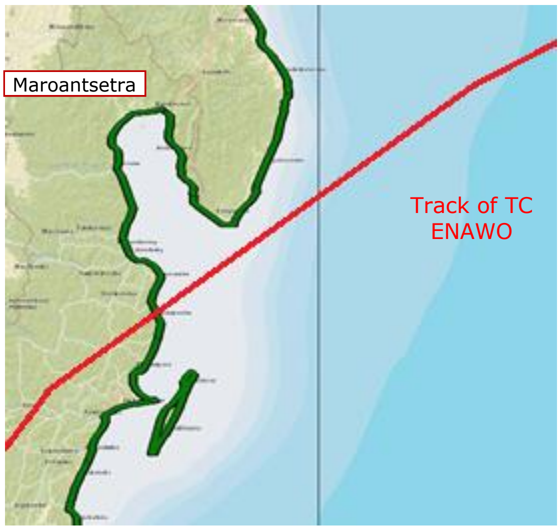
Date	Name	Country	Storm surge height (m)
07 Mar 2017 20:00:00	Soanierana Ivongo	Madagascar	1.0m
07 Mar 2017 20:00:00	Andrangazaha	Madagascar	1.0m
07 Mar 2017 19:00:00	Fandrarazana	Madagascar	0.9m
07 Mar 2017 22:00:00	Analanampotsy	Madagascar	0.9m
07 Mar 2017 22:00:00	Ampasimbe	Madagascar	0.9m
07 Mar 2017 22:00:00	Ampasina	Madagascar	0.9m
07 Mar 2017 22:00:00	Antakobola	Madagascar	0.9m
07 Mar 2017 23:00:00	Mahavanona	Madagascar	0.8m
07 Mar 2017 21:00:00	Manakalana	Madagascar	0.8m
07 Mar 2017 23:00:00	Fenerive	Madagascar	0.8m
08 Mar 2017 00:00:00	Antsikafoka	Madagascar	0.7m
07 Mar 2017 21:00:00	Ambodifototra	Madagascar	0.7m
07 Mar 2017 21:00:00	Lonkintsy	Madagascar	0.7m
07 Mar 2017 21:00:00	Lokintsy	Madagascar	0.7m

Figure 29 - *JRC storm surge calculations, as of 4 March, 06:00 UTC.*
LEFT: storm surge along the coasts (green<1m, orange≥1m)
RIGHT: locations potentially affected.

Two days BEFORE the landfall (5 March, 06:00 UTC)

JRC calculations, using as input the data of the Advisory 5 of 5 March 06:00 UTC (two days before the landfall) estimated a possible maximum storm surge of:

- **0.7 m** along the northern and eastern coasts of Helograno Antongila Bay, near **Maroantsetra (Analanjirofo region)** on 7 March at 16:00 UTC, while near Fampotabe (Sava region) on 7 March at 19:00 UTC.



Affected locations

Locations affected by Storm surge (15 of 112)
Calculation based on advisory number 5 of 05 Mar 2017 06:00:00.
(Simulation using 0.5 minute resolution)

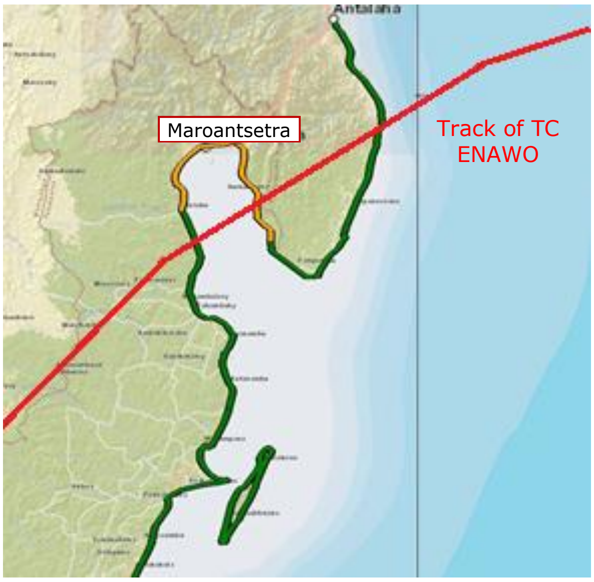
Date	Name	Country	Storm surge height (m)
07 Mar 2017 19:00:00	Fampotabe	Madagascar	0.7m
07 Mar 2017 16:00:00	Mahalevona	Madagascar	0.7m
07 Mar 2017 16:00:00	Maroantsetra	Madagascar	0.7m
07 Mar 2017 16:00:00	Andranofotsy	Madagascar	0.7m
07 Mar 2017 18:00:00	Ambatoharana	Madagascar	0.7m
07 Mar 2017 17:00:00	Ambanizana	Madagascar	0.7m
07 Mar 2017 17:00:00	Benjana	Madagascar	0.7m
08 Mar 2017 00:00:00	Manompana	Madagascar	0.7m
07 Mar 2017 19:00:00	Rantranavona	Madagascar	0.6m
07 Mar 2017 23:00:00	Antanambe	Madagascar	0.6m
07 Mar 2017 18:00:00	Tampolo	Madagascar	0.6m
07 Mar 2017 18:00:00	Antalavia	Madagascar	0.6m
07 Mar 2017 15:00:00	Anantoraka	Madagascar	0.6m
08 Mar 2017 02:00:00	Soanierana Ivongo	Madagascar	0.6m

Figure 30 *- As in **Figure 29**, but as of 5 March, 06:00 UTC*

One day BEFORE the landfall (6 March, 06:00 UTC)

JRC calculations, using as input the data of the Advisory 7 of 6 March 06:00 UTC (one day before the landfall) estimated a possible maximum storm surge of:

- **1 m** along the northern coast of Helograno Antongila Bay, near **Maroantsetra (Analanjirofo region)**, on 7 March at 13:00 UTC.



Affected locations

Locations affected by Storm surge (15 of 153)
Calculation based on advisory number 7 of 06 Mar 2017 06:00:00.
(Simulation using 0.5 minute resolution)

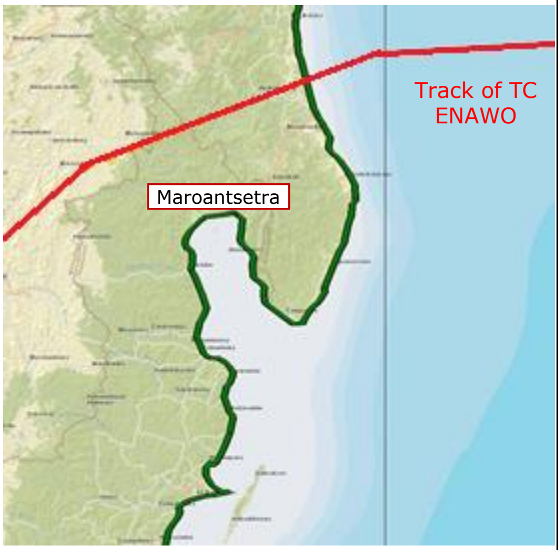
Date	Name	Country	Storm surge height (m)
07 Mar 2017 13:00:00	Mahalevona	Madagascar	1.0m
07 Mar 2017 14:00:00	Maroantsetra	Madagascar	1.0m
07 Mar 2017 14:00:00	Andranofotsy	Madagascar	1.0m
07 Mar 2017 14:00:00	Ambanizana	Madagascar	1.0m
07 Mar 2017 14:00:00	Benjana	Madagascar	1.0m
07 Mar 2017 14:00:00	Anantoraka	Madagascar	0.9m
07 Mar 2017 15:00:00	Tampolo	Madagascar	0.9m
07 Mar 2017 13:00:00	Manambia	Madagascar	0.8m
07 Mar 2017 16:00:00	Rantabe	Madagascar	0.7m
07 Mar 2017 10:00:00	Ambodivato	Madagascar	0.7m
07 Mar 2017 13:00:00	Voloina	Madagascar	0.7m
07 Mar 2017 16:00:00	Maintimbato	Madagascar	0.7m
07 Mar 2017 16:00:00	Fananehana	Madagascar	0.7m
07 Mar 2017 16:00:00	Anoromby	Madagascar	0.7m

***Figure 31 -** As in **Figure 29**, but as of 6 March, 06:00 UTC.*

Few hours BEFORE the landfall (7 March, 06:00 UTC)

JRC calculations, using as input the data of the last bulletin available before the landfall (7 March 06:00 UTC) estimated a possible maximum storm surge of:

- **0.9 m** along the coast of Antalaha district, near **Ampaha (Sava region),** on 7 March at 9:00 UTC
- **0.8 m** along the northern coast of Helograno Antongila Bay, near **Maroantsetra (Analanjirofo region)**, on 7 March at 11:00 UTC.



Affected locations

Locations affected by Storm surge (15 of 177)
Calculation based on advisory number 9 of 07 Mar 2017 06:00:00.
(Simulation using 0.5 minute resolution)

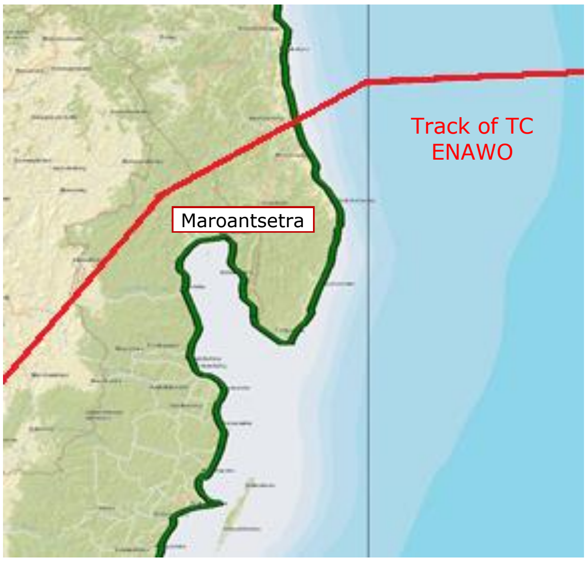
Date	Name	Country	Storm surge height (m)
07 Mar 2017 09:00:00	Ampaha	Madagascar	0.9m
07 Mar 2017 09:00:00	Andrapengy	Madagascar	0.9m
07 Mar 2017 13:00:00	Voloina	Madagascar	0.8m
07 Mar 2017 12:00:00	Manambia	Madagascar	0.8m
07 Mar 2017 12:00:00	Anantoraka	Madagascar	0.8m
07 Mar 2017 11:00:00	Maroantsetra	Madagascar	0.8m
07 Mar 2017 09:00:00	Ambinany	Madagascar	0.8m
07 Mar 2017 11:00:00	Andranofotsy	Madagascar	0.7m
07 Mar 2017 09:00:00	Ambodipont-Sahana	Madagascar	0.7m
07 Mar 2017 10:00:00	Mahalevona	Madagascar	0.6m
07 Mar 2017 13:00:00	Rantabe	Madagascar	0.6m
07 Mar 2017 09:00:00	Antalaha	Madagascar	0.6m
07 Mar 2017 09:00:00	Anjahamarina	Madagascar	0.5m
07 Mar 2017 10:00:00	Ambanizana	Madagascar	0.5m

***Figure 32** - As in **Figure 19**, but as of 7 March, 06:00 UTC.*

After landfall (7 March, 18:00 UTC)

JRC calculations, using as input the data of the first bulletin available after the landfall (7 March 18:00 UTC) estimated a possible maximum storm surge of:

- **0.8 m** along the coast of Antalaha district, near **Ampaha (Sava region)**, on 7 March at 10:00 UTC
- Nearly **1 m** along the northern coast of Helograno Antongila Bay, near **Maroantsetra (Analanjirofo region)**, on 7 March at 14:00 UTC.



Affected locations

Locations affected by Storm surge (15 of 184)
Calculation based on advisory number 10 of 07 Mar 2017 18:00:00.
(Simulation using 0.5 minute resolution)

Date	Name	Country	Storm surge height (m)
07 Mar 2017 14:00:00	Manambia	Madagascar	1.0m
07 Mar 2017 14:00:00	Anantoraka	Madagascar	1.0m
07 Mar 2017 15:00:00	Voloina	Madagascar	1.0m
07 Mar 2017 14:00:00	Maroantsetra	Madagascar	1.0m
07 Mar 2017 10:00:00	Ampaha	Madagascar	0.9m
07 Mar 2017 13:00:00	Andranofotsy	Madagascar	0.9m
07 Mar 2017 10:00:00	Ambinany	Madagascar	0.9m
07 Mar 2017 10:00:00	Antalaha	Madagascar	0.8m
07 Mar 2017 13:00:00	Mahalevona	Madagascar	0.8m
07 Mar 2017 14:00:00	Rantabe	Madagascar	0.7m
07 Mar 2017 09:00:00	Andrapengy	Madagascar	0.7m
07 Mar 2017 10:00:00	Anjahamarina	Madagascar	0.6m
07 Mar 2017 13:00:00	Ambanizana	Madagascar	0.6m
07 Mar 2017 14:00:00	Maintimbato	Madagascar	0.5m

Figure 33 – *As in **Figure 19**, but as of 7 March, 18:00 UTC.*

3.4.4. Rainfall Alert

The analysis of the GDACS rainfall alert is not included, because this system was not working during the passage of TC ENAWO. JRC is solving this problem, improving the current system including new data as described in the Technical Annex.

3.5. ARISTOTLE

3.5.1. Overview

ARISTOTLE (All Risk Integrated System TOwards Trans-boundary hoListic Early-warning) project was set-up by DG-ECHO with funds from the European Parliament in 2016, creating a pilot project aimed at the production of a multi-risk report within few hours from an event, on a limited number of primary events:

- Earthquakes (secondary induced hazard: Tsunamis);
- Volcanic Eruptions;
- Severe Weather Events (Tropical Cyclones, winter storms, major cold/heat waves and severe precipitation);
- Flooding.

ARISTOTLE aims at the provision of Multi-Hazard Advice to ERCC, either in advance or during the activation of EC Civil Protection Mechanism (CPM) to increase preparedness and response levels of the EU and improving ERCC's assessment capacity.

Three different types of products are available:

- 3 hour-informative scientific reports to ERCC (pro-active and reactive mode), delivered to ERCC through the ERCC portal;
- Situational Awareness reports – after the Multi-Hazard Operational Board weekly meetings a Bulletin is prepared with the multi-hazard assessment. Delivered to ERCC through the ERCC portal;
- Informative communication whenever appropriate following the SOP.

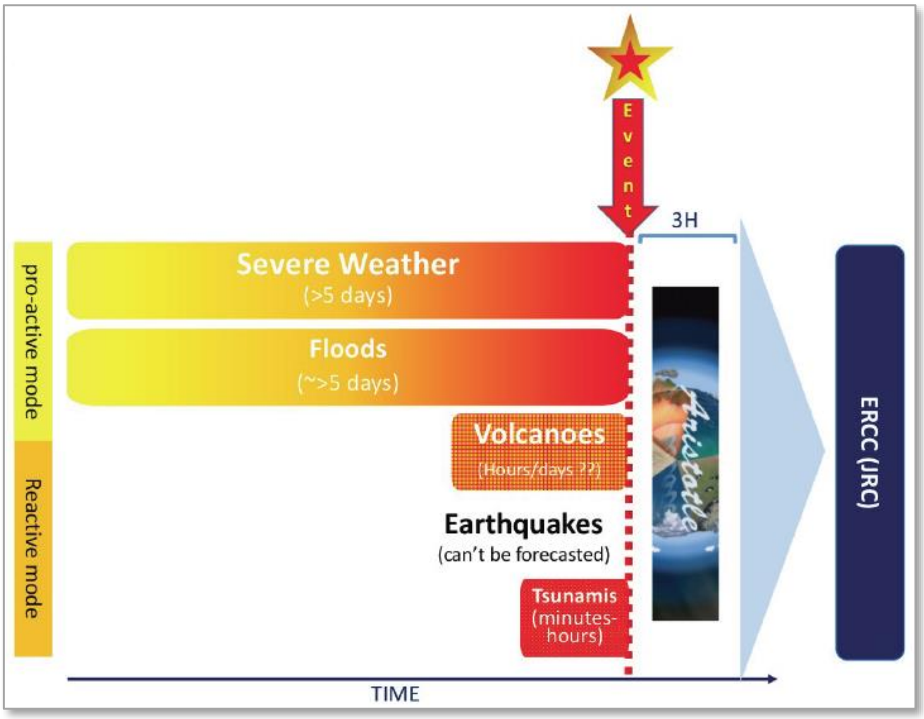


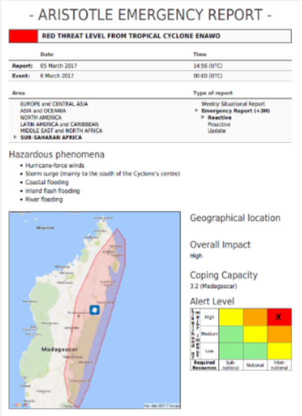
Figure 34 *- ARISTOTLE workflow*

3.5.2. Reports

ARISTOTLE was activated by the ERCC of DG ECHO on 5 March (two days before landfall) and it produced the first report after three hours from the activation and an updated report on 7 March after the landfall. The current situation and possible evolution included in the two ARISTOTLE reports are presented below.

The THREAT LEVEL for this event was RED, while the total population in the area potentially affected by the cyclone was about 14 million. This number is different from the number of people estimated by GDACS (1-2 million) and the one reported by national authorities after the landfall (434 000). This difference will be analysed in detail in Section 5.

Report 5 March 2017



Current Situation: *Tropical Cyclone Enawo is currently centred around 600km to the NE of Madagascar. It is forecast to intensify over the coming 24-48 hours and track towards NE Madagascar.*

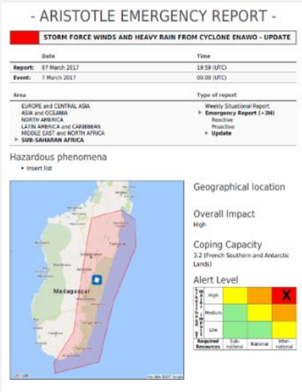
Possible evolution: *Tropical Cyclone Enawo is likely to continue to strengthen to an Intense Tropical Cyclone by late Monday through Tuesday, then make landfall on north-eastern Madagascar on Tuesday UTC time. There has been increasing agreement between models through the past 24 hours, with all deterministic solutions now showing Enawo moving WSW and continuing the strengthen through today (Sunday) and Monday into Tuesday. The system may reach its peak intensity on Monday, just prior to landfall with mean wind speeds of around 100-110 Knots (115-125 mph).*

Although the cyclone is likely to weaken through Tuesday, it is still expected to be a potent cyclone as it affects NE Madagascar. After making landfall the winds will quickly decrease and it is likely to move southwards affecting more of the E coast, with the remnants still likely to bring as much as 500 to 750 mm of rainfall to much of eastern Madagascar over the following few days, with the capital city Antananarivo also at risk of enhanced rainfall.

Destructive winds likely to damage power supplies, and buildings. Torrential rainfall likely to bring flash flooding and an enhanced risk of landslides. Significant storm surge could bring coastal erosion and flooding. Significant risk to life across the affected region.

Total population in the area: 14764500 (from LandScan 2015 DB). Note that the population shown here includes the Capital City (Antananarivo), which may receive several hundred mm of rain over the event, but will avoid the worst of the wind and rain so is not at as great a risk of significant impacts than the NE part of the country.

Updated Report 7 March 2017



Current situation: *Cyclone Enawo made landfall just north of Antalaha earlier today, with sustained winds of 110 kt (203 km/h). The system generated 186 mm of rain at Sambava in the 6 hours to 12:00 UTC. The system has weakened somewhat as it has moved over land and away from the warm waters of the Indian Ocean. Furthermore, as Enawo moves over the mountainous interior of Madagascar, its wind speeds will continue to reduce and concerns surrounding the system will become largely confined to further very heavy rain.*

Possible evolution: *Enawo is expected to continue SW, then S across Madagascar over the next few days, with wind speeds expected to be 40 kt (74km/h) by 00:00 UTC Wednesday, 38 kt (70 km/h) by 06:00 UTC, and 35 kt (64km/h) by 12:00 UTC Wednesday. This system is still expected to be moisture-laden, with a further 500-700 mm of rain possible as it tracks S across the eastern half of the country. Some 200-400 mm of rain is possible in Antananarivo. Whilst winds are expected to ease, they are still strong enough to bring down power lines and damage poorly constructed buildings. The greater concern is the continuing heavy rain, which will likely lead to mud slides, flash flooding and further damage to infrastructure in the country.*

Figure 35 *– ARISTOTLE Reports - Current Situation and Possible evolution*
(Source: ARISTOTLE)

4. Post-event: *Impact assessment*

4.1. Satellite Images Analyses

4.1.1. Copernicus EMS - Mapping

Copernicus Emergency Management Service (Copernicus EMS) provides information for emergency response in relation to different types of disasters, including meteorological hazards, geophysical hazards, deliberate and accidental man-made disasters and other humanitarian disasters as well as prevention, preparedness, response and recovery activities (see http://emergency.copernicus.eu/). Three components constitute the Copernicus EMS: *Copernicus EMS – Mapping, the European and Global Flood Awareness System (EFAS & GloFAS), the European Forest Fire Information System (EFFIS) and Global Wildfire Information System (GWIS).*

The products of Copernicus EMS - Mapping for TC ENAWO have been used in this analysis.

The **Copernicus EMS - Mapping** addresses, with worldwide coverage, a wide range of emergency situations resulting from natural or man-made disasters. Satellite imagery is used as the main datasource. It is provided during all phases of the emergency management cycle, in two temporal modes (Rapid Mapping, Risk and Recovery Mapping), and free of charge for the users. It can be activated only by authorised users. More information can be found at: *http://emergency.copernicus.eu/mapping/ems/service-overview*

Copernicus EMS (Rapid Mapping) has been activated on 7 March 2017 at 15:00 UTC by DG ECHO and several maps have been produced (see **Figure 36**):

- 2 Delineation maps which show the flood extent
- 12 Grading maps which show the results of the damage assessment (assets)

The Copernicus Areas Of Interest (AOI) are shown in the **Table 10** and in **Figure 37**, while an overview of the maps are reported in Annex 8. More information can be found at:

http://emergency.copernicus.eu/mapping/list-of-components/EMSR197/

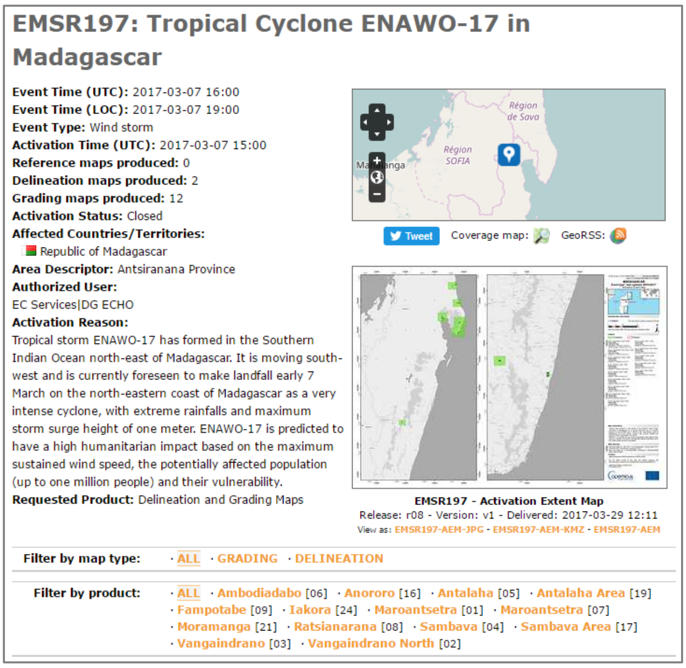


Figure 36 - *Copernicus EMS Activation for TC ENAWO in Madagascar*

Population affected:

For each AOI the % of people affected by floods has been calculated as follow:

$$\%\ Population\ affected = \frac{Tot.affected}{Tot.in\ AOI} * 100$$

Copernicus EMS uses LandScan™ data for the population. The results are shown in the table below and in **Figure 37**, while more information are in Annex 8.

AOI	Area	$\%\ Pop.affected$	Details
01	Maroantsetra	15 %	AOI 01 / Maroantsetra / Scale 1:60000 **COMPLETED** **- Delineation Map:** RADARSAT-2, 07/03/2017 15:04 UTC COSMO-SkyMed, 10/03/2017 02:22 UTC
02	Vangaindrano North	12%	AOI 02 / Vangaindrano North / Scale 1:10000 **COMPLETED** **- Delineation Map:** Pleiades-1A, 14/03/2017 07:10 UTC
03	Vangaindrano	Not estimated (*)	AOI 03 / Vangaindrano / Scale 1:10000 **COMPLETED** **- Grading Map:** Pleiades-1A, 14/03/2017 07:10 UTC
04	Sambava	14 %	AOI 04 / Sambava / Scale 1:10000 **COMPLETED** **- Grading Map:** Pleiades-1A, 10/03/2017 06:50 UTC
05	Antalaha	1.7%	AOI 05 / Antalaha / Scale 1:10000 **COMPLETED** **- Grading Map:** GeoEye-1, 16/03/2017 06:50 UTC
06	Ambodiadabo	32 %	AOI 06 / Ambodiadabo / Scale 1:10000 **COMPLETED** **- Grading Map:** GeoEye, 11/03/2017 07:10 UTC
07	Maroantsetra	12 %	AOI 07 / Marontsetra / Scale 1:10000 **COMPLETED** **- Grading Map:** GeoEye, 11/03/2017 07:10 UTC
08	Ratsianarana	0 % No damage detected *(ND)*	AOI 08 / Ratsianarana / Scale 1:70000 **COMPLETED** **- Grading Map:** SPOT-6, 10/03/2017 06:22 UTC
09	Fampotabe	0 % No damage detected *(ND)*	AOI 09 / Fampotabe / Scale 1:70000 **COMPLETED** **- Grading Map:** SPOT-6, 10/03/2017 06:22 UTC
16	Anororo	Not estimated (*)	AOI 16 / Anororo / Scale 1:10000 **COMPLETED** **- Grading Map:** Pleiades-1A, 15/03/2017 07:02 UTC
17	Sambava Area	0.5%	AOI 17 / Sambava Area / Scale 1:50000 **COMPLETED** **- Grading Map:** WorldView-3, 10/03/2017 07:08 UTC
19	Antalaha	1.8 %	AOI 19 / Antalaha / Scale 1:50000 **COMPLETED** **- Grading Map:** WorldView-3, 22/03/2017 07:02 UTC
21	Moramanga	0 % No damage detected *(ND)*	AOI 21 / Moramanga / Scale 1:35000 **COMPLETED** **- Grading Map:** GeoEye-1, 25/03/2017 07:24 UTC
24	Iakora	Not estimated (*)	AOI 24 / Iakora / Scale 1:36000 **COMPLETED** **- Grading Map:** Pleiades-1B, 25/03/2017 07:06 UTC

Table 10 - *Copernicus AOI and % of people affected by floods, map scale and sensor used.*
** Damage to assets was detected, affected population not calculated*

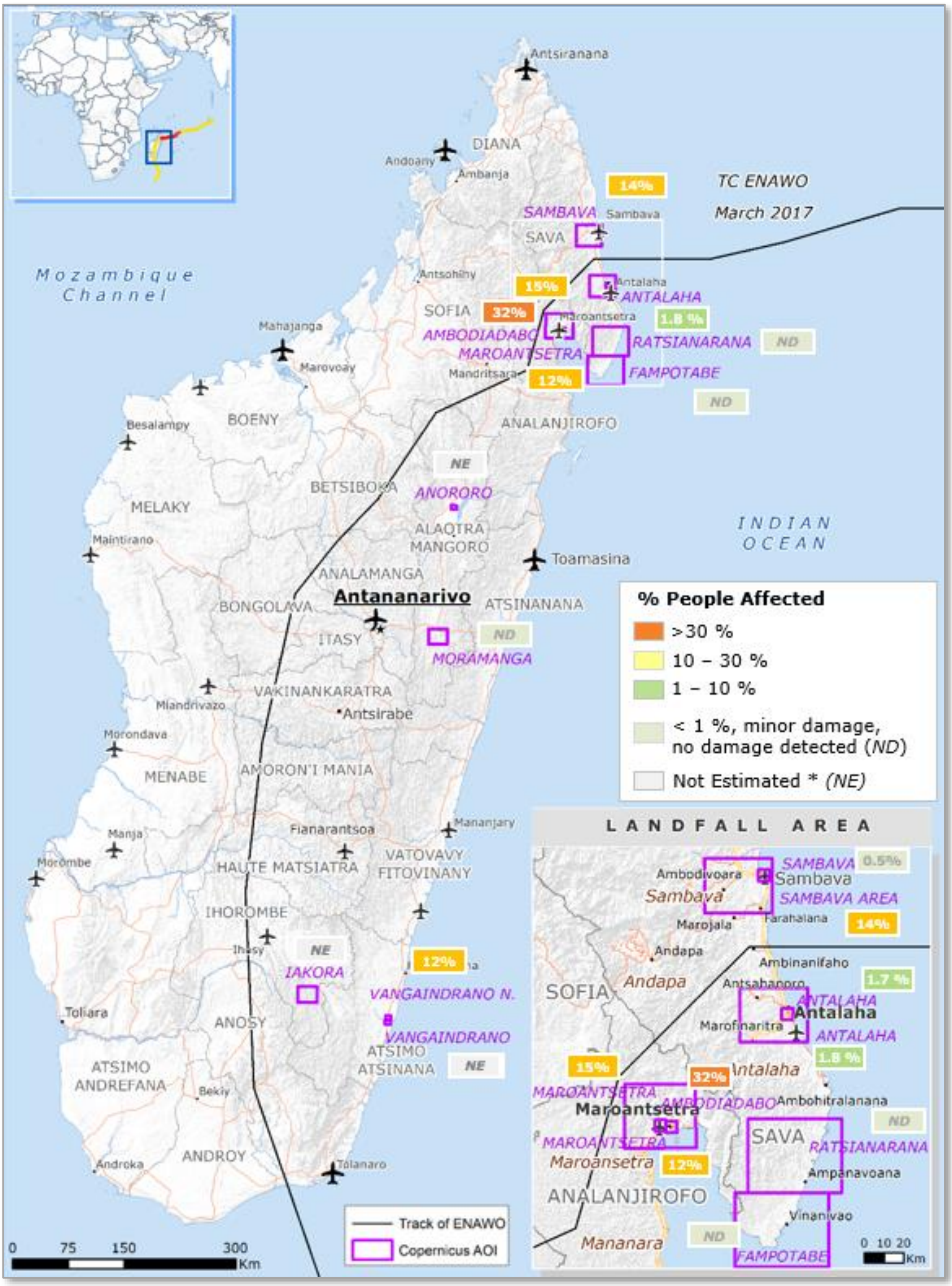


Figure 37 - *Copernicus EMS AOI and % of people affected by floods.*
** Damage to assets was detected, affected population not calculated*

According to this analysis, the AOIs with more than 10 % of people affected are:

- **Maroantsetra Area: 15 %**
- **Maroantsetra: 12 %**
- **Ambodiadabo: 32 %**
- **Sambava: 14 %**
- **Vangaindrano North: 12 %**

Maroantsetra

The map of Maroantsetra Area is shown in the figure below, while all the other maps are reported in Annex 8. This map shows the evolution of the floods, comparing the waters detected by the satellite on 7 March and on 10 March.

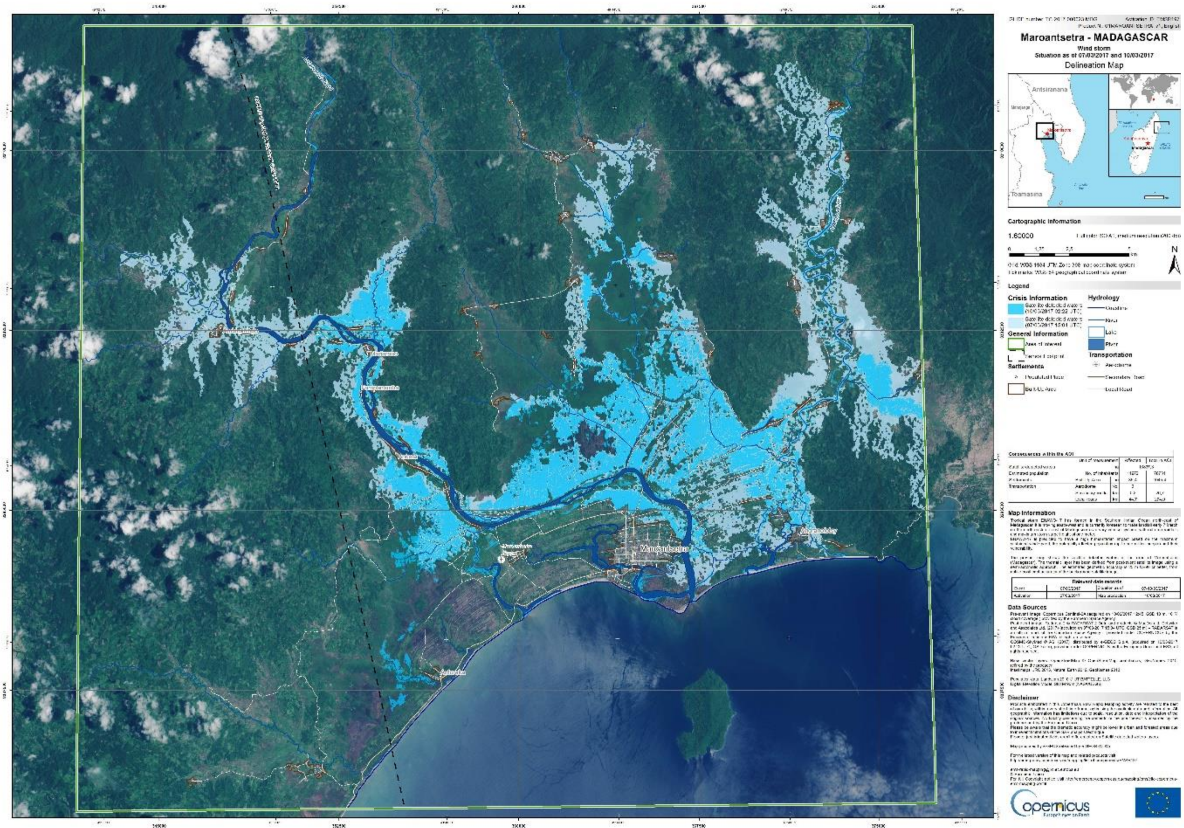


***Figure 38** – Flood extent Map of Maroantsetra Area (situation as of 7 and 10 March 2017). (Source: Copernicus EMS © 2017, [EMSR197] Maroantsetra; Delineation Map)*

4.1.2. UNITAR/UNOSAT

Several reports and maps are available on the UNITAR/UNOSAT website for TC ENAWO.

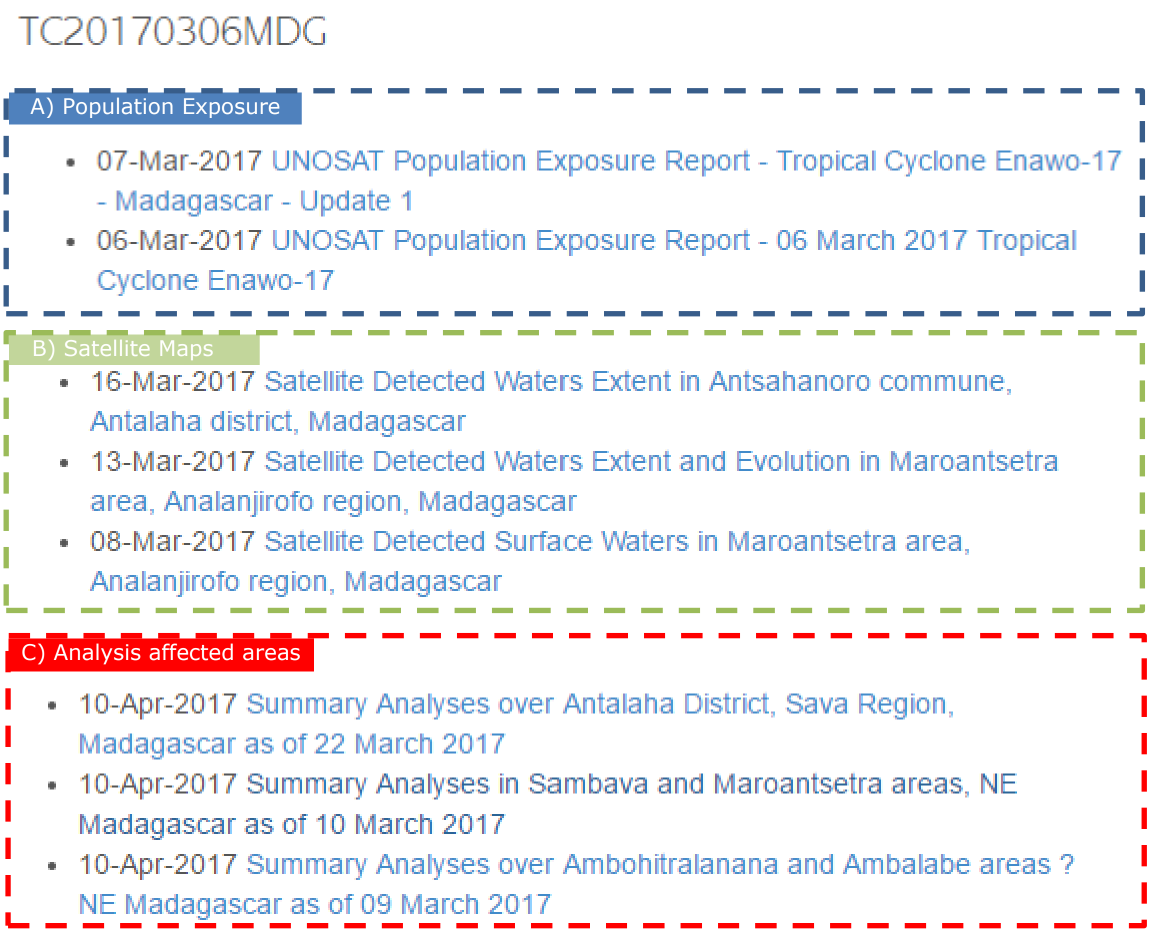
The main results are presented below, while more information and results can be found on the UNITAR / UNOSAT website at: http://www.unitar.org/unosat/maps/MDG

Three different products are available:

A) **Population Exposure Reports** (Before the landfall, just after the landfall)

B) **Satellite Maps**: Satellite detected waters after the landfall

C) **Analysis of the affected areas** based on the damage detected by satellite


TC20170306MDG

A) Population Exposure

- 07-Mar-2017 UNOSAT Population Exposure Report - Tropical Cyclone Enawo-17 - Madagascar - Update 1
- 06-Mar-2017 UNOSAT Population Exposure Report - 06 March 2017 Tropical Cyclone Enawo-17

B) Satellite Maps

- 16-Mar-2017 Satellite Detected Waters Extent in Antsahanoro commune, Antalaha district, Madagascar
- 13-Mar-2017 Satellite Detected Waters Extent and Evolution in Maroantsetra area, Analanjirofo region, Madagascar
- 08-Mar-2017 Satellite Detected Surface Waters in Maroantsetra area, Analanjirofo region, Madagascar

C) Analysis affected areas

- 10-Apr-2017 Summary Analyses over Antalaha District, Sava Region, Madagascar as of 22 March 2017
- 10-Apr-2017 Summary Analyses in Sambava and Maroantsetra areas, NE Madagascar as of 10 March 2017
- 10-Apr-2017 Summary Analyses over Ambohitralanana and Ambalabe areas ? NE Madagascar as of 09 March 2017

Figure 39 *- UNITAR / UNOSAT - TC ENAWO*

A) Population Exposure Reports

UNITAR-UNOSAT conducted a population exposure analysis for Madagascar before the landfall of ENAWO. This analysis is based on the observed and predicted TC track (GDACS), sustained wind speeds zones (GDACS, Red, Orange and Green buffers, see Annex 1), Flood hazard 25 years from GAR Risk Data Platform and population data from WorldPop.

6 Mar 2017

~20 million people are exposed to wind speed of at least 60 km/h :

- 597 427 people are exposed to the 120 km/h winds *(GDACS Red buffer, see Annex 1),*
- 5 100 218 people are exposed to the 90 km/h winds *(GDACS Orange buffer),*
- 14 293 874 people are exposed to the 60 km/h winds (GDACS Green buffer).

Taking into account the zones with a flood hazard of 25 years return period within the predicted wind speed zones, about 1 100 000 people are living in these flood hazard zones and are potentially exposed to 60 km/h winds. About 630 000 people in the flood hazard zones of 25 years of return period and exposed to 90 km/h sustained wind speed and 83 000 in the 120km/h.

7 Mar 2017

~15 million people are exposed to wind speed of at least 60 km/h :

- 1 977 530 people are exposed to the 120 km/h winds,
- 2 711 322 people are exposed to the 90 km/h winds,
- 10 208 890 people are exposed to the 60 km/h winds.

Taking into account the zones with a flood hazard of 25 years return period within the predicted wind speed zones, about 700 000 people are living in these flood hazard zones and are potentially exposed to 60 km/h winds. About 290 000 people in the flood hazard zones of 25 years of return period and exposed to 90 km/h sustained wind speed and 260 000 in the 120km/h.

Source: UNITAR-UNOSAT, see http://www.unitar.org/unosat/maps/MDG

B) Satellite Maps

Three different maps are available, as shown in **Figure 39**. One map shows the floods in Antalaha district, while the other two show the extent and evolution of the floods in Maroantsetra area. The large area flooded in Maroantsetra is clearly visible in these maps. The water detected by satellite on 8 March in the area of Maroantsetra is shown below.

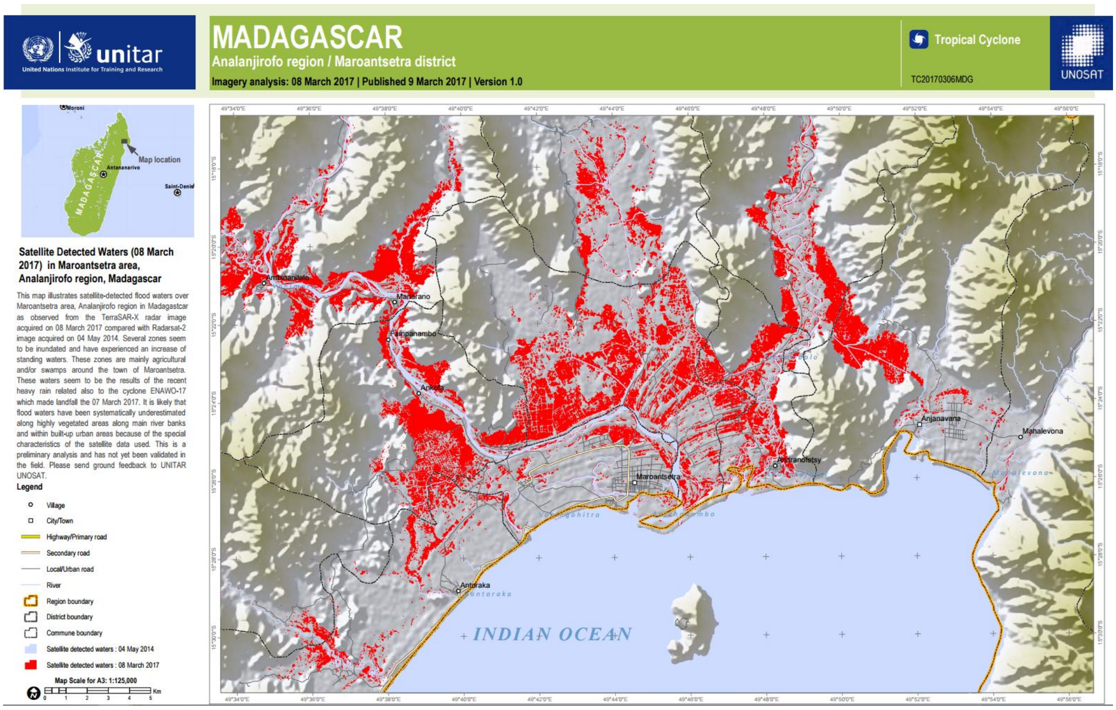


***Figure 40** - Satellite Detected Waters in Maroantsetra (source: UNITAR/UNOSAT)*

C) Analysis of the affected areas

UNITAR-UNOSAT produced also several analysis for different areas of NE Madagascar:

- Antalaha district
- Sambava and Maroantsetra areas
- Ambohitralanana and Ambalabe areas

In these analyses, the satellite images before the passage of ENAWO were compared with the satellite images detected after its passage, in order to show the affected buildings, roads, flooded areas, landslides, fallen trees.

4.1.3. International Charter Space & Major Disaster

The International Charter Space & Major Disaster has been activated on 6 March by UNITAR-UNOSAT on behalf of UNOCHA. Several maps have been produced. All the data, reports and information are available at:

https://www.disasterscharter.org/web/guest/-/flood-in-madagascar-call-600-

Flood in Madagascar

Monday, 06 March 2017

Type of Event:	Ocean Storm - Cyclone
Location of Event:	Madagascar
Date of Charter Activation:	6 March 2017
Time of Charter Activation:	11:49:00
Time zone of Charter Activation:	UTC+01:00
Charter Requestor:	UNITAR-UNOSAT on behalf of UNOCHA
Activation ID:	521
Project Management:	UNITAR

Description of the event

Tropical Cyclone Enawo has been classified as the most destructive storm to hit Madagascar in years, with winds in excess of 231 km/h, making it a Category 4 hurricane on the Saffir-Simpson Wind Scale. Aid organisations are warning that more than 700,000 people could be affected by the storm, but some reports suggest that there have already been fatalities and numerous injuries as the category-four cyclone nears the capital Antananarivo.

Furthermore, NOAA's National Hurricane Center reported that a Category 4 hurricane can severely damage homes and infrastructure; trees will fall and power poles will be downed, causing power outages to last from weeks to months. Consequently, most of the area will be uninhabitable for weeks or months.

Figure 41 *- International Charter Space & Major Disaster for the flood in Madagascar (source: International Charter Space & Major Disaster)*

4.2. SENDAI Indicators

Tropical Cyclone ENAWO caused the deaths of 81 people and affected 434 000 people, with 58 districts out of 119 reporting damages and nearly 250 000 people were temporarily displaced, as shown in Section 2.2. On 14 March, national authorities issued a "declaration of national emergency" and requested assistance from national and international partners.

The harmonisation of the disaster loss data and damages according to the Sendai Targets and related Indicators can, at first, facilitate the global comparison of the impact of the different events. In addition, it can support the EU implementation of the Sendai Indicators.

The Sendai Targets dealing with the monitor of the impact of hazardous events are 4:

Global target A	Substantially reduce global disaster mortality by 2030, aiming to lower average per 100,000 global mortality between 2020-2030 compared with 2005-2015.
Global target B	Substantially reduce the number of affected people globally by 2030, aiming to lower the average global figure per 100 000 between 2020-2030 compared with 2005-2015.
Global target C	Reduce direct disaster economic loss in relation to global gross domestic product (GDP) by 2030.
Global target D	Substantially reduce disaster damage to critical infrastructure and disruption of basic services, among them health and educational facilities, including through developing their resilience by 2030.

Table 11 - *Sendai Targets dealing with disaster loss data.*

The Sendai Framework for Disaster Risk Reduction (DRR) is an important catalyst for ensuring consistent and lasting disaster data collection over time. The first phase of the emergency response has been recognised as the key moment for setting this process in motion. In the following sessions, the disaster losses are categorised according to the related Sendai Indicators.

4.2.1. Affected population

To harmonise the data related to the affected population according to the Sendai Indicator, a consideration regarding the Target B (Affected population) and in particular to the Indicator B 3 (Number of people whose damaged dwellings were attributed to disasters) needs to be done. According to the description of the indicator provided by the Open-ended intergovernmental expert working group on indicators and terminology relating to disaster risk reduction (OEIWG) on February 2017 (http://www.preventionweb.net/drr-framework/open-ended-working-group/), this indicator reports a sub-set of the number of the affected population provided by BNGRC (434 000 people). In particular, here the number of **displaced population** is considered because of main and permanent damages to their dwellings (~247 000 people).

Target A	**Deaths and Missing**	
A-1 (compound)	**Number of deaths and missing persons attributed to disasters**	**99**
A-2	Number of deaths attributed to disasters	81
A-3	Number of missing persons attributed to disasters	18

Table 12 *-Impact of TC ENAWO according to the Sendai Indicators - Target A*

Target B	**Affected population**	
B-1 (compound)	**Number of directly affected people attributed to disasters**	**~247 000** (*)
B-2	Number of injured or ill people attributed to disasters	253
B-3	Number of people whose damaged dwellings were attributed to disasters.	~247 000 (*)
(*) number of displaced population is used in this analysis because of main and permanent damages to their dwellings (~247 000 people). *Source: http://www.unocha.org/story/madagascar-un-and-partners-appeal-us20m-assist-250000-people-affected-cyclone-enawo*		

Table 13 *- Impact of TC ENAWO according to the Sendai Indicators – Target B*

4.2.2. Economic losses

TC ENAWO affected the most exposed areas to TCs. The geographical distribution of economic loss due to previous TCs and other hazards combined are shown in Annex 5.

The economic losses from TC ENAWO are estimated to be **$400 million (€340 million)**, corresponding to about 4 % of annual GDP of Madagascar, according to an assessment conducted by the CPGU (*Cellule de Prevention et de Gestion des Urgences*) and the World Bank. The agriculture sector alone recorded losses of $207 million (see UN – BNGRC Situation Report 5 and World Bank report[15]). The estimation was developed with modelling inputs from AIR Worldwide, the African Risk Capacity, and the World Bank Group's Disaster-Resilience Analytics and Solutions (D-RAS) team. As result of the estimation:

- *The work presented in the World Bank[15] report, estimates the losses related to Cyclone Enawo to be over **USD 400 million**, corresponding to about 4% of annual GDP.*
- *By using quantitative risk modelling approach, it was possible to estimate losses resulting from direct damage to buildings and infrastructure, which are estimated to be around **USD 208 million** (2015 currency) with a standard deviation of +/- 69 million, and corresponds to a mean return period of 11 years +5/-3 years. This is comparable to Cyclone Gafilo in 2004, which caused serious damage, in excess of USD 250 million, to both agricultural production and capital stock of Madagascar"*
- *In addition, an agriculture sector model was developed to assess agricultural losses, which were estimated at approximately **USD 207 million**, dominated by the impact to the vanilla plantations, amounting to losses estimated at USD 164 million, in Sava and Diana regions.*

(source: World Bank - *Estimation of Economic Losses from Tropical Cyclone Enawo* [15])

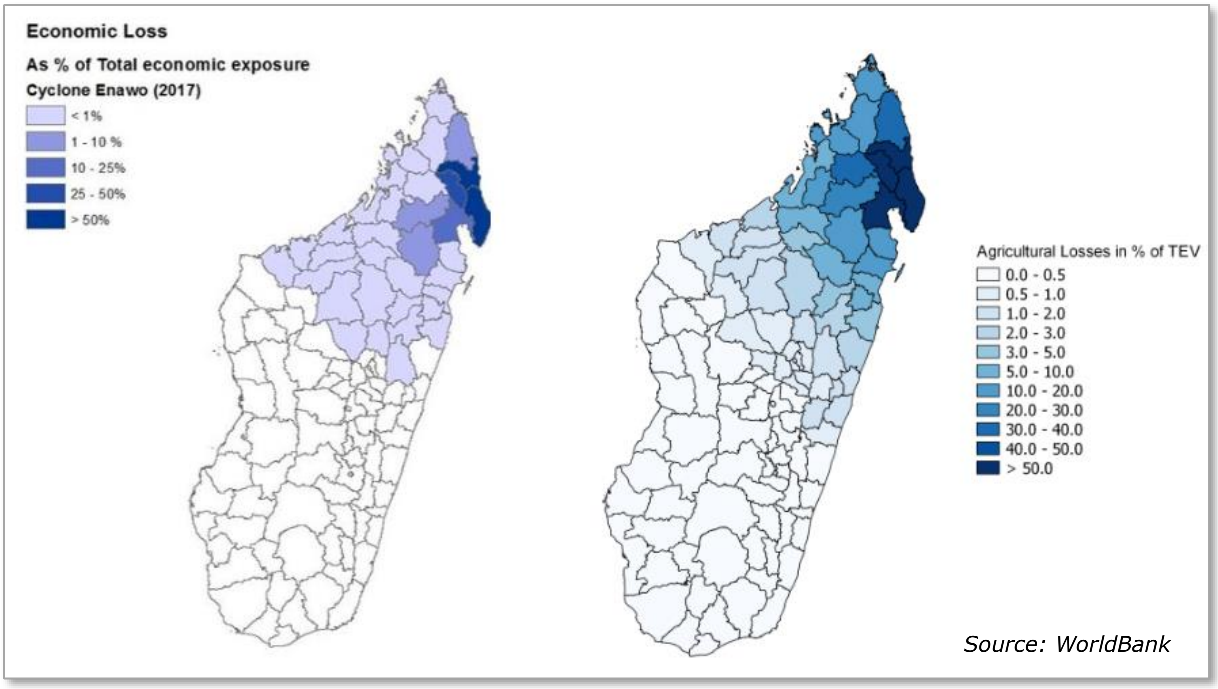


Figure 42 – *Estimation of economic losses due to Cyclone ENAWO by the World Bank on March 2017 (source: WorldBank[15])*

[15] World Bank: http://www.primature.gov.mg/cpgu/wp-content/uploads/2017/03/MG-Report-on-the-Estimation-of-Economic-Losses.pdf

Regarding the economic loss in the housing sector, the UNISDR Methodology to estimate at global level the cost of the related Sendai Indicator is outlined below:

$$C\text{–}4 = C_{damaged} + C_{destroyed}$$

Where:

- $C_{damaged} = \frac{number\ of\ houses}{damaged} * \frac{average\ size\ of}{damaged\ facilities} * \frac{construction\ cost}{per\ square\ metre} * \frac{damage}{ratio}$
- $C_{destroyed} = \frac{number\ of\ houses}{destroyed} * \frac{average\ size\ of}{destroyed\ facilities} * \frac{construction\ cost}{per\ square\ metre} * \frac{damage}{ratio}$

Destroyed / damaged	Average Size	Damaged ratio
To assess the order of magnitude of the maximum damage, the flooded and unroofed houses have been considered as damaged (see Section 2.2.2). Houses flooded = 19 290 Houses unroofed = 36 767 Total = 56 057	$50m^2$ (***overestimation***[17]) Construction cost[(16)] Houses: NA Office building: 320€/m^2 Hotel: 220€/m^2 → Construction cost used for the estimation [17]: 270€/m^2 (averaged value)	According to UNISDR methodology, for damaged building is 25%, for destroyed buildings is 100%. As it is not possible to distinguish *a priori* between damaged and destroyed buildings, in the proposed estimation, for the buildings categorised as destroyed is considered a damage ratio=100%, for buildings categorised as flooded or unroofed is considered a damage ratio=25%.

Calculation:

C-4 = cost damaged buildings (56 057 * $50m^2$ * 270€/m^2 * 25%)

\+ cost destroyed buildings (37 988 * $50m^2$ * 270€/m^2 * 100%)

= 0.19B€ (damaged buildings) + 0.51 B€ (destroyed buildings)

= 0.7 B€ *(Estimation, not the real coast[17])*

[16] http://www.fao.org/docs/up/easypol/506/snapshot_africa_madagascar.pdf

[17] This is not the real cost. This is an average value used to provide an estimation of the order of magnitude of the economic impact according to the UNISDR Methodology.

The estimation of the direct economic loss is here harmonised following the Sendai Indicators.

Sendai Indicators	Description	Billion Euro (B€)	Notes
C-1 (compound)	**Direct economic loss attributed to disasters**	**0.33***	*Total economic damages according to World Bank (Million USD), see Page 48 400$≈333€
C-2	Direct agricultural loss attributed to disasters.	0.17*	* World Bank Estimation (Million USD), see Page 48 207$≈172€
C-3	Direct economic loss to all other damaged or destroyed productive assets attributed to disasters.	Not assessed	
C-4	Direct economic loss in the housing sector attributed to disasters	0.7**	**Estimation based on the UNISDR Methodology[18] (see page 49). World Bank estimation: 208$≈173€
C-5	Direct economic loss resulting from damaged or destroyed critical infrastructure attributed to disasters.	Not assessed	
C-6	Direct economic loss to cultural heritage damaged or destroyed attributed to disasters.	Not assessed	

Table 14 *- Impact of ENAWO according to the Sendai Indicators*

The order of magnitude of the economic damageestimation[18] to the housing sector is within the total amount of economic damages estimated by the World Bank.

[18] **This is not the real cost**. This is an average value used to provide an estimation of the order of magnitude of the economic impact according to the UNISDR Methodology.

In addition to the cost categories identified by the Sendai Indicators, there are additional costs related to the emergency management in terms of Humanitarian Aid that have been estimated in a total amount of around 20 Million USD to assist 250 000 people[19] (**Figure 43**).

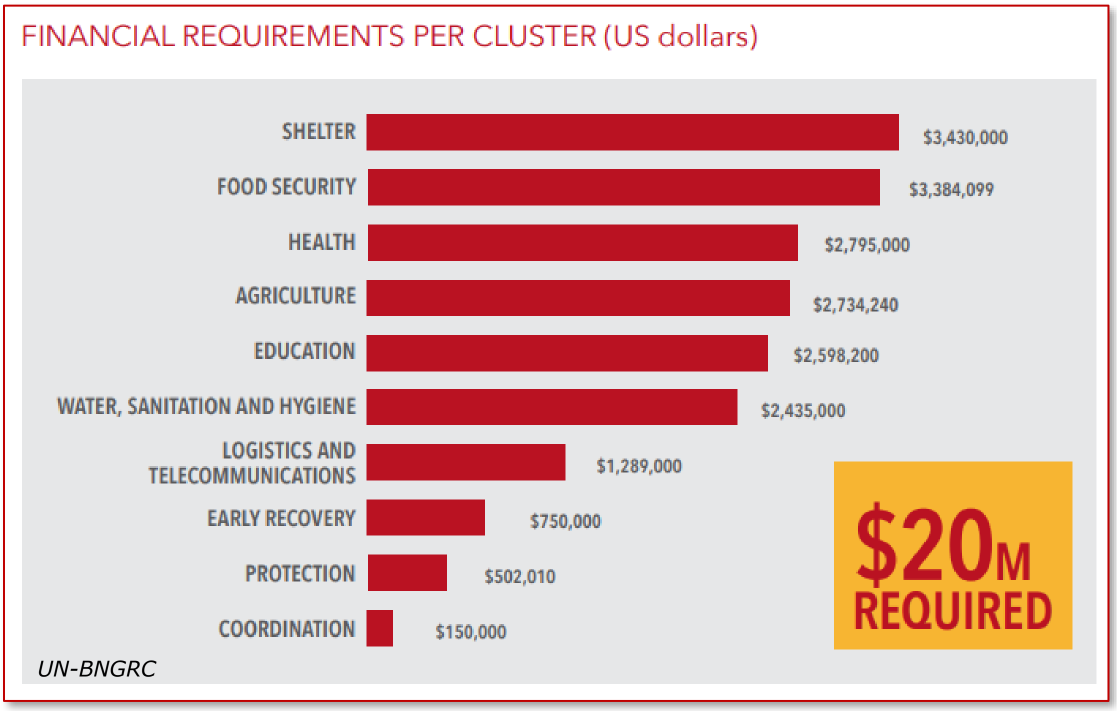


Figure 43 - *Financial Requirements per Cluster (source: BNGRC-UN[20], as of 23 March 2017)*

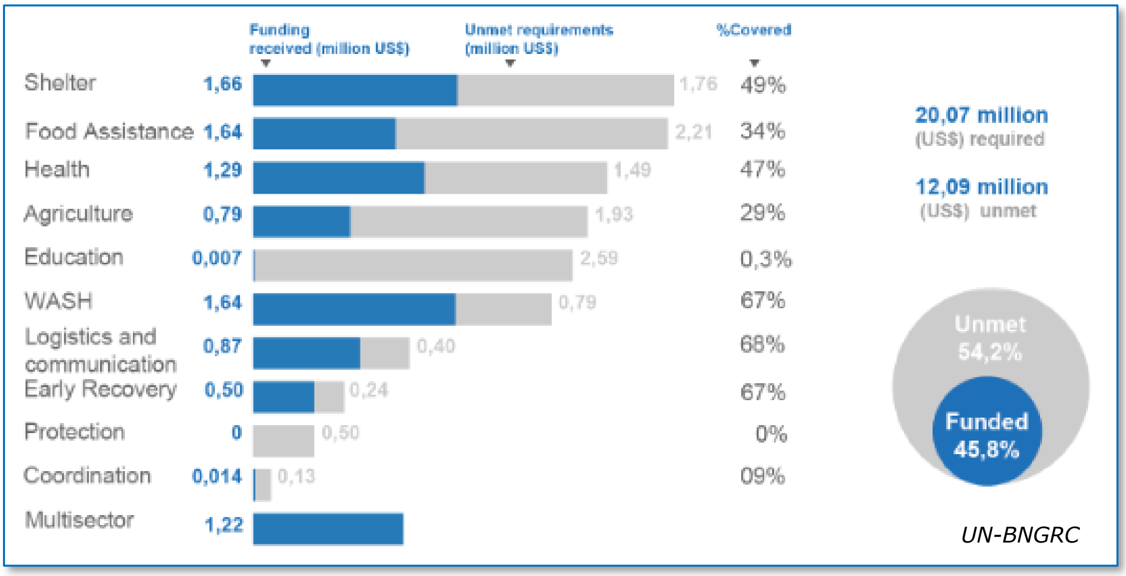


Figure 44 *- Situation (Image Source: BNGRC / UN Humanitarian Country Team in Madagascar Situation Report No. 5, 14 April 2017)*

[19] http://reliefweb.int/sites/reliefweb.int/files/resources/final_ocha_madagascar_press_release.pdf
[20] http://reliefweb.int/sites/reliefweb.int/files/resources/2017_Flash_Appeal_MG_eng.002.002.pdf

4.2.3. Critical infrastructures

BNGRC provided official data regarding the damage to critical infrastructures related to hospitals and schools (in terms of damaged classrooms).
Regarding damaged facilities, *Télécoms Sans Frontières* (TSF) in coordination with BNGRC performed a field survey in the 3 most affected area (Antalaha, Sambava et Maroantsetra). The damage assessment has been performed on the national networks Orange e Telma. Several interruption were reported (**Figure 45**). More information on TSF reports of 19 March 2017[21]. As of 28 March (UN-BNGRC report[22]), some 3 900 classrooms have been damaged nationwide (2 315 completely destroyed, 1 588 partially destroyed) and 105 health centres were damaged.

Target D - Damage to critical infrastructures		
D-1 (compound)	Damage to critical infrastructure attributed to disasters.	
D-2	Number of destroyed or damaged health facilities attributed to disasters.	105*
D-3	Number of destroyed or damaged educational facilities attributed to disasters.	3 900 classroom*
D-4	Number of other destroyed or damaged critical infrastructure units and facilities attributed to disasters.	see text above
D-5 (compound)	Number of disruptions to basic services attributed to disasters.	Not assessed
*Sources: UN-BNGRC report		

Table 15 *- Impact of TC ENAWO according to the Sendai Indicators - Target D*

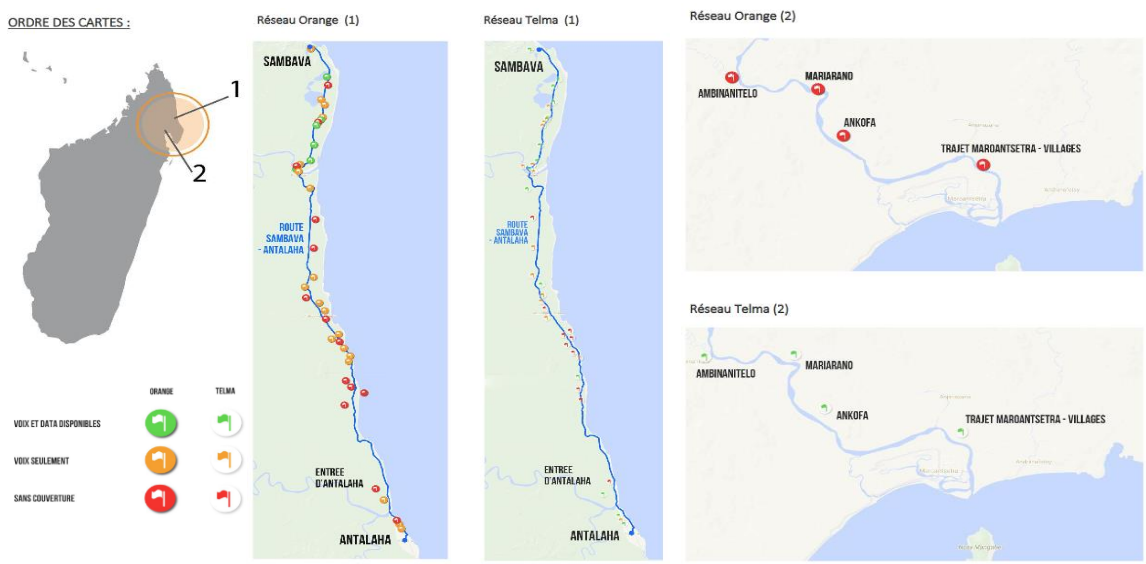


Figure 45 *– Field Survey (Source: Télécoms Sans Frontières[21])*

[21] https://www.humanitarianresponse.info/system/files/documents/files/tsf_sitrep_madagascar_enawo.pdf
[22] http://reliefweb.int/sites/reliefweb.int/files/resources/madagascar_cyclone_enawo_sitrep4_28march2017.pdf

5. Discussions

All the systems analysed in Section 3, provided a RED alert level for this event, but there were several differences among the various systems, as shown in this section.

The population potentially affected during the passage of TC ENAWO estimated by GDACS (see Section 3.4) and ARISTOTLE (see Section 3.5), as well as number of people affected reported after its passage (see Section 2.2) are presented in the figure below. Large differences exist between the impact estimations and the impact assessments, due to several different reasons, like:

a) Terminology used for "population affected"

b) TC effects included in the impact estimation

c) Methodology used to estimate the affected areas

d) Uncertainty on the forecasted track and intensity

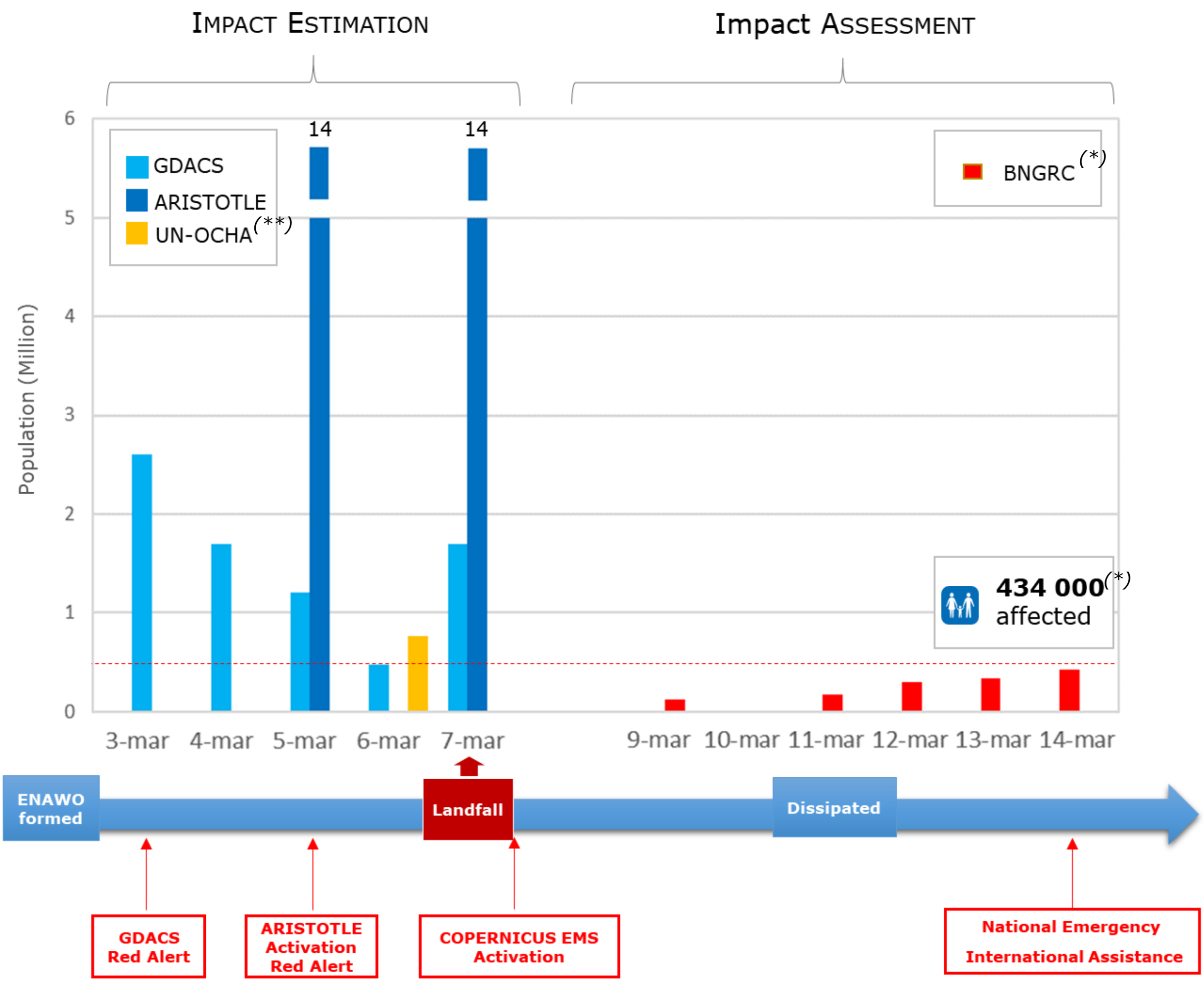


Figure 46 *- Event time-line and population affected*

(*) BNGRC (source: IOM Report - Annexes, *http://www.globaldtm.info/madagascar/)*

(**) *UN OCHA:* http://www.unocha.org/story/madagascar-tropical-cyclone-enawo-likely-affect-760000-people

a) *Terminology used for "Population affected"*

One of the most important reason is that the different systems used a different terminology for "population affected" (see **Table 16**). Therefore in order to have a better estimation of the number of people affected it's important to use the "**same terminology**" and define **specific thresholds** for winds, rain and storm surge (see point b).

		Population affected	Effects	Estimation
IMPACT ESTIMATION	**GDACS**	Population directly affected based on the number of people potentially affected by winds >118 km/h	Only wind effect (rainfall, storm surge not included)	Automatic Estimation
	ARISTOTLE	Population living in the area potentially affected by the TC	All effects	Manually Estimation
GENERAL DEFINITION	**UNISDR** *Sendai Framework for Disaster Risk Reduction (DRR)2015-2030*	People who are affected, either directly or indirectly, by a hazardous event. Directly affected are those who have suffered injury, illness or other health effects; who were evacuated, displaced, relocated or have suffered direct damage to their livelihoods, economic, physical, social, cultural and environmental assets. Indirectly affected are people who have suffered consequences, other than or in addition to direct effects, over time, due to disruption or changes in economy, critical infrastructure, basic services, commerce or work, or social, health and psychological consequences. Annotation: People can be affected directly or indirectly. Affected people may experience short-term or long-term consequences to their lives, livelihoods or health and to their economic, physical, social, cultural and environmental assets. In addition, people who are missing or dead may be considered as directly affected.		

Table 16 *– Terminology: Population affected*

b) *TC Effects included in the impact estimation*

In order to have a better impact estimation, it is important to identify all affected area, including all TC effects (wind, rainfall and storm surge). For example the area of Brickaville was particularly affected by floods and landslides, and considering only the wind impact it was not possible to identify this area, see Figure below.

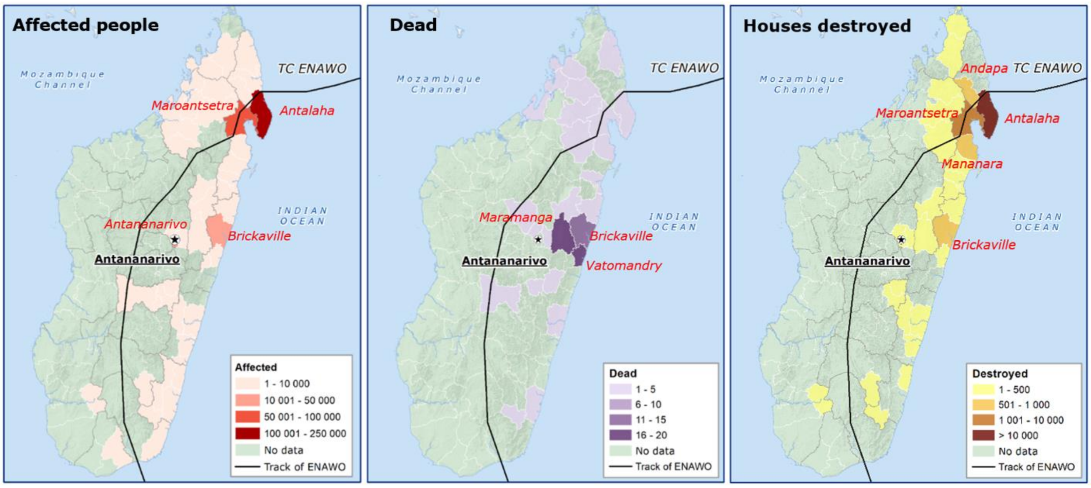


Figure 47 - *Number of people affected (left), deaths (middle) and houses destroyed (right) reported after the passage of ENAWO, see Section 2.2.*

c) *Methodology to estimate the affected area*

The system used for the TCs in GDACS is currently based on the TCs bulletins provided by the JTWC and NOAA (see Annex 1). This system has some limitations, especially it overestimates the number of people potentially affected by strong winds. Therefore the JRC is developing a new method using new TC data. The first preliminary results using the data of NOAA-HWRF (Hurricane Weather Research and Forecast System) are presented in the Technical Annex, while an example is provided in **Figure 48**:

- current GDACS system: calculation of the alert level includes the number of people within the red buffer
- future methodology: new system that the JRC is developing, using a more detailed wind field (e.g. data of NOAA-HWRF) and new classifications.

The difference between the two systems is shown in **Figure 48**: GDACS overestimated the area potentially affected by winds > 118 km/h (red area in the left figure), compared to the new results (yellow area in the right figure).

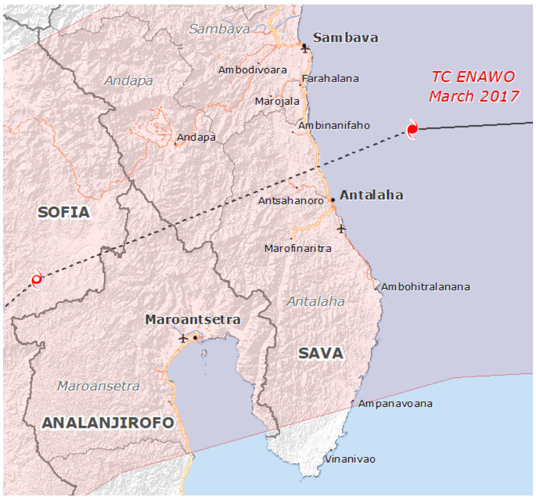
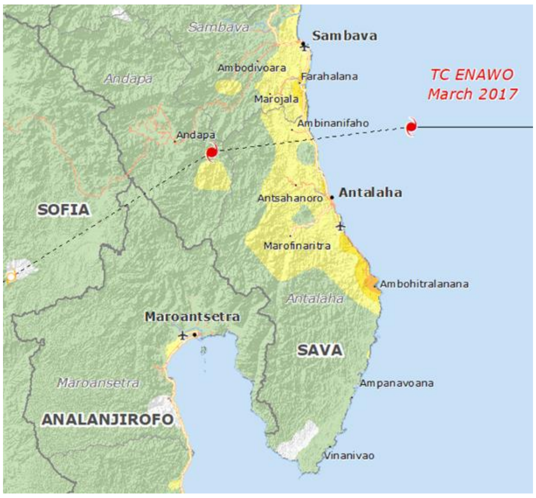
GDACS – Current System *(JTWC)*	**GDACS - New System** *(NOAA-HWRF)*
	

Figure 48 *– Forecast of 7 March 2017, 06:00 UTC: GDACS vs HWRF.*
GDACS wind buffer (red area winds> 118km/h), HWRF max. winds (yellow areas >118 km/h, green areas 63-118 km/h)

d) *Global Population Datasets used to calculate the exposed population*

The current GDACS alert level for the TCs is based on wind speed, population and vulnerability (see Annex 1). The differences between the global datasets used for the exposed population could contribute to a different number of people affected, influencing significantly the alert level. For a better estimation of the affected population and the related alert level, the JRC is testing new global population datasets (Global Human Settlement Layer – GHSL, 250m resolution), as shown in the Technical Annex.

e) Track/intensity Uncertainty

The number of people affected depends from the TC forecasts: track and intensity. These values could change significantly from one TC bulletin to another one and from models to models (see Annex 3 and **Figure 49**).

The variation of the number of people affected due to the uncertainty of the forecasted track and intensity is clear in **Figure 46**, where the number of affected people estimated by GDACS varied among the various TC bulletins (see Section 3.4).

Therefore one of the most important factor contributing to the variation of the number of people affected is the uncertainty on the forecasted track and intensity.

JRC is developing a system that includes more than one single model (see Annex 3).

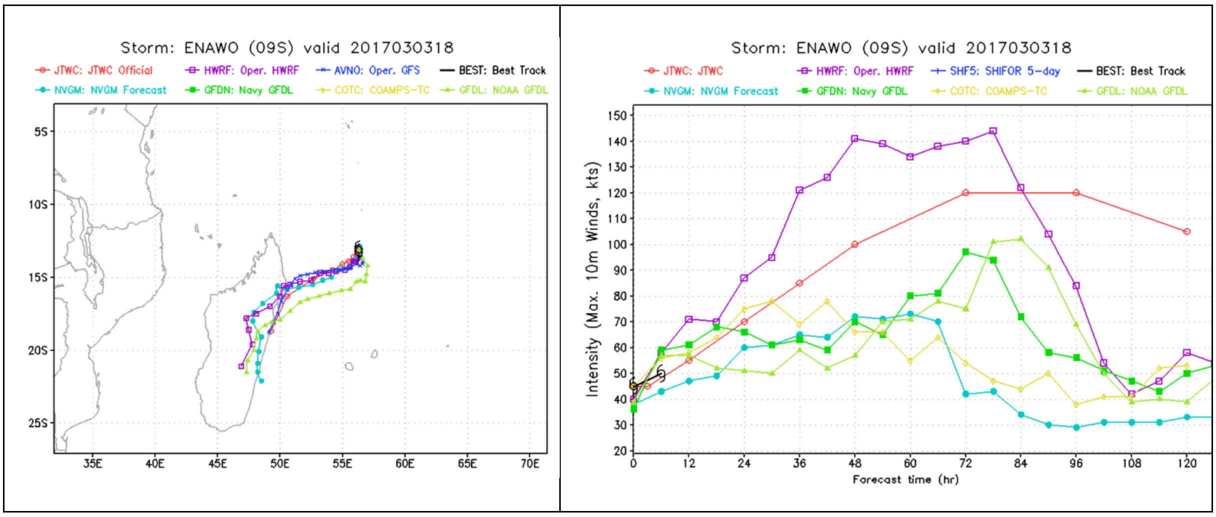


Figure 49 - *TC ENAWO's Track (left), max. 1-min sustained winds (right), as of 3 Mar 2017 18 UTC*
Source: NOAA-HWRF

All aspects described above could contribute to a different number of people affected and consequently to a **different alert level**. Therefore it is important to introduce an **ALERT UNCERTAINTY** in the alert systems and communicate this uncertainty. In order to improve the impact estimation and the alert level, the JRC is developing several new systems described in the **Technical Annex**.

6. Conclusions

This report is the first POST-EVENT Report prepared by the JRC and the event analysed is Tropical Cyclone (TC) ENAWO, that hit Madagascar on 7 March 2017, killing more than 80 people and causing extensive damage, especially in Sava and Analanjirofo regions. Global Disaster Alert and Coordination System (GDACS) issued the first RED alert on 3 March, ERCC (Emergency Response Coordination Centre) of DG ECHO activated All Risk Integrated System TOwards Trans-boundary hoListic Early-warning (ARISTOTLE) on 5 March and the Copernicus Emergency Management Service (EMS) on 7 March.

JRC has analysed the impact estimated by different systems before the landfall, comparing the results with the damage reported by national authorities after the landfall. This analysis showed a difference between the number of people potentially affected estimated before the landfall and the number reported after the landfall. JRC has analysed the possible reasons of this difference, like the terminology used for "population affected" and the track/intensity uncertainty (see Section 5). This analysis showed the importance of:

- establish a common terminology (population affected) and thresholds for the alerts
- improve the current systems: new datasets (TC and global population)
- track / intensity uncertainty: comparisons between various models
- create and communicate the alert level uncertainty

In order to take into account all the points above and improve the current system, the JRC is developing several new tools for the analysis of the TC impacts and evaluate their potential risks. The first preliminary results presented in the Technical Annex of this report.

- <u>TC impact:</u> New atmospheric data with higher resolution (NOAA-HWRF) and new classifications for wind and rainfall impact to provide a more detailed number of people potentially affected for each threshold.
- <u>Global Population:</u> New Global population with higher resolution (GHSL). The higher resolution would allow to perform more detailed estimation of the exposed population to a specific disaster. The results of the comparison between LandScan™ (1 km resolution) and GHSL (250 m resolution), allow to use GHSL in GDACS.

The analysis conducted in this report showed the importance of the "ALERT UNCERTAINTY". It is therefore important to CREATE and COMMUNICATE the alert level uncertainty.

Therefore the JRC is currently working on the development of a new system able to calculate the "ALERT SCORE" and estimate the proper "LEVEL OF UNCERTAINTY", considering all the points mentioned above that contribute to a different GDACS alert level.

Concluding, for each disaster, it could be very useful to collect all the information available into a single database including:

- Reports, maps, websites (e.g. Virtual OSOCC, Reliefweb)
- Historical events (e.g. EM-DAT CRED)
- Background information: Population, climatological information
- General information on the natural disaster

In the future it will be possible to analyse the new events with different and more effective tools.

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List of abbreviations and definitions

ACAPS	Assessment Capacities Project
ARISTOTLE	All Risk Integrated System TOwards Trans-boundary hoListic Early-warning
BNGRC	Bureau National de Gestion des Risques et Catastrophe
CRED	Centre for Research on the Epidemiology of Disasters
DDR	Disaster Risk Reduction
EC	European Commission
DG ECHO	Director General for European Civil Protection and Humanitarian Aid Operations
ECMWF	European Centre for Medium Weather Forecast
EM-DAT	Emergency Events Database
ERCC	Emergency Response Coordination Centre of DG ECHO
FAO	Food and Agriculture Organization of the United Nations
GDACS	Global Disasters Alerts and Coordination System
GFS	Global Forecasting System
GHSL	Global Human Settlement Layer
GPM	Global Precipitation Measurement
HWRF	Hurricane Weather Research and Forecast System
IOM	International Organization for Migration
JRC	Joint Research Centre
JTWC	Joint Typhoon Warning Center
MTCSW	Multiplatform Tropical Cyclone Surface Winds Analysis
NESDIS	National Environmental Satellite, Data, and Information Service
NHC	National Hurricane Centre
NOAA	National Oceanic and Atmospheric Administration
NWS	National Weather Service
PDC	Pacific Disaster Centre
RSMC	Regional Specialized Meteorological Centres
SSHS	Saffir Simpson Hurricane Scale
TC	Tropical Cyclone
TCWC	Tropical Cyclone Warning Centres
UNICEF	UN Children's Fund
UNISDR	United Nation Office for Disaster Risk Reduction
UNITAR	United Nations Institute for Training and Research
UN OCHA	United Nation Office for the Coordination of Humanitarian Affairs
UNOSAT	UN Operational Satellite Applications Programme
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting

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Annexes

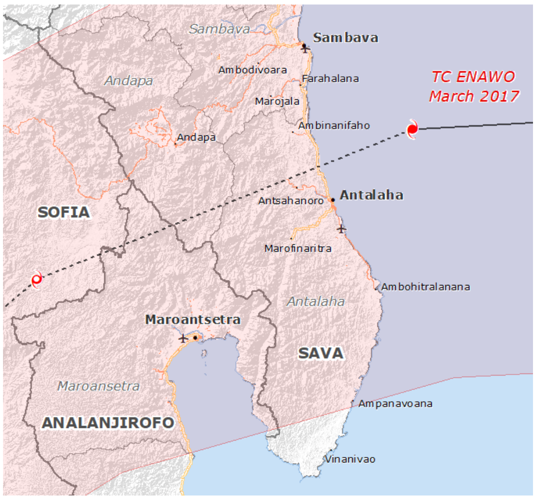
Technical Annex: *Future developments to improve the impact estimation*

A. TC effects: new data and classifications

A.1 Methodology

The system used for the TCs in GDACS is currently based on the TCs bulletins provided by the JTWC and NOAA (see Annex 1). This system has some limitations, especially it overestimates the number of people potentially affected by strong winds. As shown in **Figure 50**, GDACS overestimated the area potentially affected by winds > 118 km/h (red area in the left map, compared to the new results using the new system described below (yellow area in the right map).

GDACS – Current System (*JTWC*)



GDACS - New System (*NOAA-HWRF*)

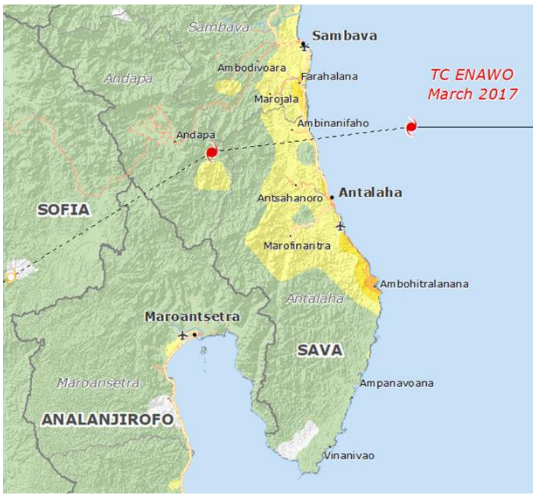


Figure 50 *– Wind buffer according to the forecast of 7 March 2017, 06:00 UTC: GDACS vs HWRF. GDACS (red: winds > 118 km/h), HWRF (yellow: >118 km/h, green: 63-118 km/h)*

To improve the current system, JRC is developing several new tools, introducing:

- **New input procedures** (e.g. new atmospheric data like NOAA-HWRF)
- **New classifications** (e.g. new wind & rainfall thresholds)

Several data sources could be used to obtain the TC forecast information: TC bulletins, Numerical Weather Forecasts (e.g. global scale, regional scale). JRC is testing the following atmospheric inputs described in Annex 2:

1. NOAA – HWRF
2. ECMWF - HRES
3. NOAA – GFS

JRC has recently implemented a new storm surge system that uses as input these atmospheric data and the Deltares Delft3D[23] code (see Probst et al., 2016) and it is developing a new system able to use these data sources also for the other two effects: Wind and Rainfall. The first preliminary results of the system developed for the HWRF data are presented in this Annex.

[23] https://oss.deltares.nl/web/delft3d

In order to have a more detailed number of people affected, JRC is using a new classification method for the TC effects to estimate the population potentially affected by a TC.

It should be noted that the new system calculates only the population potentially affected for each category, but doesn't provide a GDACS alert. The JRC is working to create a proper alert system that includes all the different forecasts, effects, population and vulnerability.

Wind Classification

The new system that the JRC is developing is based on the intensity equivalent to the Saffir-Simpson Hurricane Wind Scale (SSHS)[24], instead of using one single class for the Hurricane/Typhoon winds (≥ 119 km/h, GDACS red buffer). This new classification is shown in the table below.

CATEGORY	1-min Sustained Winds	
	knots	km/h
Cat. 5	≥ 137	≥ 252
Cat. 4	113 - 136	209 - 251
Cat. 3	96 - 112	178 - 208
Cat. 2	83 - 95	154 - 177
Cat. 1	64 - 82	119 - 153
Tropical Storm	34 – 63	63 - 118
Tropical Depression	≤ 33	≤ 62

Table 17 *– Wind classification (Cat. = Category equivalent to SSHS)*

The method includes the calculation of the total population potentially affected by the following three thresholds, that correspond to a Tropical Storm, Category 1 Hurricane and Category 3 Hurricane (Major Hurricane)

Total population potentially affected by winds	
Winds	**Category**
> 63 km/h	From Tropical Storm to Cat 5
> 118 km/h	From Cat 1 to Cat 5
> 177 km/h	From Cat 3 to Cat 5 (≥ Cat. 3 equivalent to a Major Hurricane)

Table 18 *- Wind classification - Cumulative*

[24] Saffir-Simpson Hurricane Wind Scale is a 1 to 5 rating based on a hurricane's sustained wind speed (see http://www.nhc.noaa.gov/aboutsshws.php). This scale estimates potential property damage. It's the official scale used by NOAA for the Atlantic and East Pacific TC basins.

Wind Alert: This new system provides the population potentially affected for each category and the cumulative, but does not yet provide a GDACS alert. It is important to note that the damage produced by a TC does not increase linearly from one category to another one, but the potential damage increment is logarithmic, then small increases in wind strength can lead to increasingly greater damage potential. In the Figure below the Damage Potential Multiplier (data source: NOAA) is reported as an example to show this difference between the damage potential produced by different TC intensities.

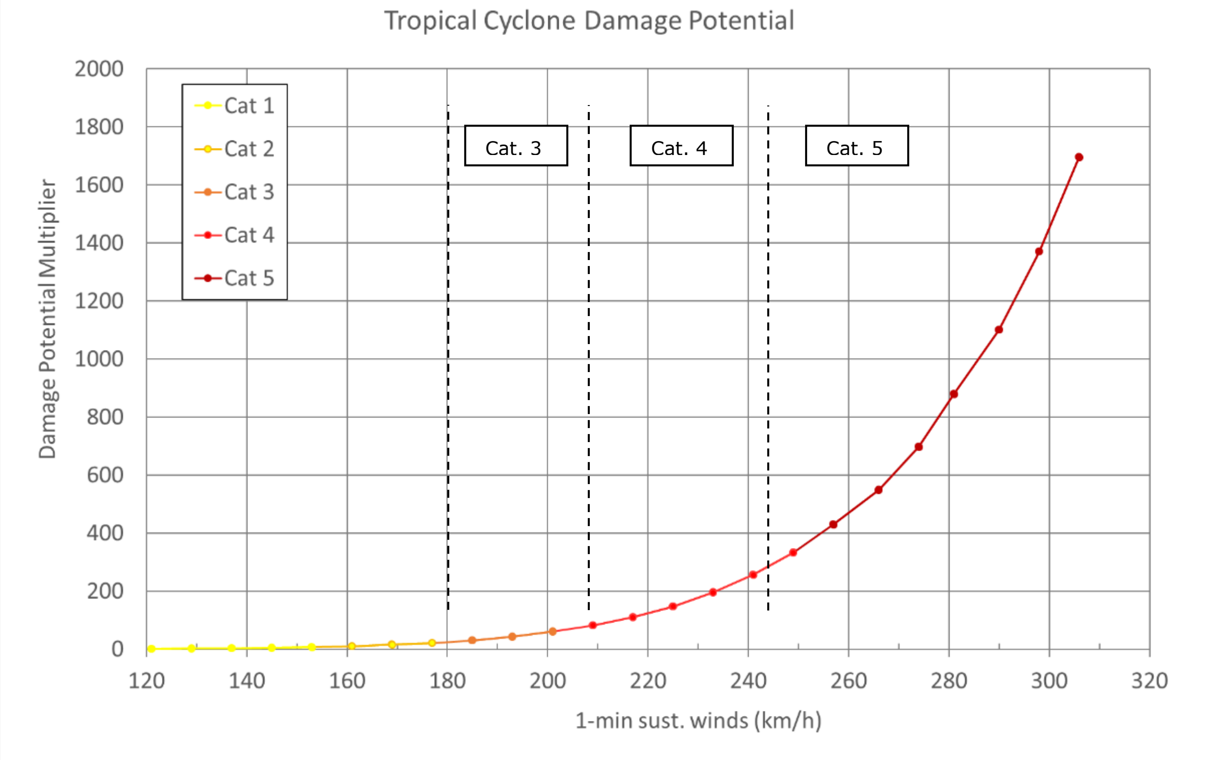


Figure 51 *– Example of Tropical Cyclone Damage Potential*
(data source: NOAA http://www.srh.noaa.gov/jetstream/tropics/tc_potential.html)

Storm surge Classification

The classification used in this system is the same of the one used for the current GDACS alerts (see Annex 1) and it is based on the maximum storm surge height calculated by the JRC systems.

Rainfall Classification

In this analysis, the classification shown in **Table 19** has been adopted, using as input the NOAA HWRF total rainfall accumulation over 126 h. For each class, the cumulative value has been calculated (for example the total population potentially affected by rainfall > 500 mm / 126h).

This system provides the population potentially affected by different interval of rainfall.

However it's is important to note that this is only a preliminary analysis on the Total accumulation and not on the **rain rate (mm/h)**, which is a key factor for an alert system.

The heaviest precipitation occurs where the rainfall rate is the highest for the longest period of time.

Total rainfall accumulation (mm/126h)
50 - 100 mm
100 – 250 mm
250 – 500 mm
500 – 750 mm
750 – 1 000 mm
> 1 000 mm

Table 19 *- Rainfall classification*

Rainfall Alert: the following factors must be taken into account to define a Rainfall Alert:

- **Total accumulation:** Forecast of the total rainfall accumulation during the passage of the TC.
- **Rain rate:** Forecast of the rainfall rate (mm/h or mm/24 h).
- **Vulnerability:** Vulnerability of the country to TCs (rainfall effect)
- **Climatological information** (see Annex 6): This is a key factor for the alert system. It is important to understand if the forecasted rainfall is above or below the average rainfall.
- **Past rainfall:** If the area has been recently affected by heavy rainfall and floods there could be major risk and damage.

The next step will be to create a specific alert for each rainfall class considering the aspects above, however it is important to note that **it is not a flood, flash floods & landslides forecast system.**

A.2. Impact estimations

In this analysis the results of the NOAA Hurricane Weather Research and Forecast (HWRF) model for TC ENAWO[25] have been used (see description in Annex 2).

Track and intensity

The forecasted track of all the bulletins available are shown in the map below, while the maximum sustained winds forecasted for each TC bulletins can be found in **Figure 52.** As can be seen the landfall area in Sava Region was identified the first time on 3 March at 18:00 UTC, while the forecast of the maximum sustained winds of the 3-7 March forecasts varied from 220 km/h (Cat. 4) to 280 km/h (Cat. 5), see **Figure 52**.

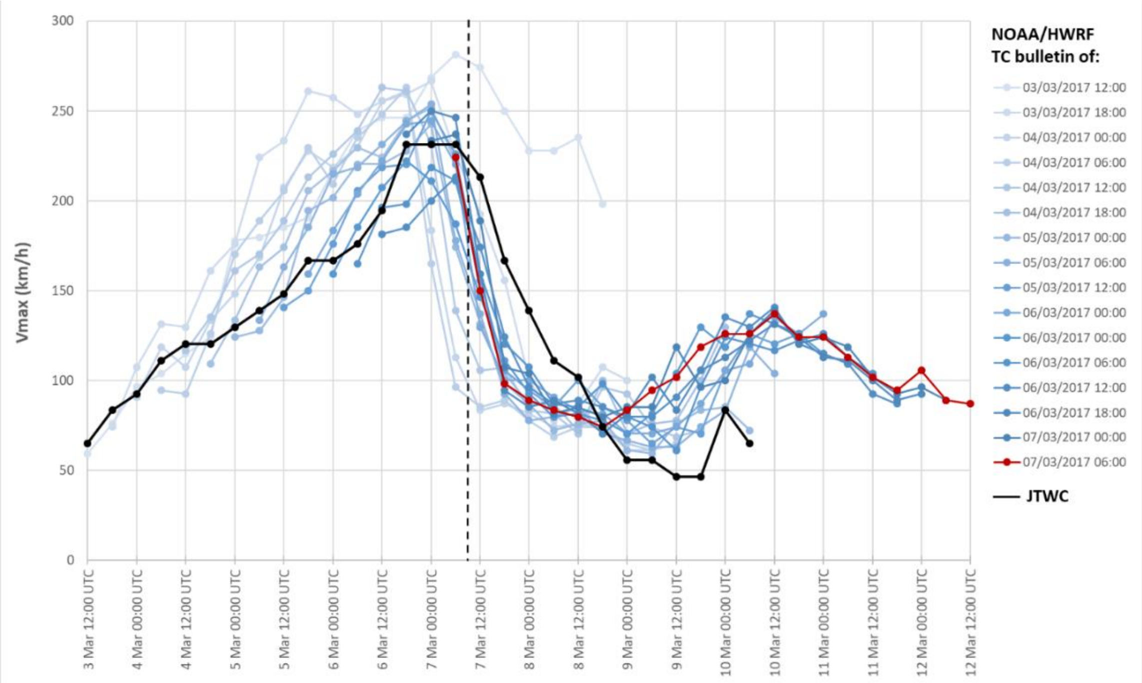


Figure 52 *- HWRF forecasts: maximum winds for each bulletin. Red line: last bulletin before the landfall. Black dotted line: Landfall time. Black line: Best Track JTWC.*

Population potentially affected

JRC has analysed the population potentially affected for all HWRF forecasts. In this report only the results for the following bulletins are presented on the next pages:

NOAA-HWRF	
4 March 06:00 UTC	Three days before the landfall
5 March 06:00 UTC	Two days before the landfall
6 March 06:00 UTC	One day before the landfall
7 March 06:00 UTC	Few hours before the landfall
7 March 12:00 UTC	First bulletin available after the landfall
7 March 18:00 UTC	After the landfall

Table 20 *-List of Forecasted maps included in* ***Figure 54***

[25]NOAA/HWRF:http://www.emc.ncep.noaa.gov/gc_wmb/vxt/HWRF/tcall.php?selectYear=2017&selectBasin=Southern+Hemisphere&selectStorm=ENAWO09S

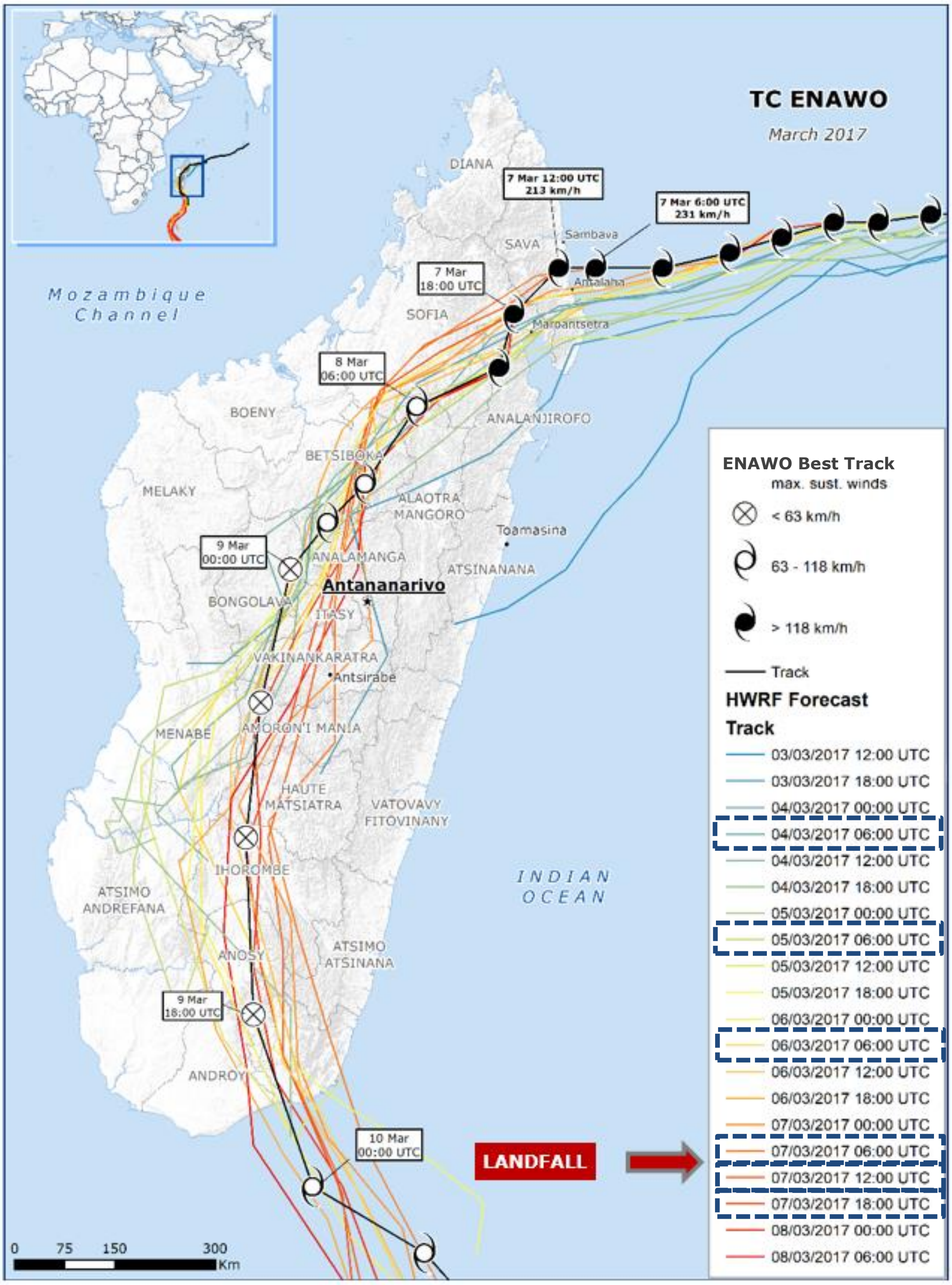


Figure 53 *- Forecasted track of TC ENAWO (data source: HWRF)*

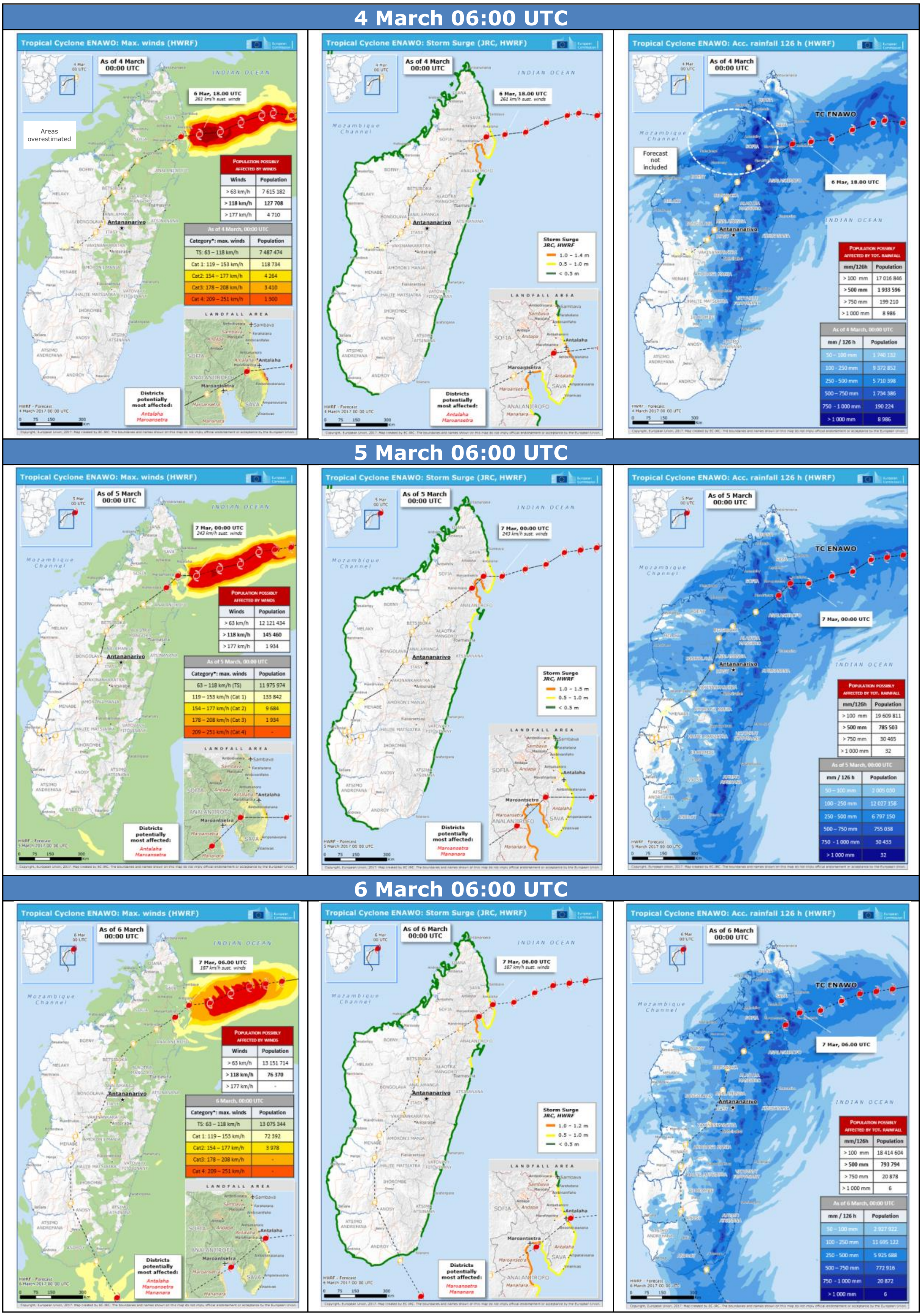


***Figure 54 -** Wind impact (left), storm surge (middle), rainfall (right), using the HWRF forecasts of 4 March 06:00 UTC (top), 5 March 06:00 UTC (middle), 6 March 06:00 UTC (bottom). The population potentially affected for each class (Table 17- Table 19) are included.*

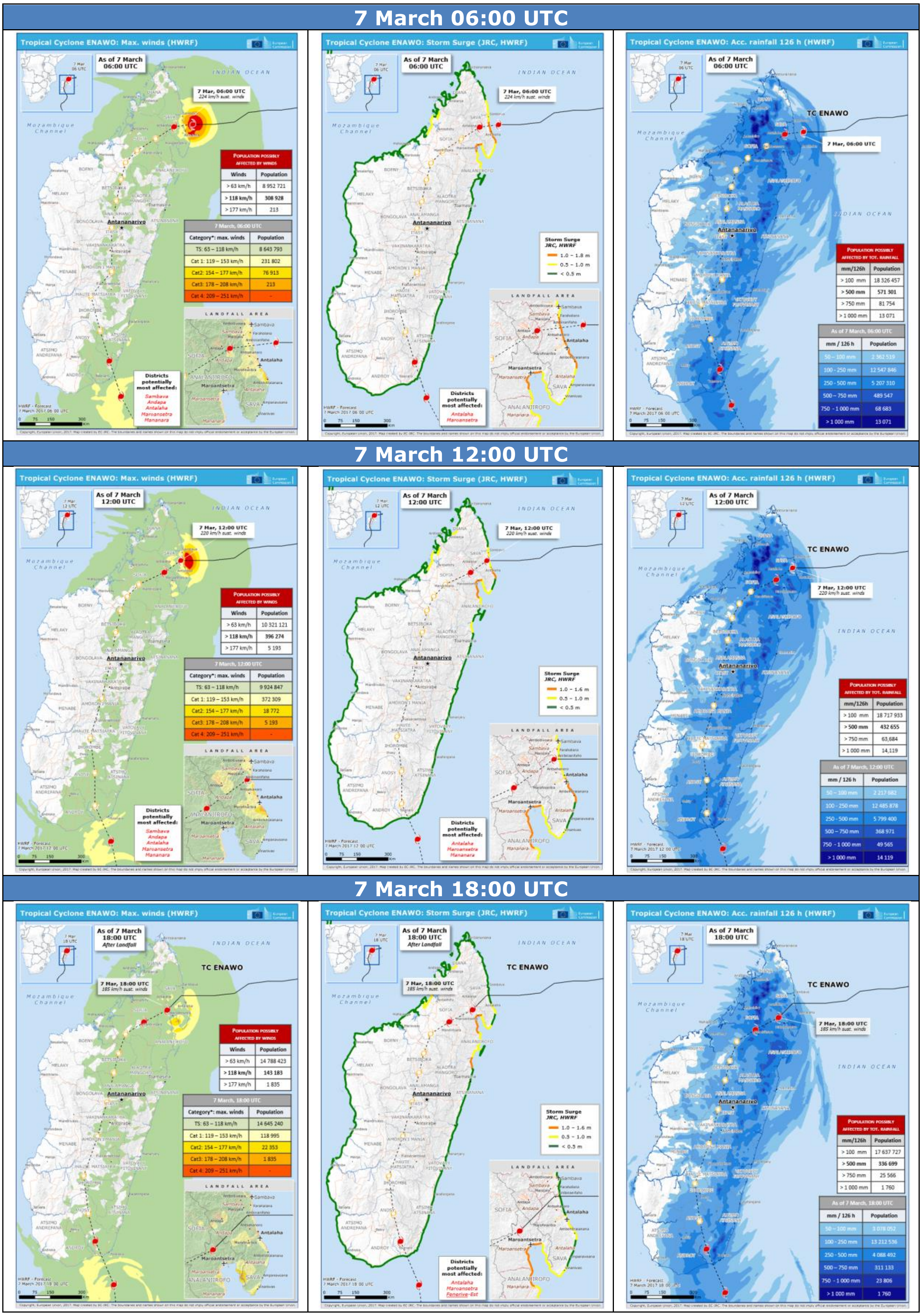


***Figure 55** - As in **Figure 54**, but for 7 March 06:00 UTC, 12:00 UTC and 18:00 UTC.*

a) WIND EFFECT

The total number of people affected reported by BNGRC is 434 000 (see Section 2.2). This number has been compared with the number of people potentially affected obtained using the HWRF forecasts and the wind classes shown in **Table 22**. The results are shown in **Figure 56** (logarithmic scale). It's important to note that the number of people potentially affected change significantly varying the forecasted track as shown in this figure.

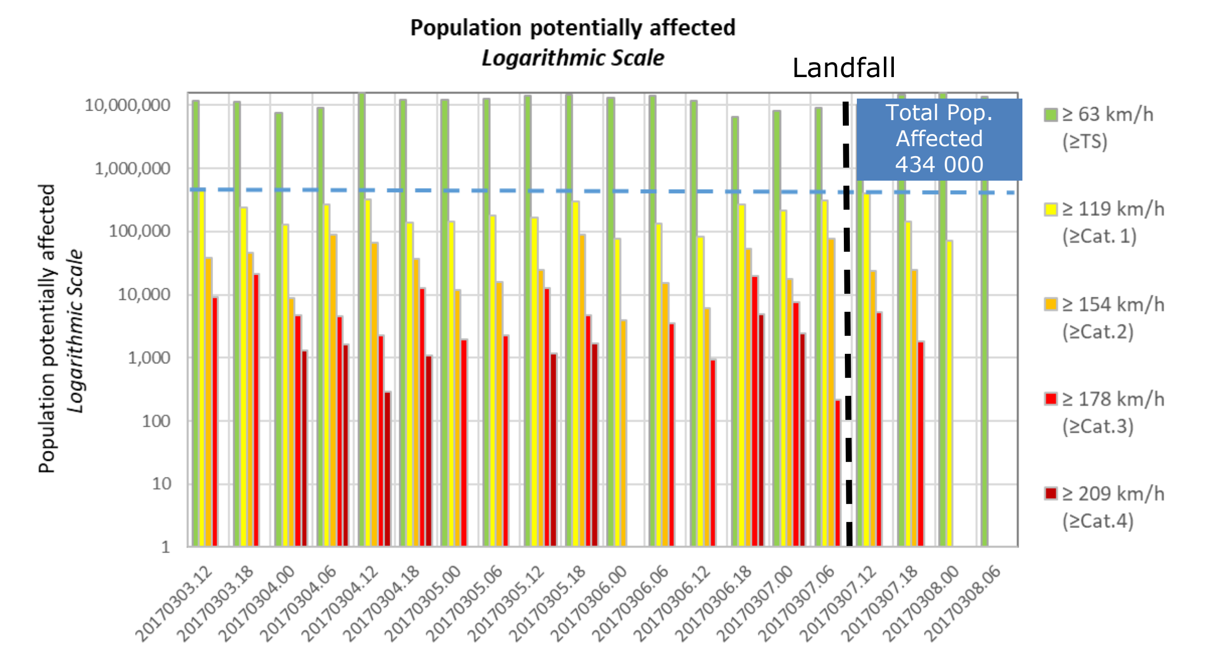


***Figure 56 -** Population potentially affected by strong winds calculated using HWRF forecasts. Blue dotted line: tot. population affected reported by national authorities. Black dotted line: landfall time*

The "wind class" having the total number of people closest to the number of people affected of BNGRC (all three effects) is:

Winds ≥ 119 km/h *(26)*

While the threshold of ≥ 63 km/h (Tropical Storm condition) provides a number of people affected too large compared with the total number of people affected (see **Figure 57**).

In addition to the threshold of 119 km/h, another one can be used to identify the areas particularly affected by very strong winds, like Antalaha district, that is

Winds ≥ 178 km/h *(3)*

Analysing the population potentially affected by strong winds during the passage of TC ENAWO the districts potentially most affected are Antalaha and Maroantsetra. This is consistent with the damaged reported.

Region	**District**
SAVA	***Antalaha***
ANALANJIROFO	***Maroantsetra***

[26] *1-min sustained winds ≥ 118 km/h is equivalent to a Category 1 in the SSHS, while ≥ 177 km/h is equivalent to a Category 3 (Major Hurricane), see* ***Table 17***.

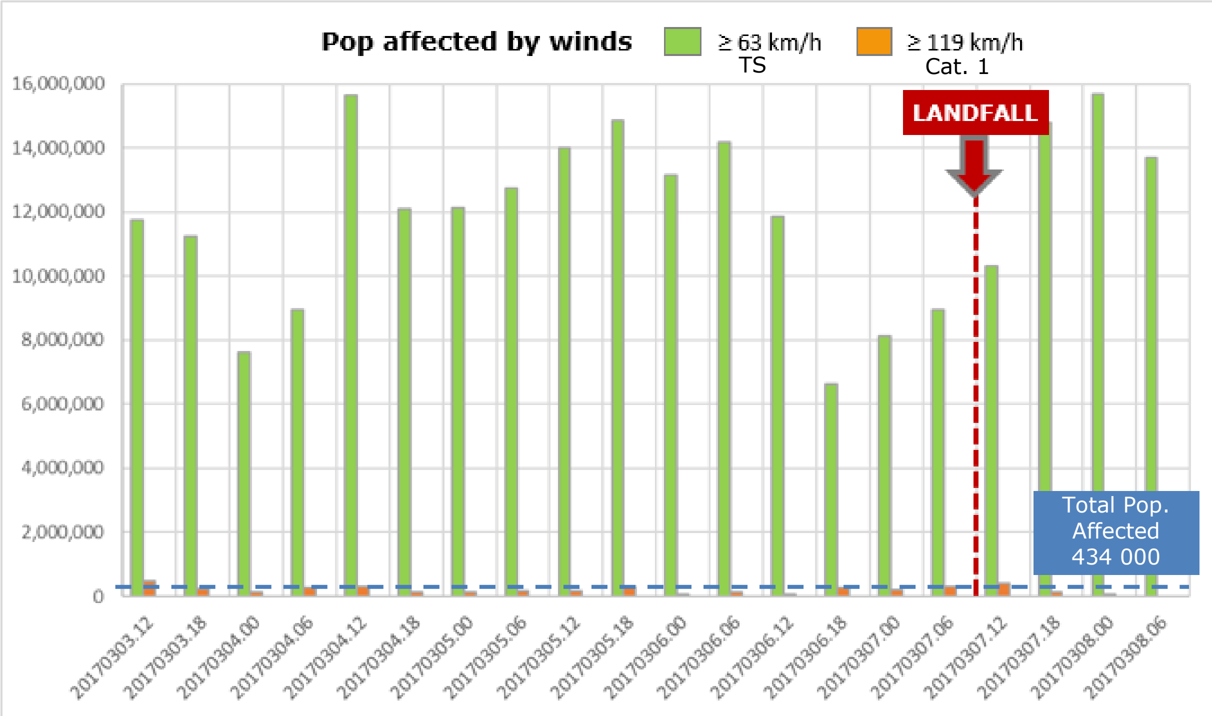


Figure 57 - *Population potentially affected by strong winds calculated using HWRF forecasts. Green bars: population potentially affected by winds ≥ 63 km/h, Orange bars: winds ≥ 119 km/h*

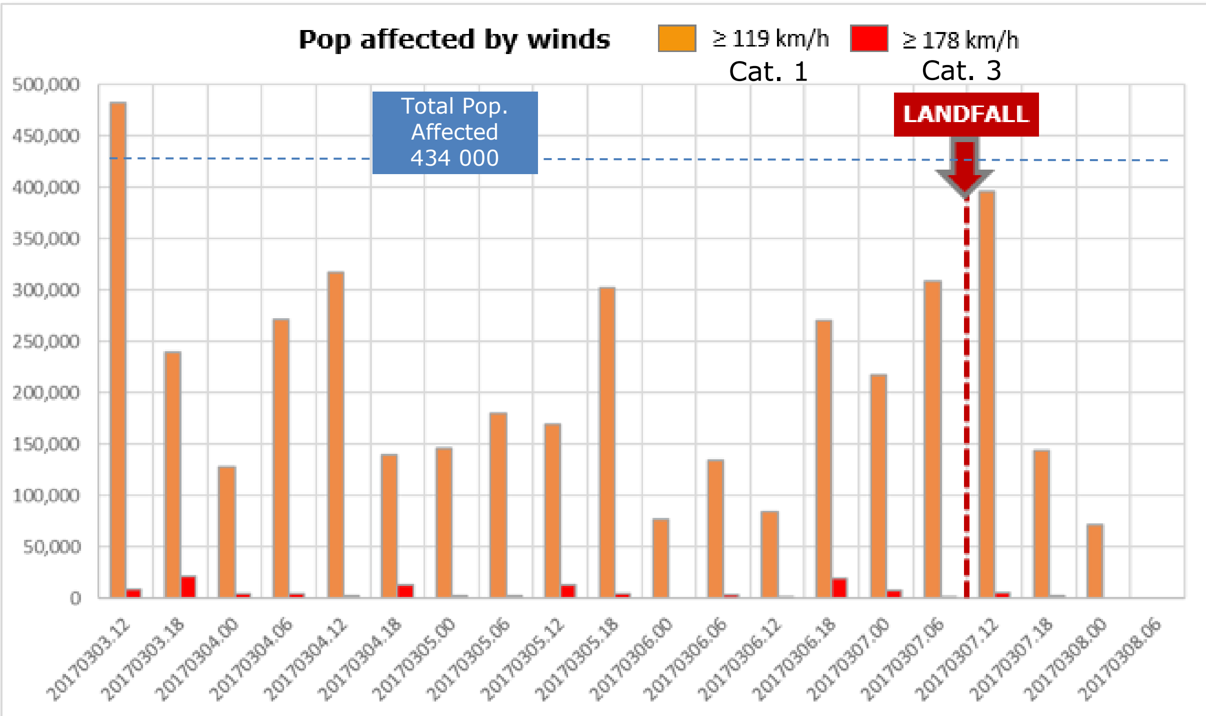


Figure 58 *– As in **Figure 57**, but Orange bars: winds > 119 km/h, Red bars: > 178 km/h*

b) STORM SURGE EFFECT

Analysing the population affected by storm surge during the passage of TC ENAWO the districts potentially most affected are shown in the table below.

Region	District
SAVA	***Antalaha***
ANALANJIROFO	***Maroantsetra***

The thresholds that could be used to define the area potentially affected is **> 1 m**.

This result is consistent with the damaged reported, but there are not sea level measurements available to validate this new system (see Section 2.1.1.3). However the results based on three different JRC calculations are presented in the figure below. As can be seen, the values of storm surge estimated using HWRF are higher than the results of using the atmospheric forcing of ECMWF and the GDACS results (wind radii method).

Note: For the moment this system doesn't calculate the population potentially affected but provides only the storm surge height along the coast.

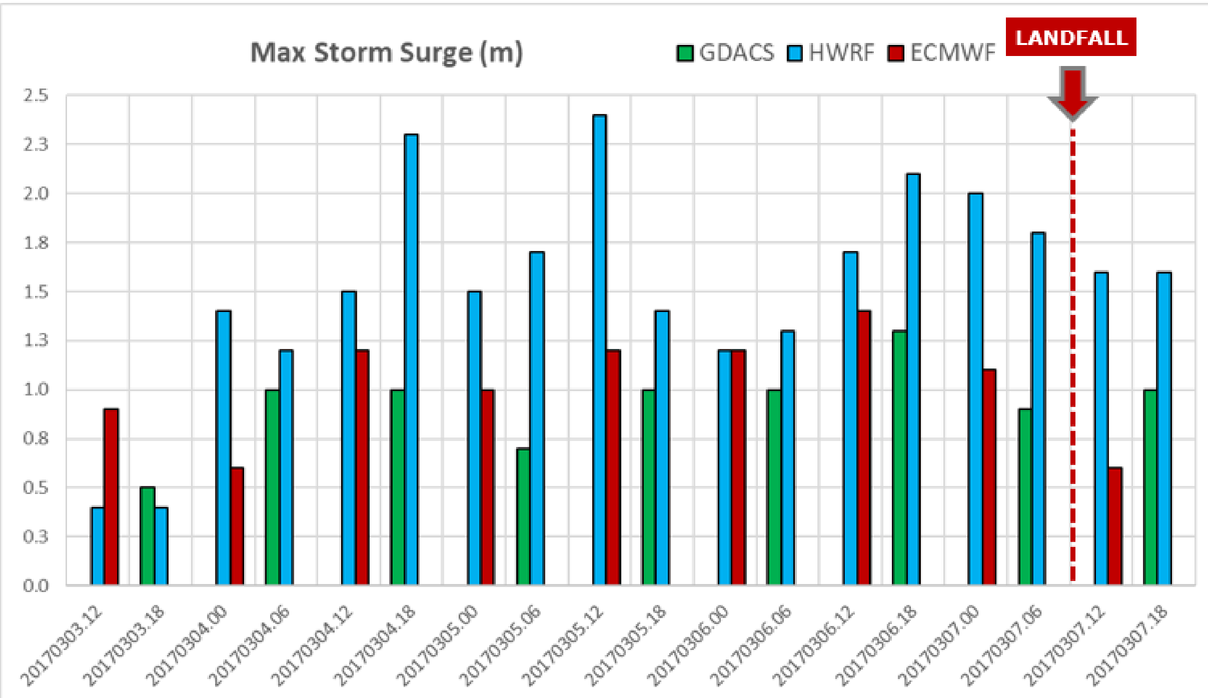


Figure 59 *– Maximum storm surge calculations for each forecast. Green bars: Maximum storm surge estimated by JRC-GDACS (wind radii method), Blue bars: JRC (HWRF atmospheric input), Red bars: JRC (ECMWF atmospheric input)*

c) RAINFALL EFFECT

Analysing the population affected by heavy rains (> 500 mm/126h) during the passage of TC ENAWO several districts of the eastern part of Madagascar were potentially affected by heavy rains. These results are consistent with the damaged reported (see Section 2.2) However this system underestimated the possible impact in Maroantsetra, where there was a problem with a dam, according to media reports (see **Figure 10** and Section 2.2.2).

It should be noted that the number of people potentially affected change significantly varying the forecasted track as shown in the figure below. However considering the total number of people affected of **434 000** that includes all three effects, the threshold that could be used is:

Total rainfall accumulation ≥ 500 mm /126 h (*)

(*) This threshold is valid for this analysis. A more general threshold has to be decided introducing also the climatology information and vulnerability of the area (see Page 69)

The threshold of > 250 mm/126h provides a number of people affected too large compared with the total number of people affected (see **Figure 60**), while the thresholds > 750 mm/126h provides a number of people affected too small (see **Figure 61**).

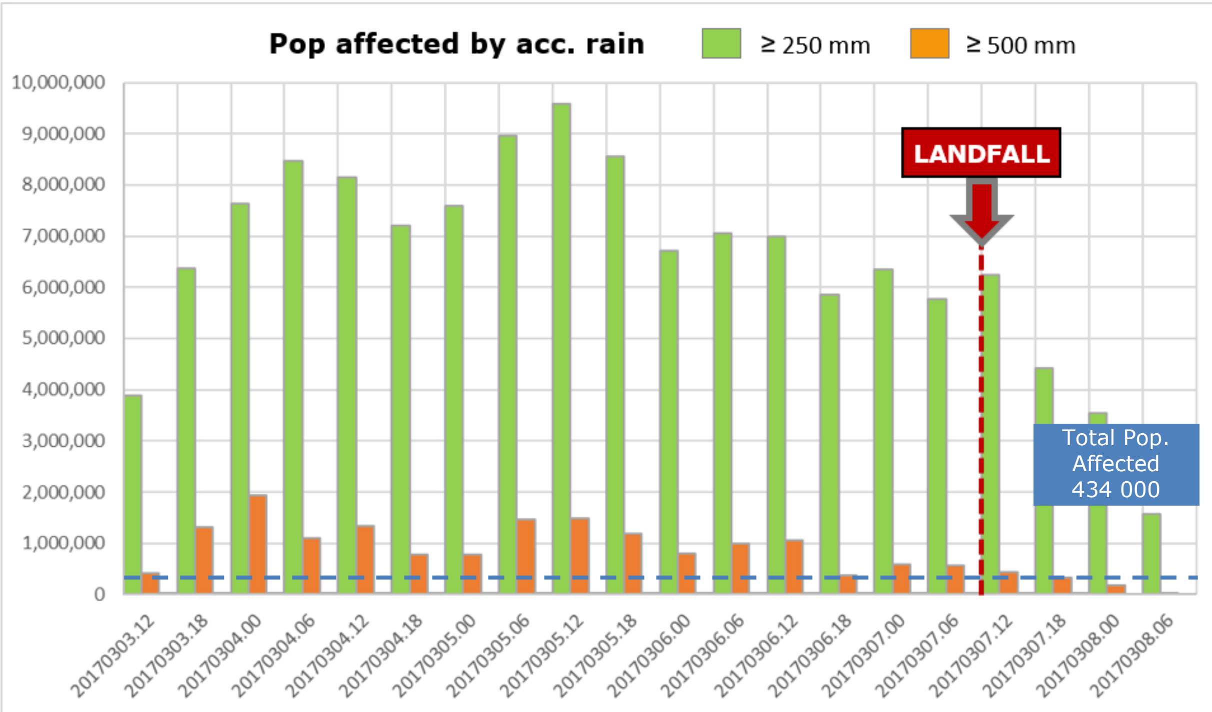


Figure 60 *- As in **Figure 57**, but for accumulation rainfall (mm/126h). Green bars: acc. rainfall mm/126h ≥ 250 mm. Orange bars: acc. rainfall mm/126h ≥ 500 mm.*

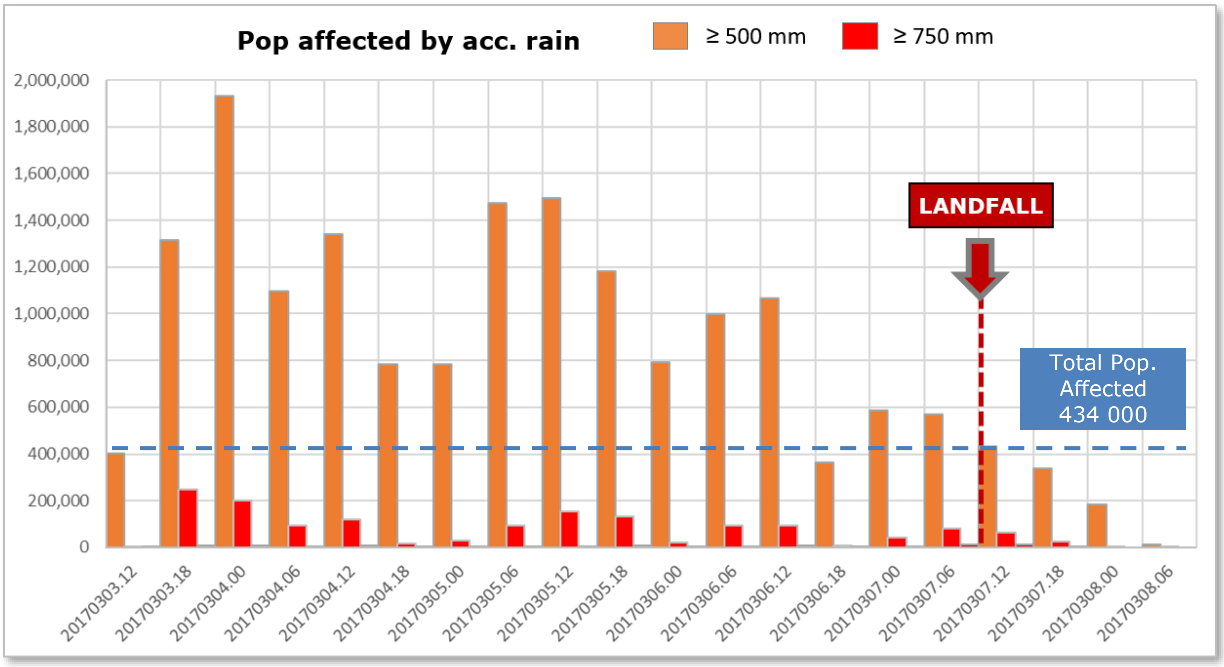


Figure 61 *- As in **Figure 61**, but for accumulation rainfall (mm/126h). Orange bars: acc. rainfall mm/126h ≥ 500 mm. Red bars: acc. rainfall mm/126h ≥ 750 mm.*

<u>NOAA-HWRF vs NASA-GPM</u>

The rainfall forecasted by HWRF on 7 March 00:00 UTC has been compared with the rainfall observed from satellite (NASA-GPM). In this comparison seems that HWRF overestimated the total amount of rainfall. The total population affected, according to NOAA-HWRF and NASA-GPM data for each rainfall class is also shown in this figure.

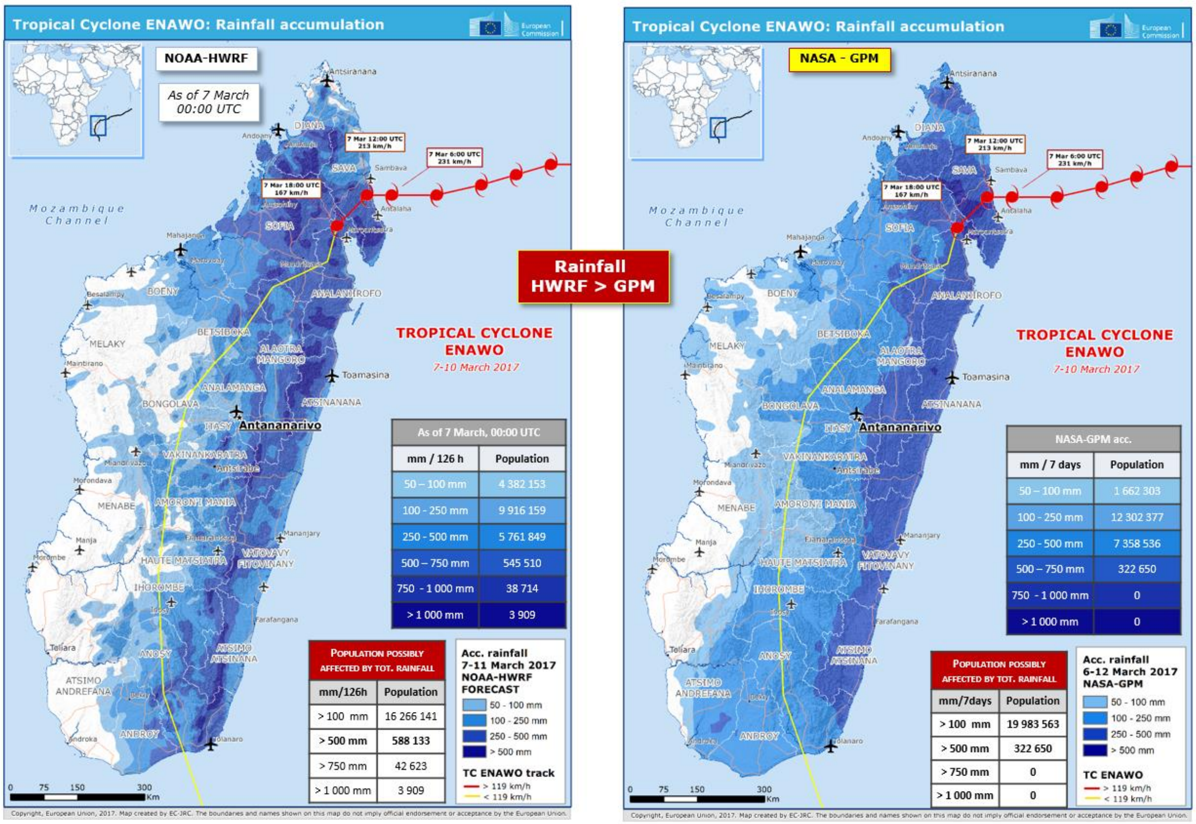


Figure 62 *- Rainfall comparison between NOAA-HWRF and NASA GPM.*

NOAA-HWRF vs Monthly Average Rainfall

The rainfall forecasted by HWRF on 7 March 00:00 UTC (accumulation over 126h, ~5 days) has been compared with the average rainfall of March obtained using the climate data of WorldClim 2.0[27] (see Fick and Hijmans, 2017) to identify the areas most affected by heavy rainfall. The results are presented in **Figure 63**: the areas where the forecasted rainfall due to TC ENAWO is higher than the monthly average are shown in blue.

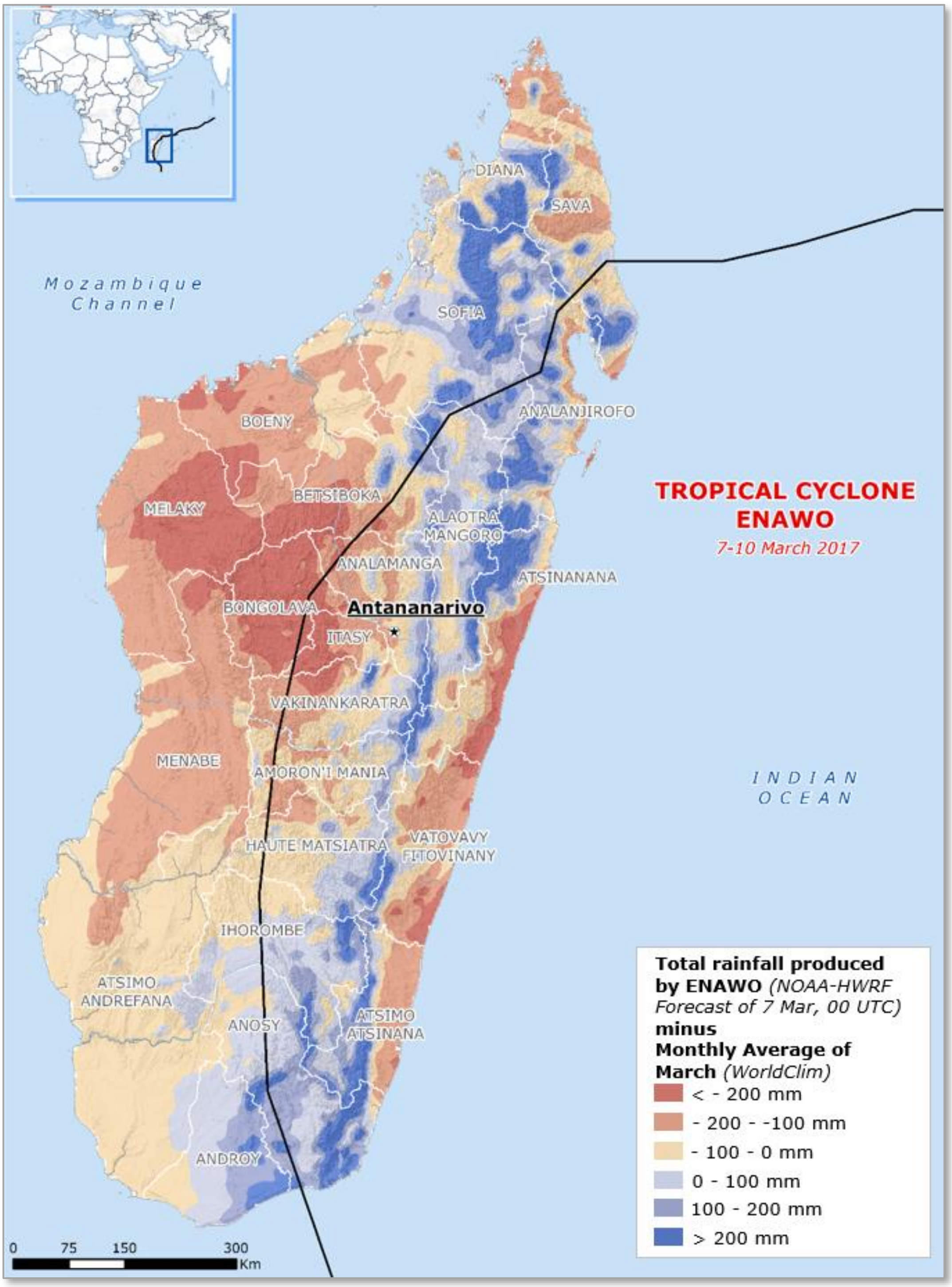


Figure 63 - *Total rainfall produced by TC ENAWO forecasted by NOAA-HWRF (as of 7 March 00:00 UTC) minus the average monthly rainfall mean of March using the climate data of WorldClim 2.0 (see Fick and Hijmans, 2017).*

[27] See Fick and Hijmans, 2017. http://worldclim.org/version2

A.3. Impact estimations vs Damage reported

The impact estimations using the data of NOAA-HWRF have been compared with the damage reported after the landfall (see Section 2.2). The results of the analysis obtained using the the last HWRF bulletin available before the landfall (7 March 06:00 UTC) are reported below.

Based on this analysis:

Wind	the districts most affected (Antalaha and Maroantsetra) have been properly identified using the threshold of 119 km/h.
Rainfall	this system identify only the areas potentially affected by heavy rain and not the flooded areas (this system is not a flood forecast system). The inset map with the damage reported shows the number of houses flooded. The new method using the threshold of 500 mm/126 h identified the areas of heavy rainfall in the districts most affected by floods, but overestimated the areas potentially most affected in northern Madagascar. Moreover this threshold is valid for this analysis and this system doesn't identify the areas affected by landslides. A more general threshold has to be decided introducing also the climatology information and vulnerability of the area.

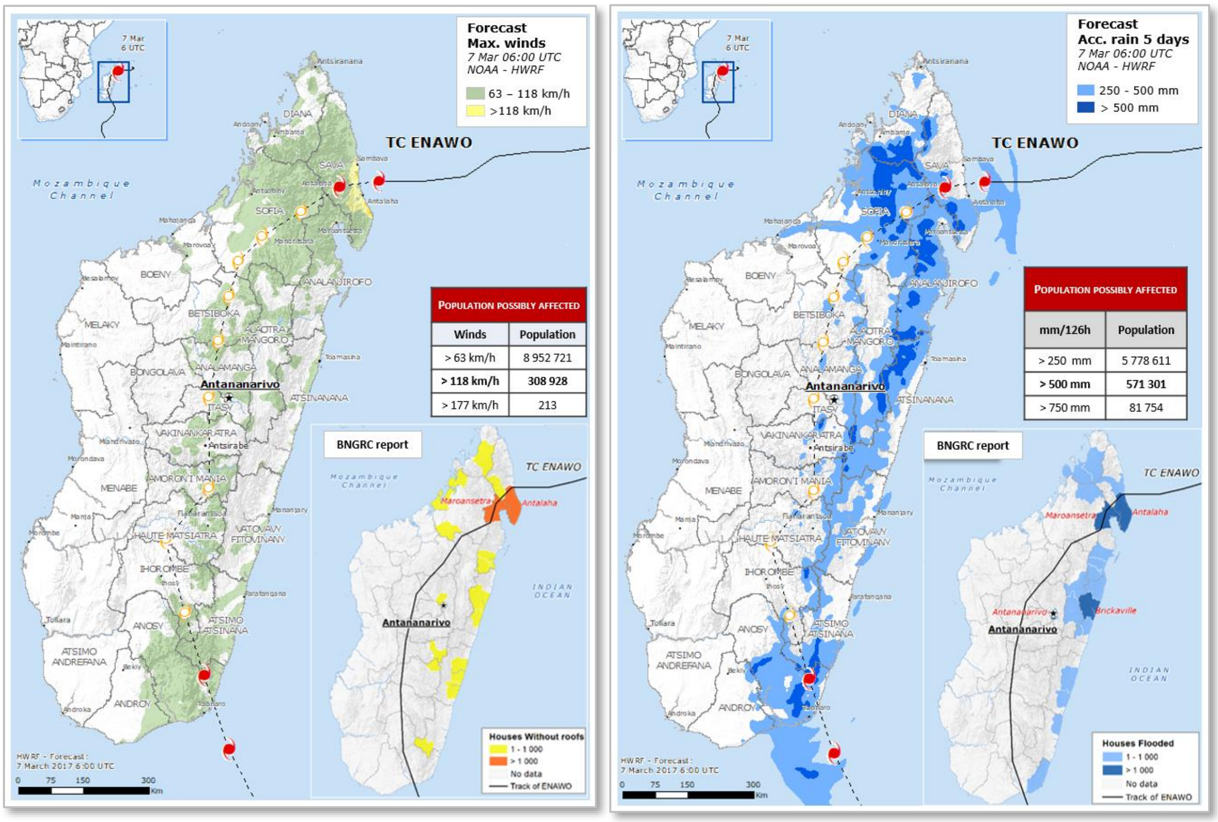


Figure 64 - *NOAA-HWRF forecasts vs damage reported by BNGRC. LEFT: wind, RIGHT: rainfall.*

B. Global population: new dataset and resolution

Exposure represents the people and assets at risk of potential losses or that may suffer damage to a hazard impact. It covers several dimensions like the physical (e.g. the built-up environment), the social (e.g. population distribution) and the economic dimensions. The exposed population to natural hazardous events is one of the factors considered in the GDACS alert system[28] (see Annex 1).

GDACS is currently using LandScan™ (1km resolution, see Table below). The challenge of using higher resolution data to estimate the exposed population at global level is discussed in this session. A comparison and related assessment of the GDACS alerts based on the available global population dataset is here proposed (**Figure 65**).

B.1. Global Population Datasets

The most complete and reliable population dataset available at global level are:

LandScan™	
Resolution	1km (30" X 30")
Source	http://web.ornl.gov/sci/landscan/
LandScan™ represents an ambient population (average over 24 hours). The LandScan™ algorithm uses spatial data and imagery analysis technologies and a multi-variable dasymetric modelling approach to disaggregate census counts within an administrative boundary.	

Global Human Settlement Layer (GHSL)	
Resolution	250m
Source	http://ghsl.jrc.ec.europa.eu/
The Global Human Settlement (GHS) framework produces global spatial information about the human presence on the planet over time. This in the form of built up maps, population density maps and settlement maps. This information is generated with evidence-based analytics and knowledge using new spatial data mining technologies. The framework uses heterogeneous data including global archives of fine-scale satellite imagery, census data, and volunteered geographic information. It is supported by the Joint Research Centre (JRC) and the DG for Regional Development (DG REGIO) of the European Commission, together with the international partnership GEO Human Planet Initiative.	

LandScan™ is the wider-used dataset to perform risk-analysis at global level, while the GHSL dataset is more recent but with a higher resolution (250m vs 1km). To assess the reliability of the two datasets in Madagascar, the population data at regional administrative level are compared to the population data provided by the National Statistical Office – NSO (see Annex 4).

[28] GDACS alert calculations: Risk = Severity of the event * Population Exposure * Vulnerability of the country

Total Population per regions *(National Statistical Office 2014)*	**Population Distribution** *(GHSL 2015, 250 m)*	**Population Distribution** *(LandScan™ 2014, 1 km)*

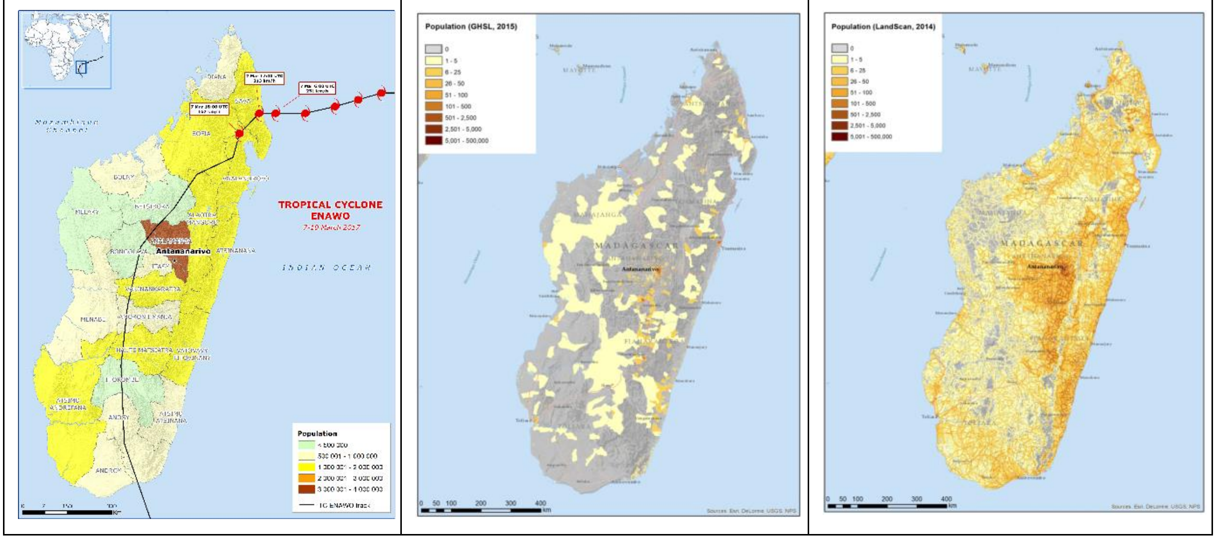


Figure 65 *- Population data for Madagascar: National dataset (National Statistical Office), GHSL2015 (JRC), LandScan™ 2014*

The preliminary comparison of the population data is performed at regional administrative level, without considering any hazardous event (**Figure 66**). At regional level, the comparison allow to calculate an average population ratio[29] compared to NSO's data of 0.09 for GHSL and 0.03 for LandScan™ (**Figure 67**). No significant differences have been detected at regional administrative level between the global datasets and the national dataset.

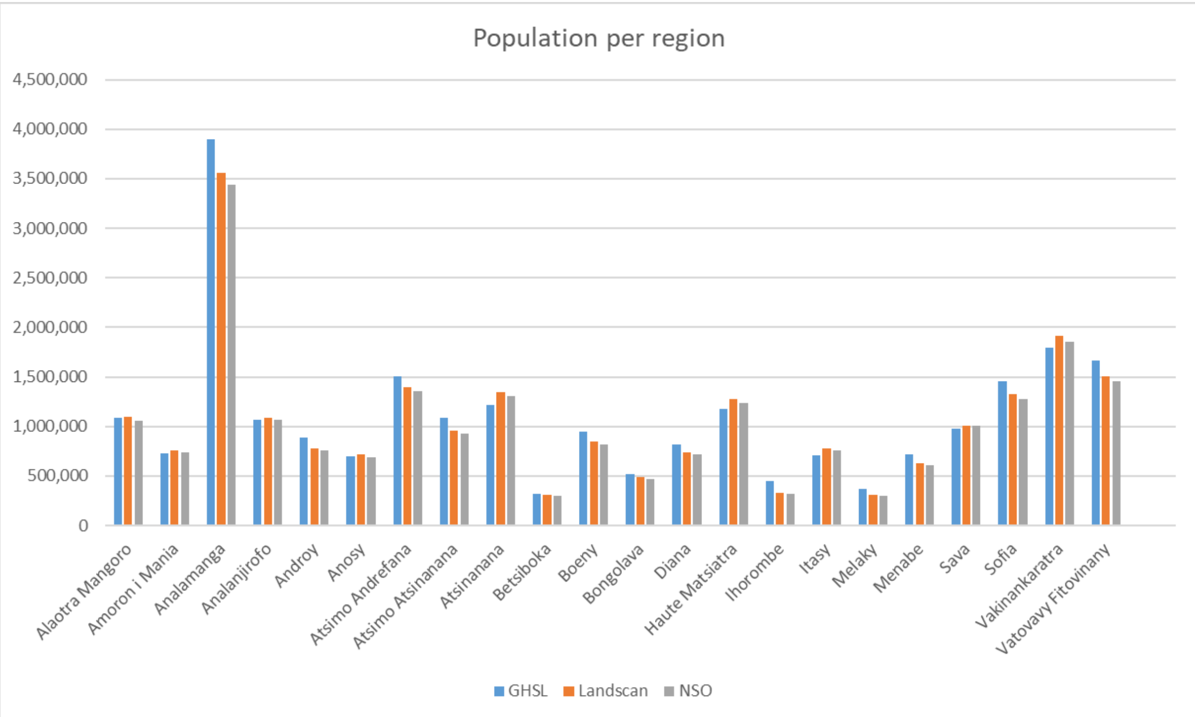


Figure 66 - *Regional comparison of the population data (GHSL, LandScan, NSO)*

[29] $\textit{Ratio Pop. per region} = \frac{\textit{Global Pop.Dataset} - Pop_{NSO}}{Pop_{NSO}}$

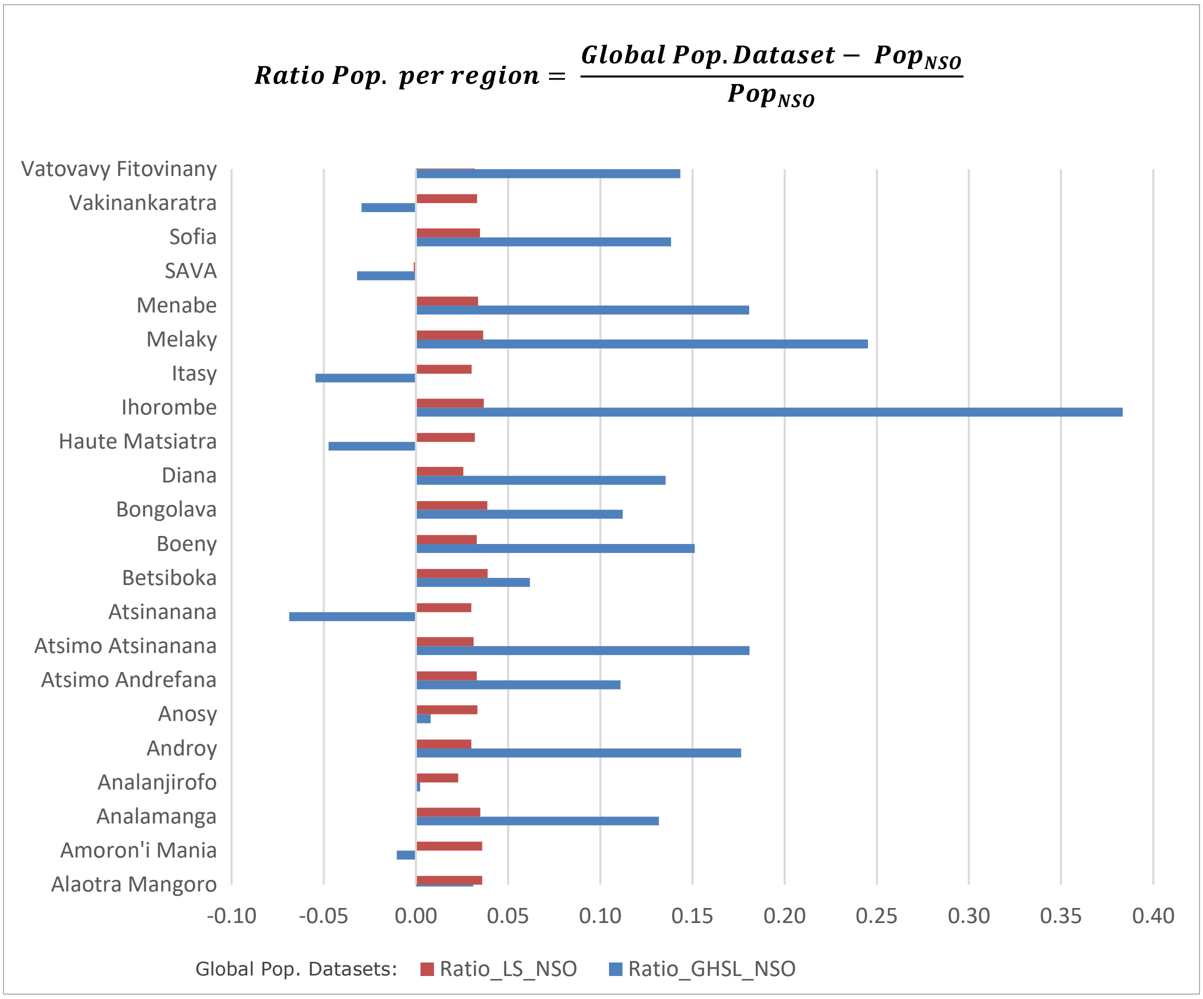


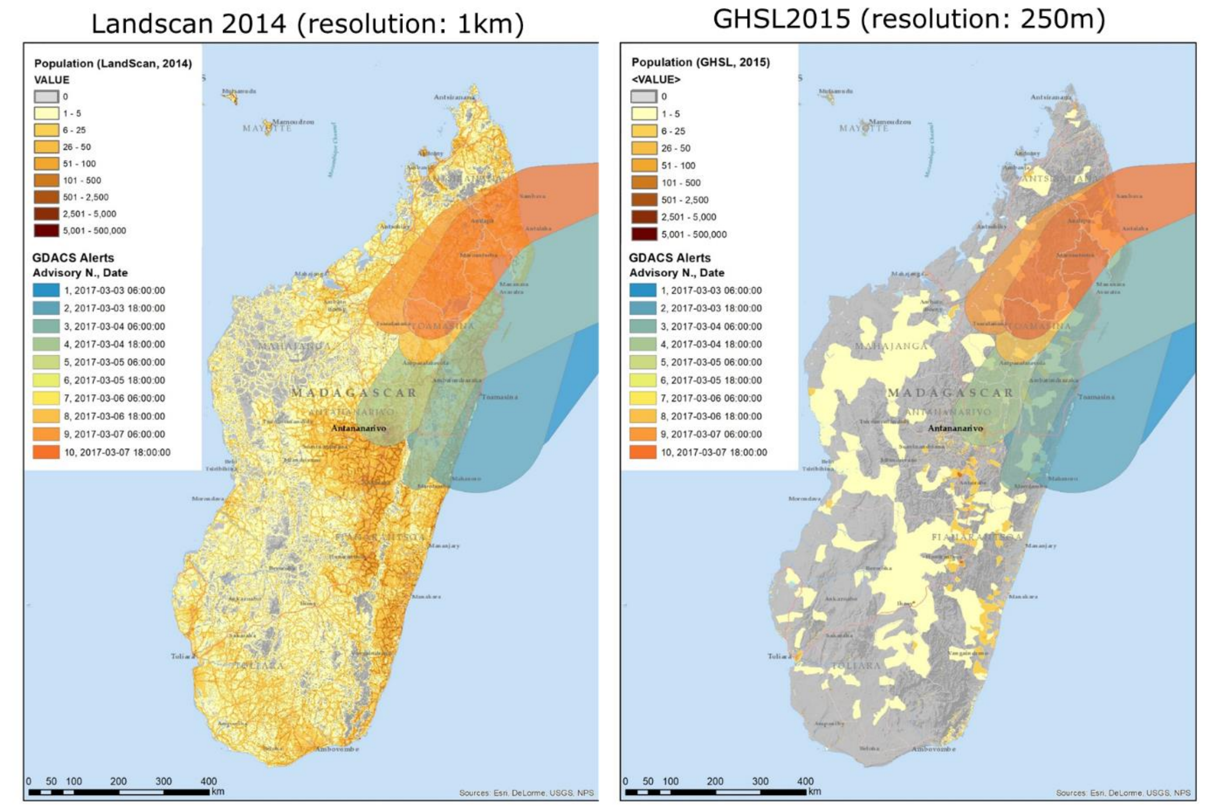
***Figure 67** - Ratio between GHSL and LandScan™ population compared to the data provided by the National Statistical Office – NSO*
[Avarage ratio (GHSL) = 0.09, Avarage ratio (LandScan™) = 0.03]

B.2. Impact on GDACS Alerts using different population datasets

Based on the comparison of population dataset, promising results come from the GHSL 250m resolution. The higher resolution would allow to perform more detailed estimation of the exposed population to a specific disaster. A comparison of the GDACS alerts based on LandScan™ data (actual dataset) and GHSL is provided for this event.

To assess the impact on each single alert provided for this event, the exposed population has been calculated using GHSL. The results of this comparison are shown in **Figure 68**. In this test case, the use of GHSL would not change the GDACS Alert level. In addition, the ratio between the exposed population per alert using GHSL vs LandScan™ is very low (mean= 0.06).

The low variation in the score of the GDACS alerts based on the different dataset allow to keep on basing the GDACS alerts on higher resolution population dataset available at global level (GHSL).



GDACS Alert (Avisory N.)	GDACS Alert (LandScan)	Population (Landscan)	GDACS Alert (GHSL)	Population (GHSL)	Ratio Population= (GHSL-LS)/LS
1	Green	0	Green	0	
2	Red	2,476,226	Red	2,496,169	0.008
3	Red	1,533,240	Red	1,655,152	0.080
4	Red	5,921,827	Red	6,399,997	0.081
5	Red	250,848	Red	200,391	-0.201
6	Red	1,132,831	Red	1,301,031	0.148
7	Orange	485,868	Orange	655,495	0.349
8	Red	1,192,504	Red	1,211,948	0.016
9	Red	2,053,246	Red	2,138,885	0.042
10	Red	1,642,692	Red	1,739,625	0.059

$$\textit{Ratio Population per GDACS Adv.} = \frac{Population_{GHSL} - Population_{LS}}{Population_{LS}}$$

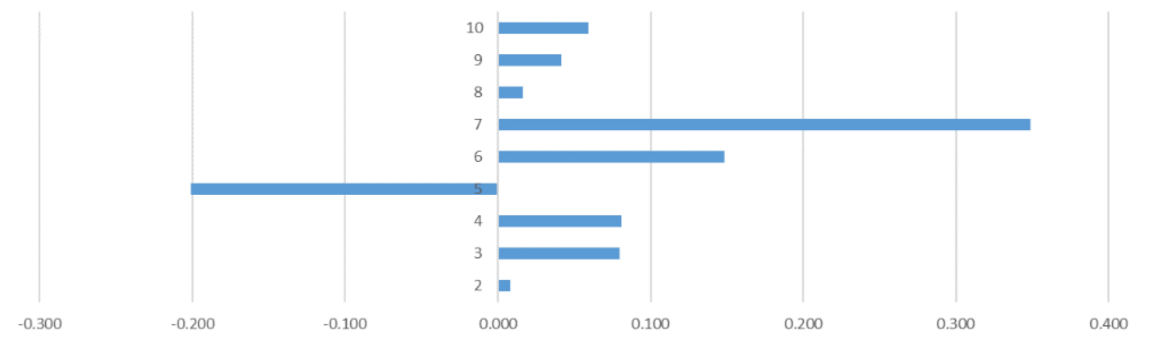


Figure 68 – Comparison of the GDACS Alerts and population ratio using LandScan™ (Current GDACS System) and GHSL data. As a result of the comparison, the value of the population ratio per alert is low and in this cases would not influence the alert level.

Annex 1 – GDACS alerts

JRC is responsible for the operation of GDACS, that plays a major role in alerting the international community to humanitarian emergencies during natural disasters. The alerts of GDACS (Green, Orange, Red) are elaborated based on the severity of the event, the population involved and the vulnerability of the countries. GDACS also sends e-mail and SMS alerts to subscribed recipients. A detailed description of GDACS can be found in the GDACS Guidelines available at:

http://www.gdacs.org/Documents/GDACS%20Guidelines%202014 - FINAL.PDF

Overview

The TCs are among the most damaging events. They affect the population with three dangerous effects: strong wind, heavy rain and storm surge. Therefore the JRC has developed a system used in GDACS that includes the analysis of all these effects for every TC occurring worldwide, using several different data sources, as shown in figure below. JRC set up an automatic routine that includes the TC bulletins produced by the National Oceanic and Atmospheric Administration (NOAA) and the Joint Typhoon Warning Center (JTWC) into a single database, covering all TC basins. This information is used in GDACS for the wind impact, while the heavy rain impact is obtained using the NOAA Ensemble Tropical Rainfall Potential (eTRaP) data. For the storm surge, JRC has developed an analytical tool, introducing the atmospheric forcing in the JRC's HyFlux2 code and using as input the TC bulletins (see http://portal.gdacs.org/Models)

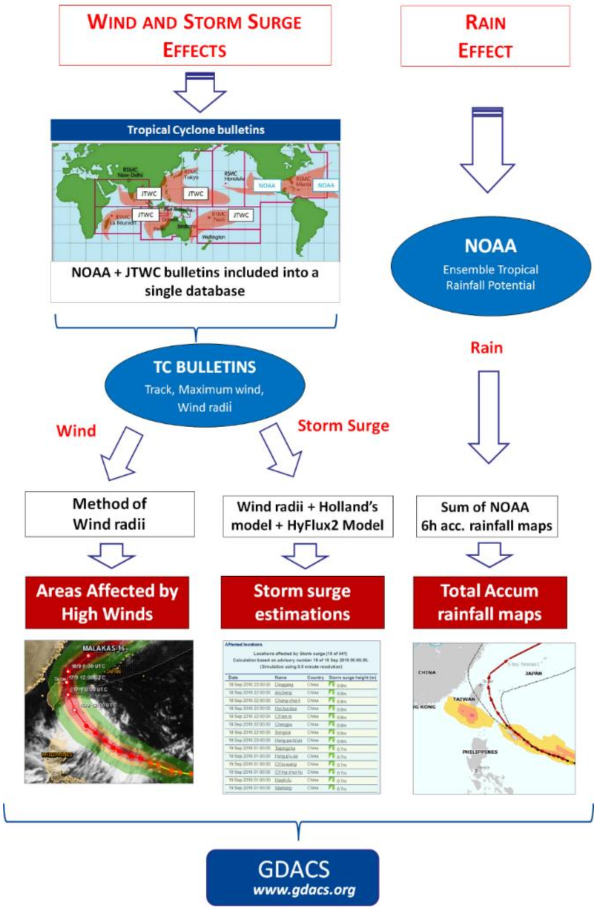


Figure 69 *- Tropical Cyclones in GDACS*

Wind Alert

In the current GDACS Wind Alert System, the wind radii[30] data (34, 50, 64 kt equivalent to 63, 93, 119 km/h) provided in the TC bulletins are used to calculate the three wind buffers (see more information in Vernaccini et al. 2007 and Probst et al. 2012), shown in the table below. The system automatically calculated the population inside these buffers.

Wind Buffer (GDACS)	Sustained Winds	
	knots	km/h
RED	≥ 64	≥ 119
ORANGE	50 – 63	93 - 118
GREEN	34 – 49	63 - 92

Table 21 *- Wind buffers used in GDACS*

The GDACS alert levels for the TCs are based on the risk formula that includes:

- TC wind speed (hazard)
- Population affected
- Vulnerability of the affected country

Depending on these parameters the following alert levels have been set up:

MAXIMUM WIND SPEED	POPULATION	VULNERABILITY	ALERT LEVEL
Tropical Depression < 63 km/h	-	Low – Medium - High	**Green**
Tropical Storm 63 – 118 km/h	< 10 Million	Low – Medium - High	**Green**
Tropical Storm 63 – 118 km/h	> 10 Million	High	**Orange**
Cat 1 – 2 119 – 177 km/h	> 100 000 or 10 %	Medium - High	**Orange**
Cat 1 – 2 119 – 177 km/h	> 1 Million	High	**Red**
Cat 3 178 - 208 km/h	> 100 000 or 10 %	Medium - High	**Red**
Cat 3 178 - 208 km/h	> 1 Million	Low	**Orange**
Cat 4-5 > 208 km/h	> 1 Million	Low	**Red**

Table 22 *- GDACS wind alert system*
(see http://portal.gdacs.org/Models)

Note: Currently the OVERALL GDACS alert is based only on the Wind impact and not also on the rainfall and storm surge impacts.

[30] Wind radii represents the maximum radial extent – in nautical miles - of winds reaching 34, 50, and 64 kt in each quadrant (NE, SE, SW, and NW). These data are provided in each TC bulletin issued by the TC warning centres at least every six hours. The threshold of the velocity (34, 50, 64kt) could vary from centre to centre.

Rainfall Alert

Currently, GDACS uses the NOAA Ensemble Tropical Rainfall Potential (eTRaP) accumulation data for its alert model. The eTRaP is created using observations from several microwave sensors (AMSU, TRMM, SSMI and AMSRE) initialized at several observation times, and possibly using several different track forecasts. The eTRaP is a simple ensemble whose members are the 6-hourly totals from the single-orbit TRaPs. This ensemble approach allows for the generation of probabilistic forecasts of rainfall in addition to deterministic rainfall totals similar to what is currently provided by the TRaP product. More information are available at:

http://www.ssd.noaa.gov/PS/TROP/etrap-info.html

The GDACS model sets alert levels based on total accumulation and maximum rain rate (mm/h) using this product. The thresholds used are shown in the table below.

Alert level	Tot cyclone accumulation (mm)	Maximum rain rate (mm/h)
Green	< 200 mm	< 17 mm/h
Orange	200 – 500 mm	17-33 mm/h
Red	> 500 mm	> 33 mm/h

Table 23 *- GDACS rain alert system*

Storm Surge Alert

Storm surge is an abnormal rise of water above the predicted astronomical tides, generated by strong winds and by a drop in the atmospheric pressure.

JRC has developed a specific system, implementing the atmospheric forcing in the HyFlux2 code, routinely used in GDACS to model inundation due to tsunami run-up (see more information in Probst and Franchello, 2012).

The GDACS alert levels are based on the maximum storm surge height calculated by this system and the thresholds used are shown in the table below.

Alert level	Maximum storm surge (m)
Green	< 1.0 m
Orange	1.0 – 3.0 m
Red	> 3.0 m

Table 24 - *GDACS storm surge alert system*

Note: JRC storm surge calculations don't include wave, tide and river effects. In the area of a delta river, bays, the storm surge may be higher. The torrential rains that may affect the mountains areas during the passage of a Tropical Cyclone may increase the river flow and its outflow could be blocked by the incoming storm surge. This could create floods in the surrounding areas of the cities close to a delta river.

Annex 2 - Tropical Cyclone (TC) information

Several data sources are available to obtain the TC information: TC bulletins, Numerical Weather Forecasts (e.g. global scale, regional scale specific for the TCs) and Satellite data. A brief description of the data and models used by the JRC are presented below, while more information can be found in the WMO - Global Guide to Tropical Cyclone Forecasting, 2017.

TC bulletins

The most important sources of TC information are the TC bulletins provided by the Regional Specialized Meteorological Centres (RSMCs) and the Tropical Cyclone Warning Centres (TCWCs). These centres have the regional responsibility to forecast and monitor each area of TC formation. Every 6-12 hours the TC warning centres publish a TC bulletin, including several TC information, which vary from centre to centre. For examples the TC bulletins can include: track, wind speed, central pressure and wind radii.

Wind radii represents the maximum radial extent – in nautical miles - of winds reaching 34, 50, and 64 knots in each quadrant (NE, SE, SW, and NW). These data are provided in the TC bulletin issued by the TC warning centres at least every six hours. The threshold of the velocity (34, 50, 64 kt) could vary from centre to centre.

In addition to the RSMCs and TCWCs other organizations, as the Joint Typhoon Warning Center (JTWC), provide TC information. Since these centres by themselves don't cover all basins, one has to aggregate information. Using JTWC and National Oceanic and Atmospheric Administration (NOAA) data it is possible to cover all TC basins. Therefore, in 2007, the Pacific Disaster Centre (PDC) set up an automatic routine which includes the TC bulletins from the JTWC and NOAA into a single database, covering all TC basins. In 2014, the JRC set up a new automatic routine, without the need to use the PDC's systems. This new routine collects the data from JTWC and NOAA into a single database, covering all TC basins. More information can be found at: http://portal.gdacs.org/Models

NOAA NHC bulletin: NHC issues tropical and subtropical cyclones advisories every six hours at 03:00, 09:00, 15:00, and 21:00 UTC. The covered areas are the Atlantic and eastern Pacific Oceans. The NHC bulletin contains a list of all current watches and warnings on a tropical or subtropical cyclone, as well as the current latitude and longitude coordinates, intensity, system motion and wind radii. The intensity includes the analysis of the central pressure (Pc is not forecasted), and the maximum sustained (1-min average) surface wind (Vmax) analysed and forecasted for 12, 24, 36, 48 and 72 h.

— More information at: http://www.nhc.noaa.gov/.

JTWC bulletin: JTWC is the agency within the U.S. Department of Defence responsible for issuing tropical cyclone warnings for the Pacific and Indian Oceans. TC bulletins are issued for the Northwest Pacific Ocean, North Indian Ocean, Southwest Pacific Ocean, Southern Indian Ocean, Central North Pacific Ocean. JTWC products are available on 03, 09, 15 or 21 UTC (in the North Pacific and North Indian Ocean tropical cyclone warnings are routinely updated every six hours, while in South Indian and South Pacific Ocean every twelve hours). The bulletins include position of TC centre, the maximum sustained wind based on 1-min average and the wind radii.

— More information at: www.usno.navy.mil/JTWC/.

Numerical Weather Forecast Models

The JRC developed the tropical cyclone system used in GDACS in 2007 and the storm surge system in 2011. At that time the global numerical weather forecast models couldn't resolve the high wind and pressure gradients inside a TC due to their coarse resolution, while a TC weather forecast was not globally available. Recently, the global forecasting models and TC models have improved their resolutions and are now globally available. These models provide wind, pressure and rainfall data and could be used in GDACS and in the JRC storm surge system and for the wind and rainfall impacts. The JRC is assessing the possibility to use these products, especially the TC products based on the NOAA Hurricane Weather Research and Forecast (HWRF) model (see Technical Annex) and the outputs of the global high resolution model of European Centre for Medium Weather Forecast (ECMWF). A brief description of these products is presented below:

NOAA Hurricane Weather Research and Forecast (HWRF) model

The development of the Hurricane Weather Research and Forecast (HWRF) model began in 2002 at the National Centers for Environmental Prediction (NCEP) - Environmental Modeling Center (EMC) in collaboration with the Geophysical Fluid Dynamics Laboratory (GFDL) scientists of NOAA and the University of Rhode Island. HWRF is a non-hydrostatic coupled ocean-atmosphere model, which utilizes highly advanced physics of the atmosphere, ocean and wave. It makes use of a wide variety of observations from satellites, data buoys, and hurricane hunter aircraft. The ocean initialization system uses observed altimeter observations, while boundary layer and deep convection are obtained from NCEP GFS. Over the last few years, the HWRF model has been notably improved, implementing several major upgrades to both the atmospheric and ocean model components along with several product enhancements. The latest version of HWRF model has a multiply-nested grid system: 18, 6, 2 km of resolutions. The TC forecasts are produced every six hours (00, 06, 12, and 18 UTC) and several parameters are included (e.g. winds, pressure and rainfall).

— More information at: http://www.nws.noaa.gov/os/notification/tin15-25hwrf_cca.htm

— Active TCs: http://www.emc.ncep.noaa.gov/gc_wmb/vxt/HWRF/index.php

— Data download: http://www.nco.ncep.noaa.gov/pmb/products/hur/

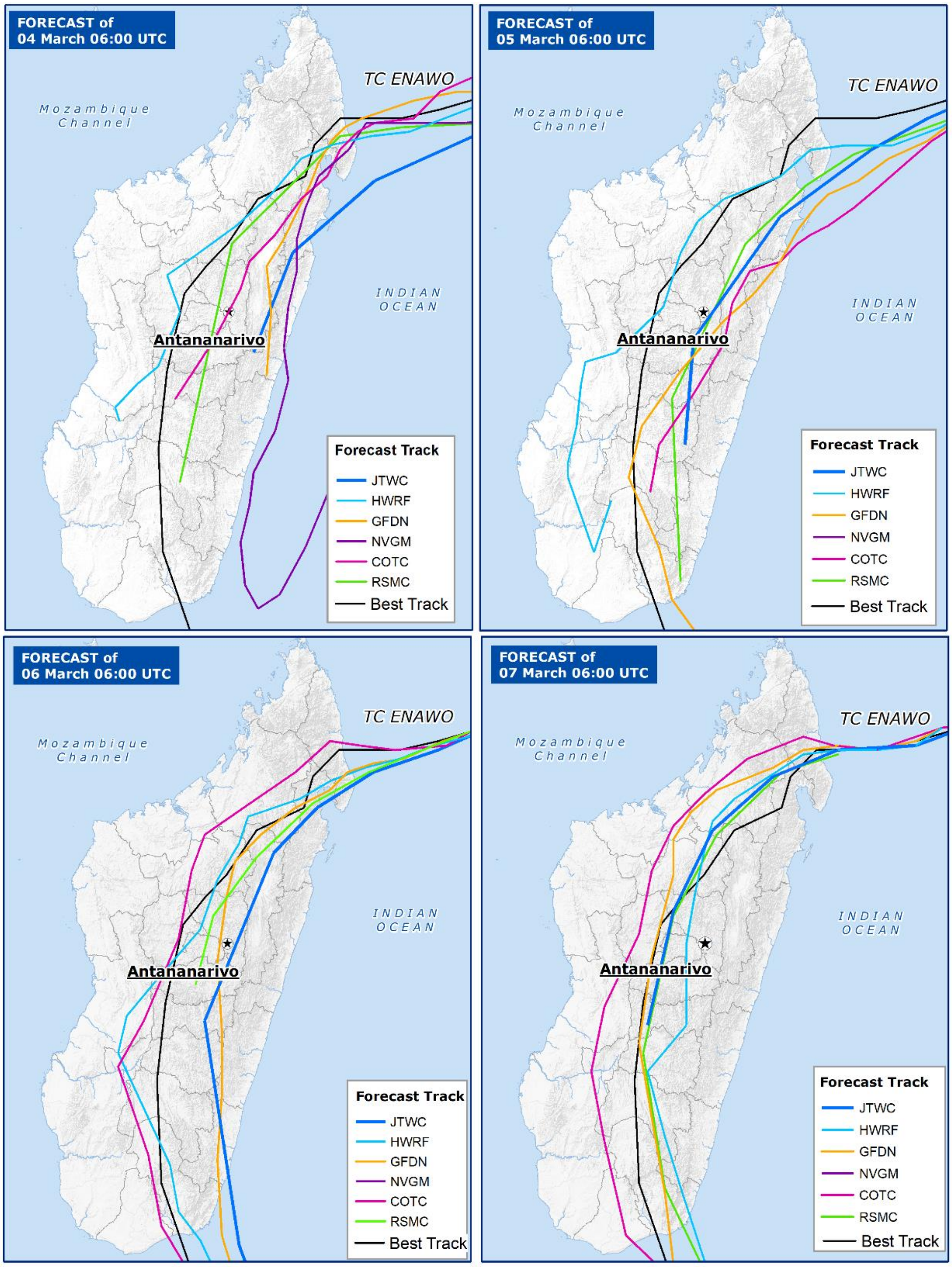
ECMWF Weather Deterministic Forecast – HRES:

Before March 2016: the HRES horizontal resolution corresponded to a grid of 0.125° x 0.125° lat / long (≈16 km), while its vertical resolution was equal to 137 levels. This deterministic single-model HRES configuration runs every 12 hours and forecasts out to 10 days on a global scale.

After March 2016, the ECMWF has started using a new grid, with up to 904 million prediction points. The new cycle has reduced the horizontal grid spacing for high-resolution from 16 km to just 9 km, while the vertical grid remained unchanged.

— More information at: http://www.ecmwf.int/en/about/media-centre/news/2016/new-forecast-model-cycle-brings-highest-ever-resolution

Annex 3 – Track of ENAWO according to different models



JTWC	*Joint Typhoon Warning Center official track used in GDACS*
HWRF	*NOAA Hurricane Weather Research and Forecasting (HWRF) model*
GFDN	*GFDL model using Navy NOGAPS initial conditions*
NVGM	*NAVGEM model*
COTC	*Navy Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) - TC model*
RSMC	*RSMC La Reunion – Meteo France*

Data source: *http://www.ral.ucar.edu/hurricanes/repository/techlist/index.php*

Table 25 - *Track of ENAWO according to different models*

Annex 4 - Demography of Madagascar

Total Population & density

The population of Madagascar is over 23 million people (estimation 2015), with over 3 million people living in the region of the capital Antananarivo: ANALAMANGA. The population and the density of population per region and district are shown in **Figure 70**.

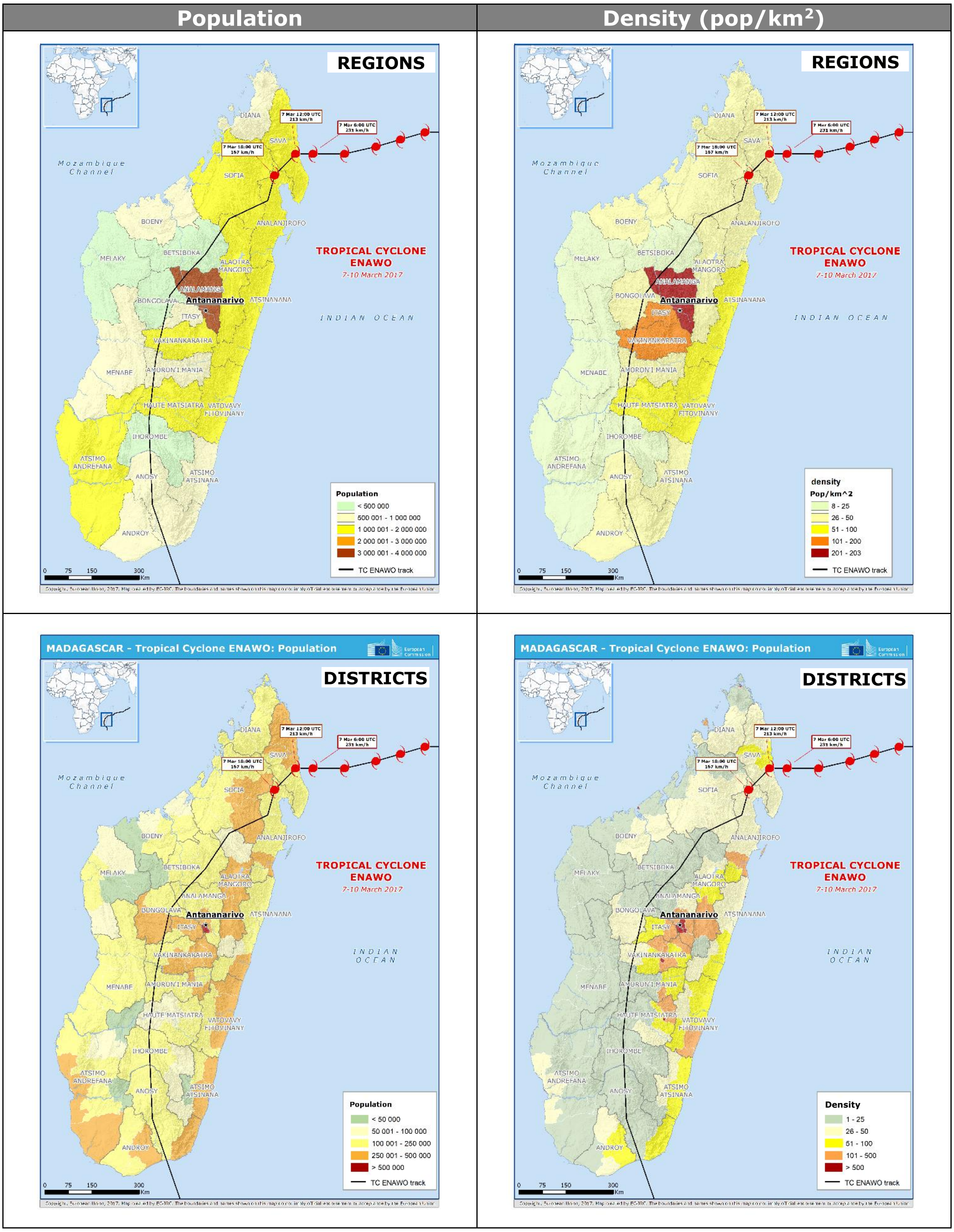


Figure 70 *- Population per regions (top left) and districts (bottom left). Density (pop/km²) per regions (top right) and per districts (bottom right)*

Note: The latest Census in Madagascar was in 2009. The latest official estimations available on the Official "Instat Madagascar" website are only available for the regions[31] and not for the single districts. Therefore, in this report, the number of people estimated per districts are based on the reports of the "*Office National pour l'Environnement*[32]" (as of 2015).

Landfall Area

Tropical Cyclone ENAWO made landfall in Sava region as an intense Tropical Cyclone with max 1-min sustained winds of over 210 km/h, then it moved over Analanjirogo region still with maximum sustained winds of over 160 km/h. As in Section 3, the two regions of the possible landfall were SAVA and ANALANJIROFO (see **Figure 71**). The population of the districts of these two regions are shown in the table below.

LANDFALL AREA: REGIONS & DISTRICTS		
Region	**Population**	**Density** (pop./km^2)
SAVA	**1 034 599**	**41**
Andapa	200 296	47
Antalaha	244 174	42
Sambava	321 059	64
Vohémar	269 070	30
ANALANJIROFO	**1 091 901**	**50**
Maroantsetra	233 091	34
Mananara N.	179 262	41
Soanierana-Ivongo	143 515	28
St. Marie	28 003	133
Fénérive Est	325 308	127
Vavatenina	182 722	57
TOTAL	**2.1 million**	-

Table 26 - *Population in the regions and districts of the possible landfall*

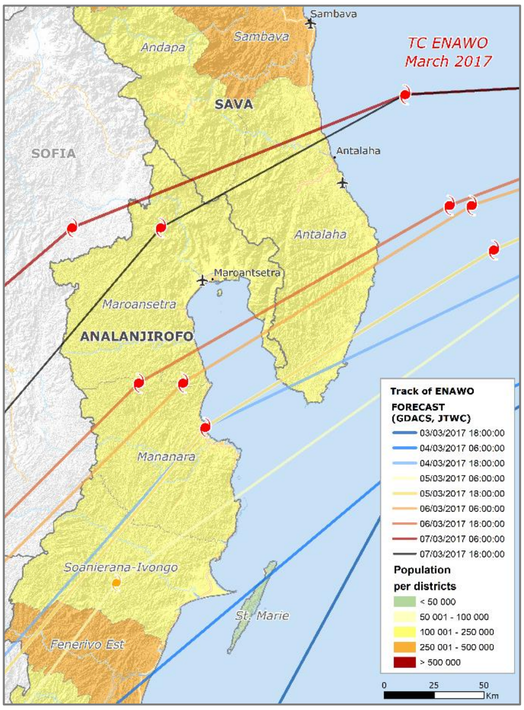


Figure 71 *- Population in the districts of the possible landfall. Track of TC ENAWO, according to JTWC forecasts (GDACS).*

Note: The total population of the regions of the possible landfall is 2.1 million. Considering only the districts potentially affected and not the whole regions the total population is 1.6 million (Vohémar and Vavatenina districts not included).

[31] *Instat Madagascar:* https://www.instat.mg/madagascar-en-chiffre/

[32] *Office National pour l'Environnement: http://www.pnae.mg/tbe/national.html*

Annex 5 – Risk of TCs in the area

TCs seasons

Madagascar is affected by Tropical Cyclones (TCs) during the Indian Ocean TC season that officially is: **from mid-Nov to mid-Apr.**

World Bank, Global Facility for Disaster Reduction and Recovery, GFDRR

TCs are the most significant risk in Madagascar, according to the Disaster Risk Profile of Madagascar (World Bank, Global Facility for Disaster Reduction and Recovery, GFDRR[33]), where the following hazards have been considered: Earthquake, Floods, Tropical Cyclones. This study shows that the TCs caused approximately 85 % of the annual average loss from all three perils (see table and map below, data source: World Bank, GFDRR). A detailed analysis on the damage due to TC ENAWO, using Sendai Targets and related Indicator, is included in Section 4.2.

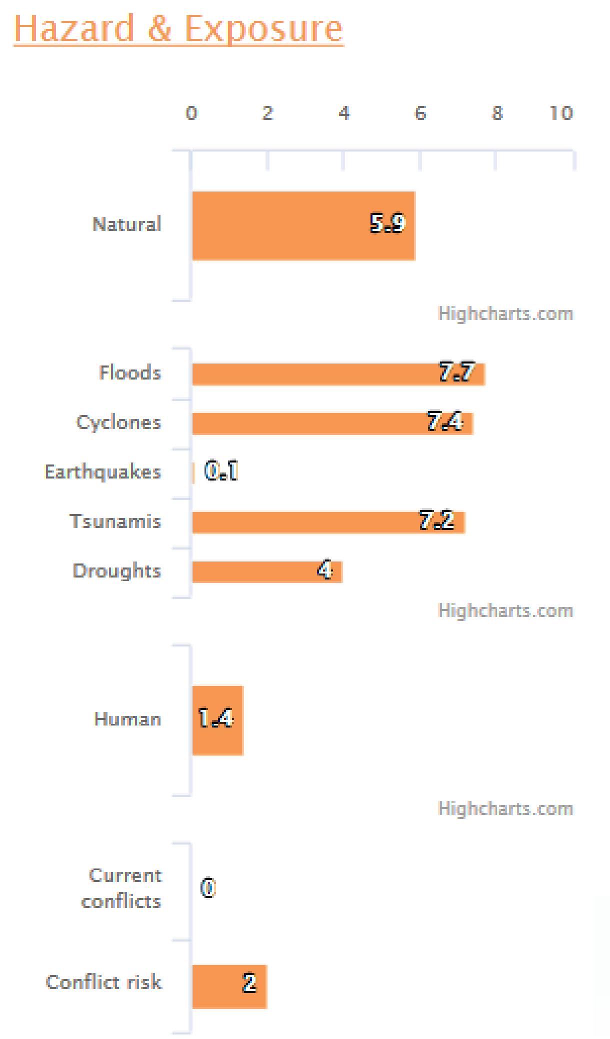
Hazard	Average Annual Loss		100-Year Return Period Loss	
	Total Direct Losses	Emergency Costs	Total Direct Losses	Emergency Costs
Earthquakes	1.3 million	200 000	15 million	2.3 million
Floods	13 million	3.1 million	120 million	27 million
Tropical Cyclones	87 million	20 million	810 million	190 million

[33] https://www.gfdrr.org/sites/default/files/madagascar.pdf

INFORM

According to the country risk profile of Madagascar from Index for Risk Management – **INFORM**[34] - and in particular to the single indicators for Hazard and Exposure, TCs are one of the most relevant hazard.

	Value	Rank	Trend
INFORM Risk	5	46	—
Hazard & Exposure	4	78	—
Vulnerability	4.1	73	—
Lack of Coping Capacity	7.6	14	—



[34] http://www.inform-index.org/Portals/0/InfoRM/2017/Country_Profiles/MDG.pdf

Annex 6 - Climatological information: Monthly Average rainfall

The Monthly Average Rainfall provided by WMO for Madagascar are shown in **Figure 72** below, while the Monthly Average Rainfall for the month of March for the whole country is shown in **Figure 73**. This map has been created using the climate data of WorldClim 2.0[35] (see Fick and Hijmans, 2017). The eastern areas of Madagascar, including Sava and Analanjirofo regions) are the areas most affected during the month of March.

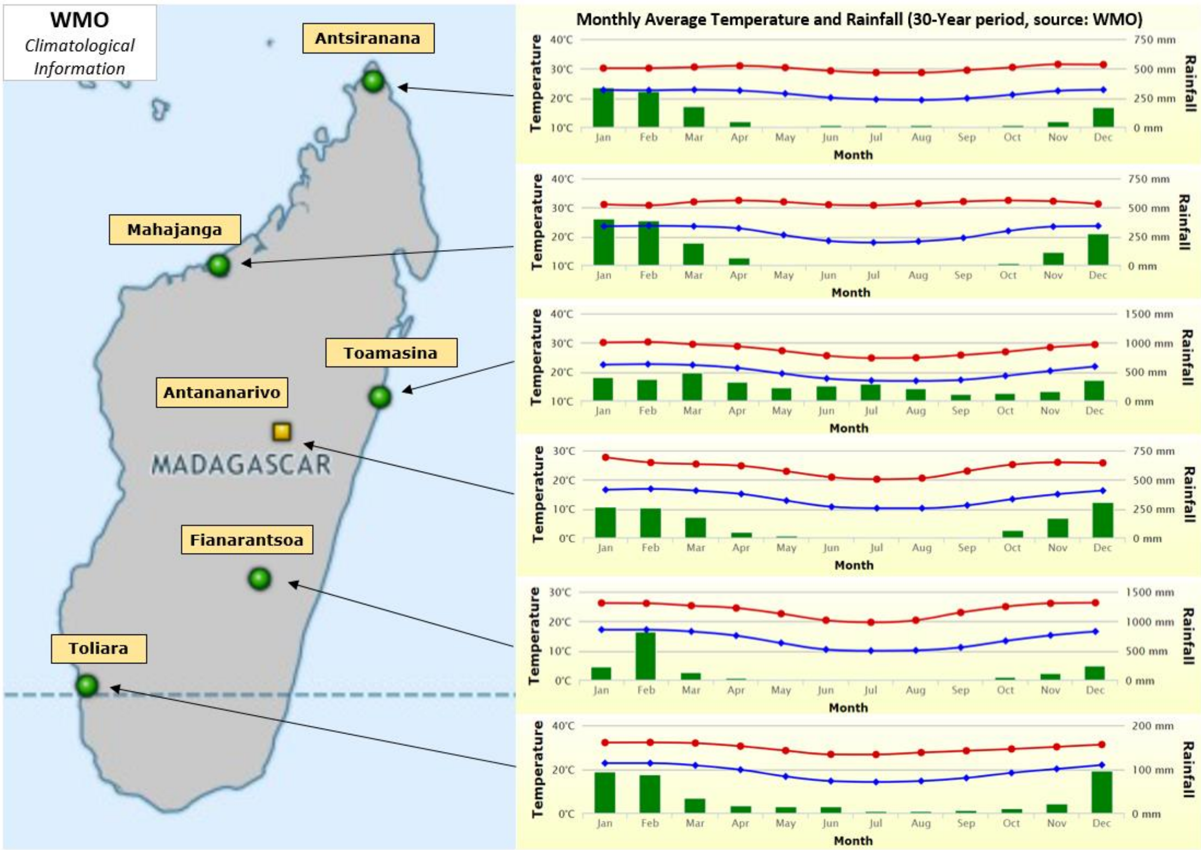


Figure 72 - *WMO Climatological Information (source: WMO[36])*

[35] See Fick and Hijmans, 2017. http://worldclim.org/version2

[36] http://worldweather.wmo.int/en/home.html

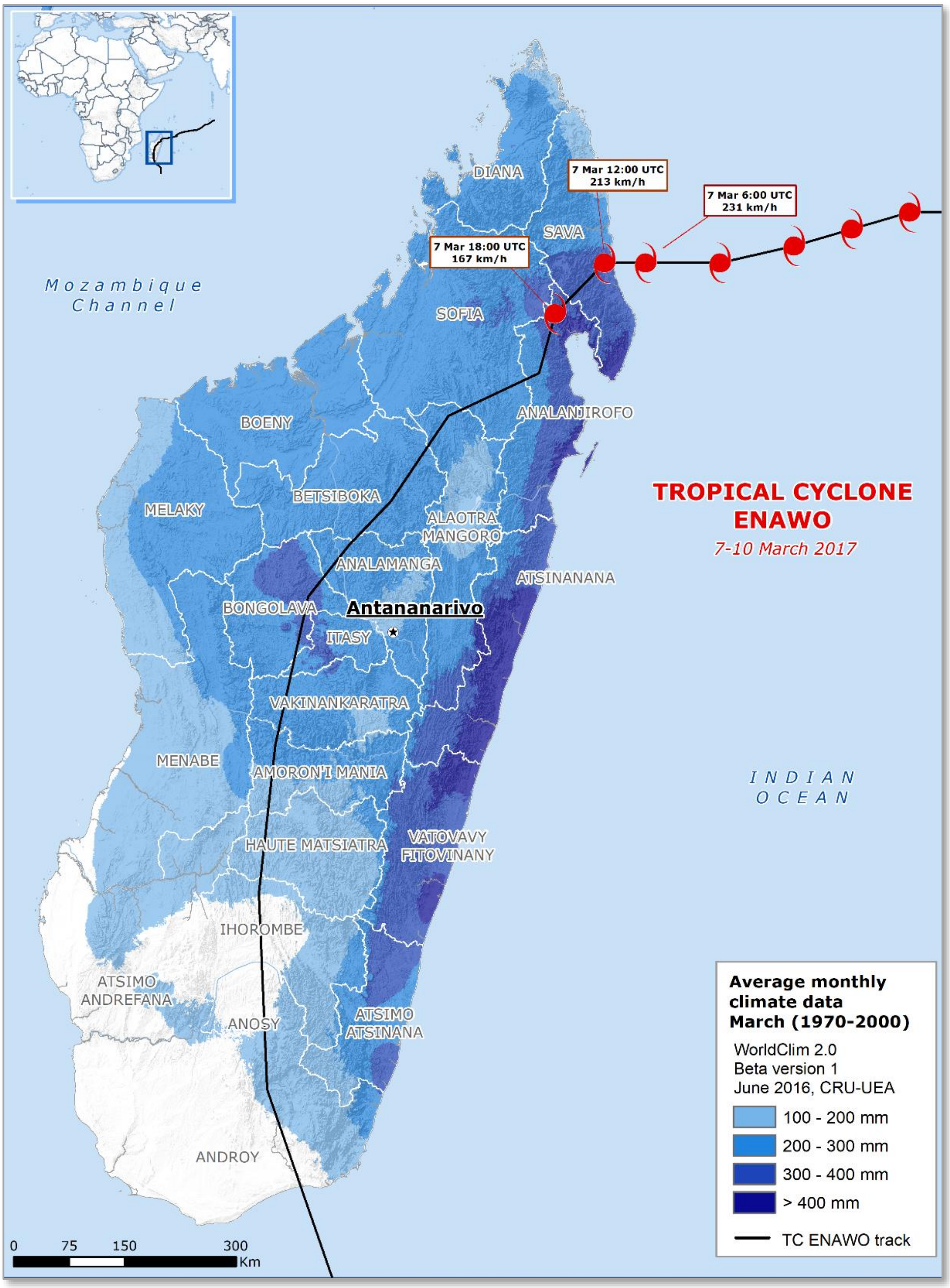


Figure 73 *- Monthly Average Rainfall for March (data source: WorldClim 2.0[35]), 1970-2000*

Annex 7 – Storm surge due to Tropical Cyclone GIOVANNA - 2012

Tropical Cyclone GIOVANNA made landfall in the area south of Toamasina in 2012. JRC prepared a specific analysis for this event. The most importart results of the storm surge analysis are presented below, while more information can be found in Probst et al. (2012).

Sea Level Measurements

The tide gauge measurements in Toamasina showed an increase of sea level above 2 m (the instrument went off scale), with strong oscillations probably due to the cyclone winds. JRC calculations estimated in that location a storm surge lower than 20 cm. According to local port authority (Personal Communication, 02/2012), a sea level increase of 2 m didn't occur: they noted an increase not more than 50 cm. Under the device there is a **barbed wire** (see yellow circle in **Figure 75**). When this wire is wet, the signal of the sensor reflected over it before reaching the sea, consequently a wrong sea level is recorded (Personal Communication, 09/2012). Therefore the recorded value of 2 m is **due to this barbed wire**. Moreover in front of the device there is a wave breaker, where the cyclone waves break and the remaining seawater and sea sprays fly over this device, affecting the observations correctness. Other tide gauges, suitable to evaluate our calculations, were not available in the area, making validation of the storm surge calculation with in-situ data impossible. It should be noted that those measurements have been installed to measure tsunami surge and not tropical cyclones storm surge.

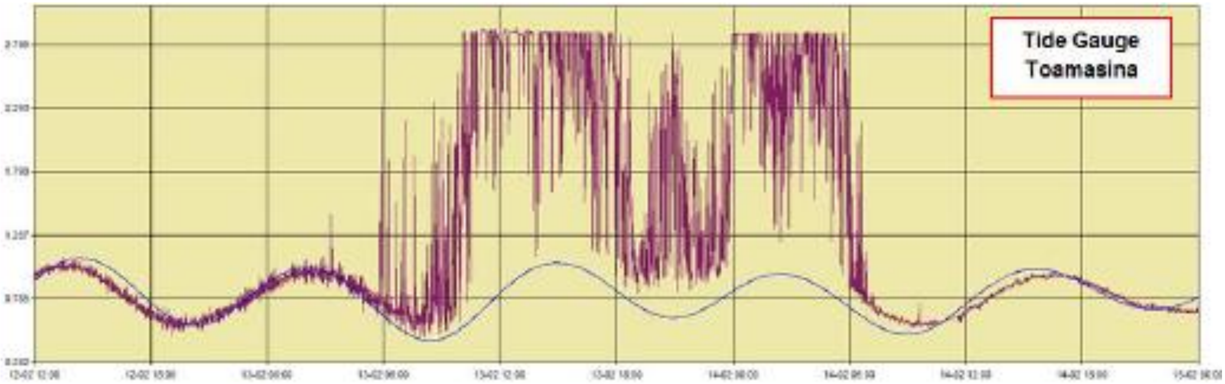


Figure 74 *- Sea level measured in Toamasina during the passage of TC GIOVANNA in 2012.*

Tide gauge Toamasina: it is the "VEGA VEGAPULS62 CONTACT FREE RADAR SENSOR", deployed by SHOM, a pulsed-wave contact-free radar that transmits in the K band (around 26 GHz). The operating principle is based on the measurement of the transmission time of the microwave pulse-transmitted by the radar and reflected by the interface to be measured. Half of this time is equivalent to the distance between the sensor's reference point and the surface of the water. The location and the image of this tide gauge are shown in the Figure below.

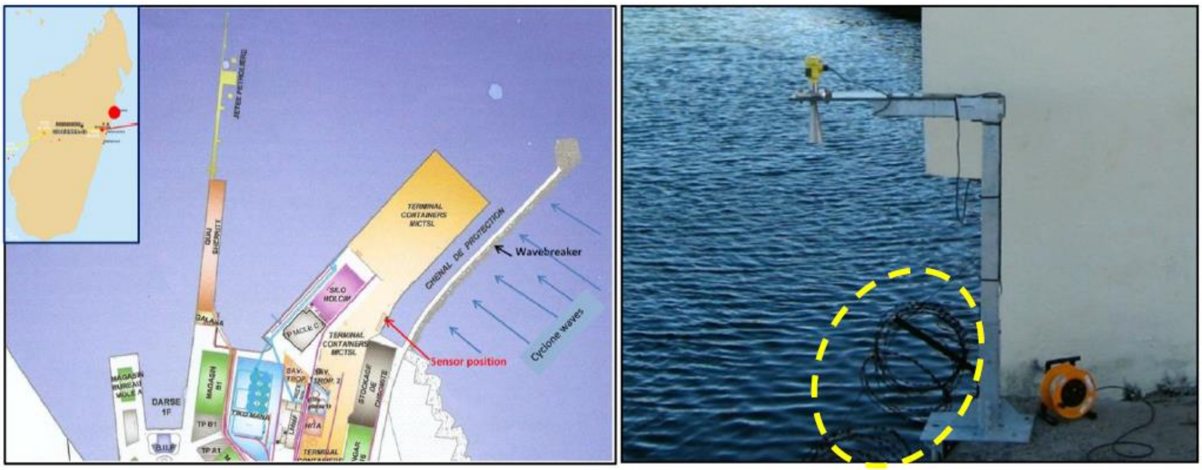
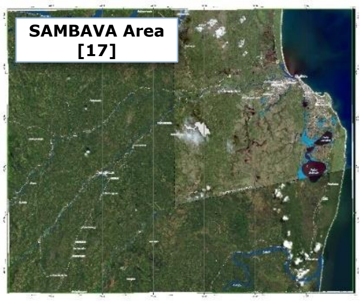
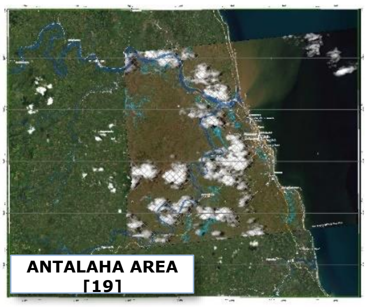


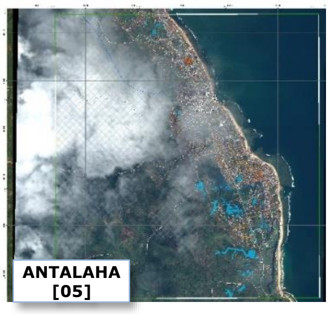
Figure 75 *- Vega Vegapuls62 radar sensor, Toamasina (Madagascar) tide gauge observatory (Source: SHOM http://refmar.shom.fr/image/image_gallery?uuid=b4a9dc3f-de85-4b72-91e8-5ad1a864ca78&groupId=10227&t=1312547547320), as of 2012.*

Annex 8 – Copernicus EMS Maps

A. SAVA Region: Sambava and Antalaha







$$\% \, Pop. affected = \frac{Tot. affected}{Tot. in \, AOI} * 100$$

Consequences within the AOI

SAMBAVA Area [17]		Unit of measurement	Destroyed	Highly damaged	Moderately damaged	Total affected	Total in AOI
Flooded area		ha				360.0	
Estimated population		No. of inhabitants				557	114206
Transportation	Secondary roads	km	0.0	0.0	0.0	0.0	60.0
	Local roads	km	0.03	0.4	2.0	0.0	241.0
	Bridges	No.	0	0	1	0	14
	Aerodromes	No.	0	0	0	0	1

$$\frac{557}{114\,206} * 100 = 0.5\,\%$$

Consequences within the AOI

SAMBAVA [04]		Unit of measurement	Destroyed	Highly damaged	Moderately damaged	Negligible to slight damage	Total affected	Total in AOI
Flooded area		ha					67.5	
Estimated population		No. of inhabitants	0	2463	2835	0	5298	38521
Settlements	Residential	No.	0	821	945	0	1766	N/A
Transportation	Bridge	No.	0	0	0	0	0	6
	Local roads	km	0.0	5.1	0.0	0.0	5.1	52.7

$$\frac{5\,298}{38\,521} * 100 = 13.8\,\%$$

Consequences within the AOI

ANTALAHA AREA [19]		Unit of measurement	Destroyed	Highly damaged	Moderately damaged	Negligible to slight damage	Total affected	Total in AOI
Flooded area		ha					679.0	
Estimated population		No. of inhabitants					2133	117414
	Secondary roads	km	0.0	0.0	10.1	0.0	10.1	69.8
	Local roads	km	0.8	0.0	16.2	0.0	17.0	170.6
	Bridges	No.	0	0	2	0	2	22
	Aerodrome	No.	0	0	0	0	0	1

$$\frac{2\,133}{117\,414} * 100 = 1.8\,\%$$

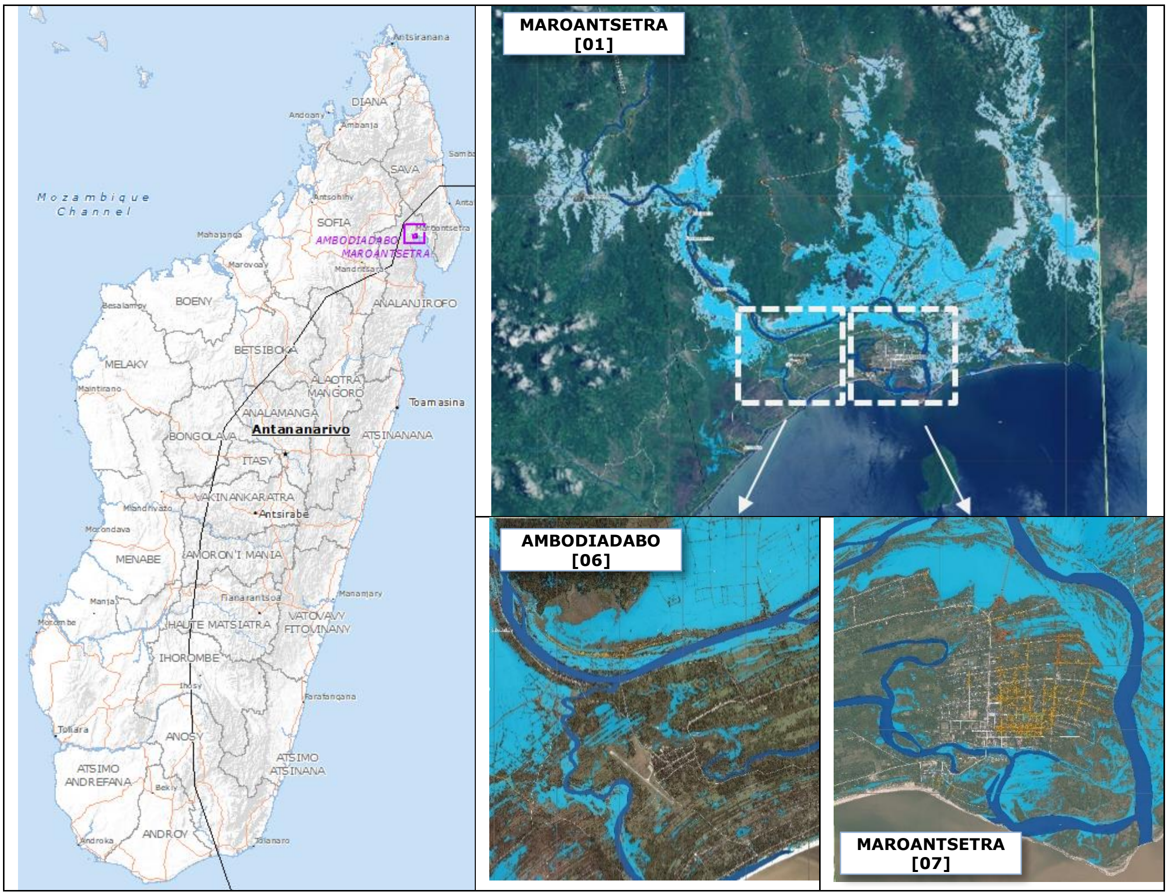
Consequences within the AOI

ANTALAHA [05]		Unit of measurement	Destroyed	Highly damaged	Moderately damaged	Negligible to slight damage	Total affected	Total in AOI
Flooded area		ha					28.8	
Estimated population		No. of inhabitants	0	513	369	0	882	53160
Settlements	Residential	No.	0	171	123	0	294	N/A
	Other	No.	0	16	13	0	29	N/A
	Industrial	No.	0	13	26	0	39	N/A
	Religious	No.	0	0	1	0	1	N/A
Transportation	Secondary roads	km	0.0	0.0	0.0	0.0	0.0	15.1
	Local roads	km	0.0	3.3	6.7	0.0	10.0	64.1

$$\frac{882}{53\,160} * 100 = 1.7\,\%$$

Figure 76 - *Copernicus EMS © 2017, [EMSR197] Sambava Area [17]: Grading Map; Sambava [04]: Grading Map; Antalaha Area [19]: Grading Map; Antalaha [05]: Grading Map.*

B. ANALANJIROFO Region: Maroantsetra and Ambdiadabo



	% Pop. affected
	$\% \, Pop.affected = \frac{Tot.affected}{Tot.in\,AOI} * 100$

MAROANTSETRA [01]

		Unit of measurement	Affected	Total in AOI
Satellite detected waters		ha	13837,3	
Estimated population		No. of inhabitants	11972	78731
Settlements	Built-Up Area	ha	35,4	1045,4
Transportation	Aerodrome	No.	0	1
	Secondary roads	km	0,2	26,7
	Local roads	km	44,7	274,0

$$\frac{11\,972}{78\,731} * 100 = 15.2\,\%$$

Consequences within the AOI

MAROANTSETRA [07]	Unit of measurement		Destroyed	Highly damaged	Moderately damaged	Negligible to slight damage	Total affected	Total in AOI
Flooded area		ha					758.7	
Estimated population	No. of inhabitants						5524	45378
Settlements	Residential	No.	0.0	202.0	2015.0	0.0	2217.0	N\A
Transportation	Secondary roads	km	0.0	0.0	0.0	0.0	0.0	9.5
	Local roads	km	0.0	6.7	12.2	0.0	18.9	57.7

$$\frac{5\,524}{45\,378} * 100 = 12.2\,\%$$

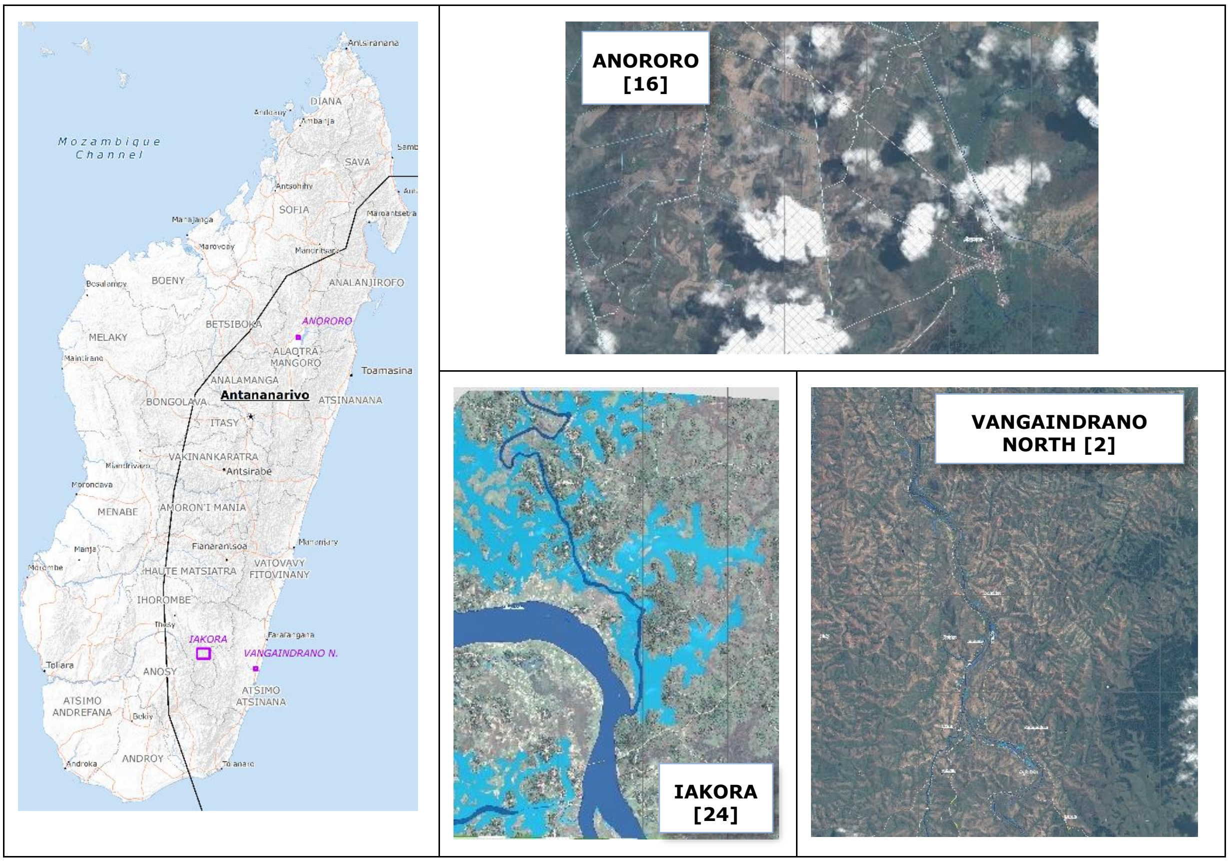
Consequences within the AOI

AMBOFIADABO [06]	Unit of measurement		Destroyed	Highly damaged	Moderately damaged	Negligible to slight damage	Total affected	Total in AOI
Flooded Area		ha					1017.4	
Estimated population	No. of inhabitants						1388	4376
Settlements	Residential	No.	0.0	86.0	225.0	0.0	311.0	N/A
Transportation	Secondary roads	km	0.0	0.0	0.0	0.0	0.0	26.7
	Local roads	km	0.0	3.2	3.0	0.0	6.2	274.0

$$\frac{1\,388}{4\,376} * 100 = 31.7\,\%$$

Figure 77 - *Copernicus EMS © 2017, [EMSR197] Maroantsetra [01]: Delineation Map; Maroantsetra [07]: Grading Map; Ambodiadabo [06]: Grading Map.*

C. ALAOTRA MANGORO, IHOROMBE, ATSIMO ATSINANA Regions: Anororo, Iakora and Vangaindrano North



$$\% \, Pop.affected = \frac{Tot.affected}{Tot.in \, AOI} * 100$$

Consequences within the AOI

ANORORO [16]	Unit of measurement		Destroyed	Highly damaged	Moderately damaged	Negligible to slight damage	Total affected	Total in AOI
Estimated population	No. of inhabitants						NA	3790
Settlements	Residential	No.	9	2	4	0	15	NA
Transportation	Local roads	km	0.1	0.0	0.0	0.0	0.1	39.2

$$\frac{NA}{3\,790} * 100 = NA$$

Consequences within the AOI

IAKORA [24]	Unit of measurement		Destroyed	Highly damaged	Moderately damaged	Negligible to slight damage	Total affected	Total in AOI
Burnt/Flooded/Affected area		ha	NA	NA	NA	NA	20.4	
Estimated population	No. of inhabitants						NA	4773
Transportation	Bridge	No.	0	0	0	0	0	3
	Local roads	km	0.0	0.0	0.0	2.5	2.5	57.8

$$\frac{NA}{4\,773} * 100 = NA$$

Consequences within the AOI

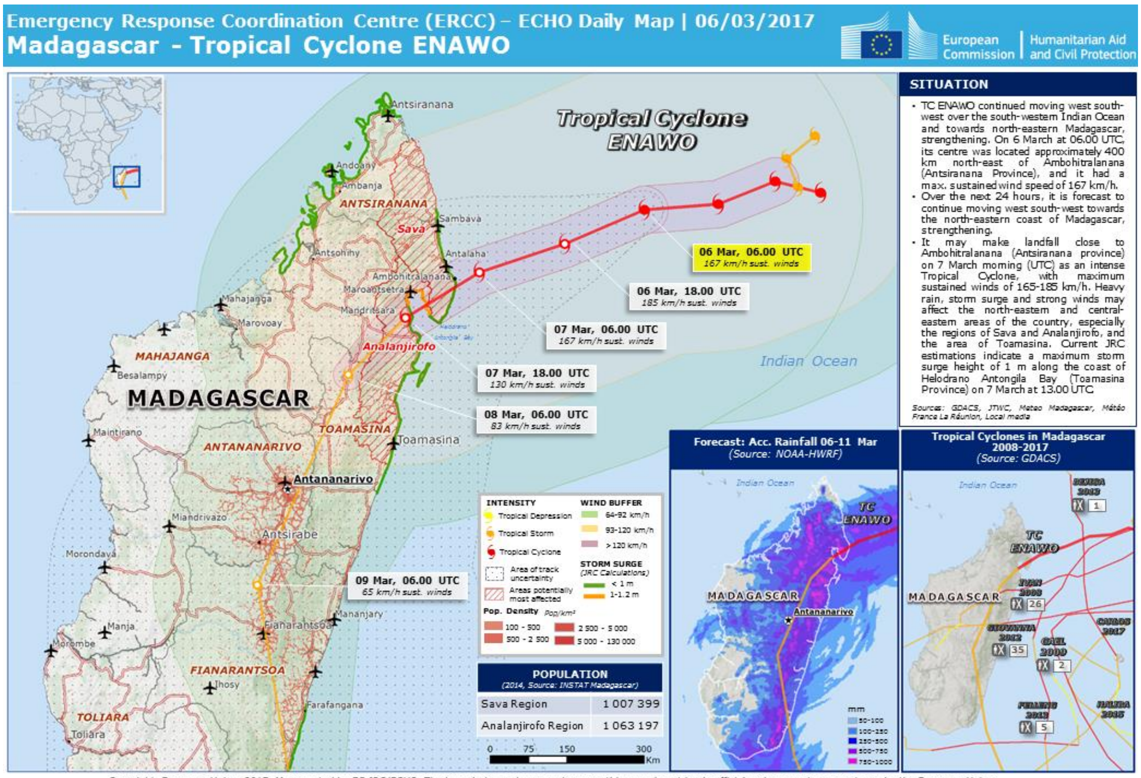
VANGAINDRANO NORTH [2]	Unit of measurement		Affected	Total in AOI
Flooded area		ha	394.9	
Estimated population	No. of inhabitants		480	4165
Transportation	Bridge	No.	2	6
	Secondary roads	km	0.1	6.8
	Local roads	km	0.2	49.6

$$\frac{480}{4\,165} * 100 = 11.5\,\%$$

Figure 78 - *Copernicus EMS © 2017, [EMSR197] Anororo [16]: Grading Map; Iakora [24]: Grading Map; Vangaindrano North [02]: Delineation Map.*

Annex 9 – ERCC ECHO Daily Maps

6 March 2017



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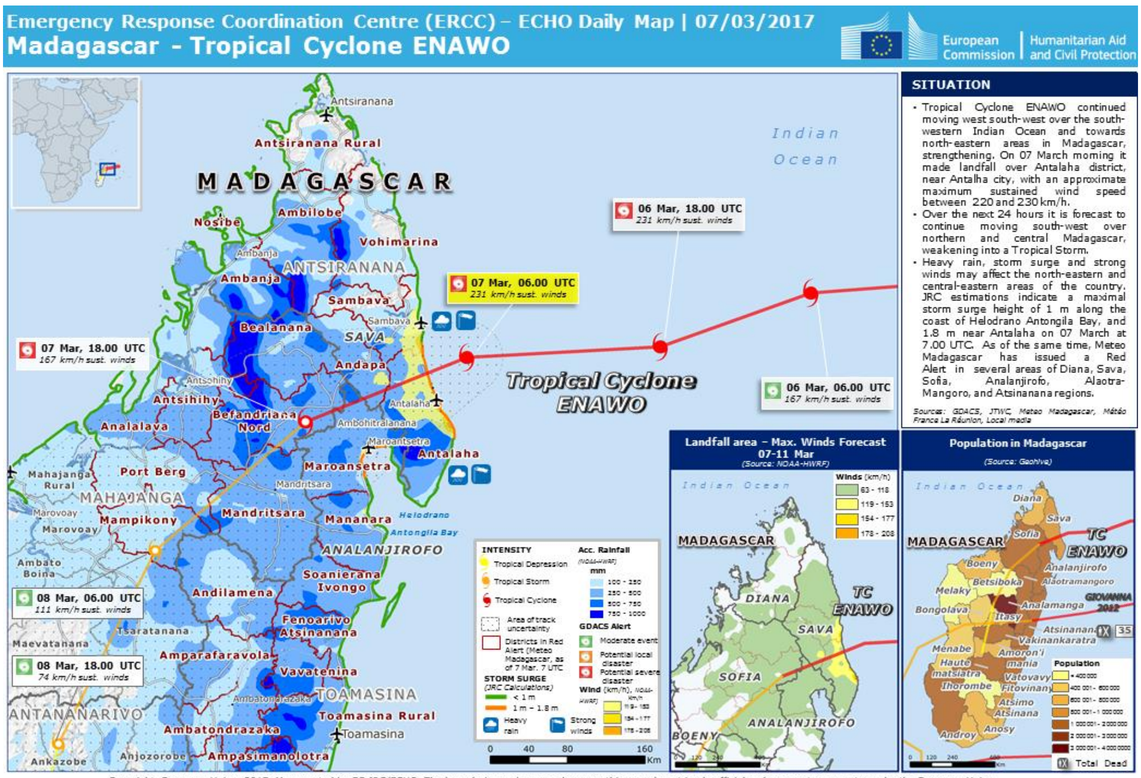
7 March 2017



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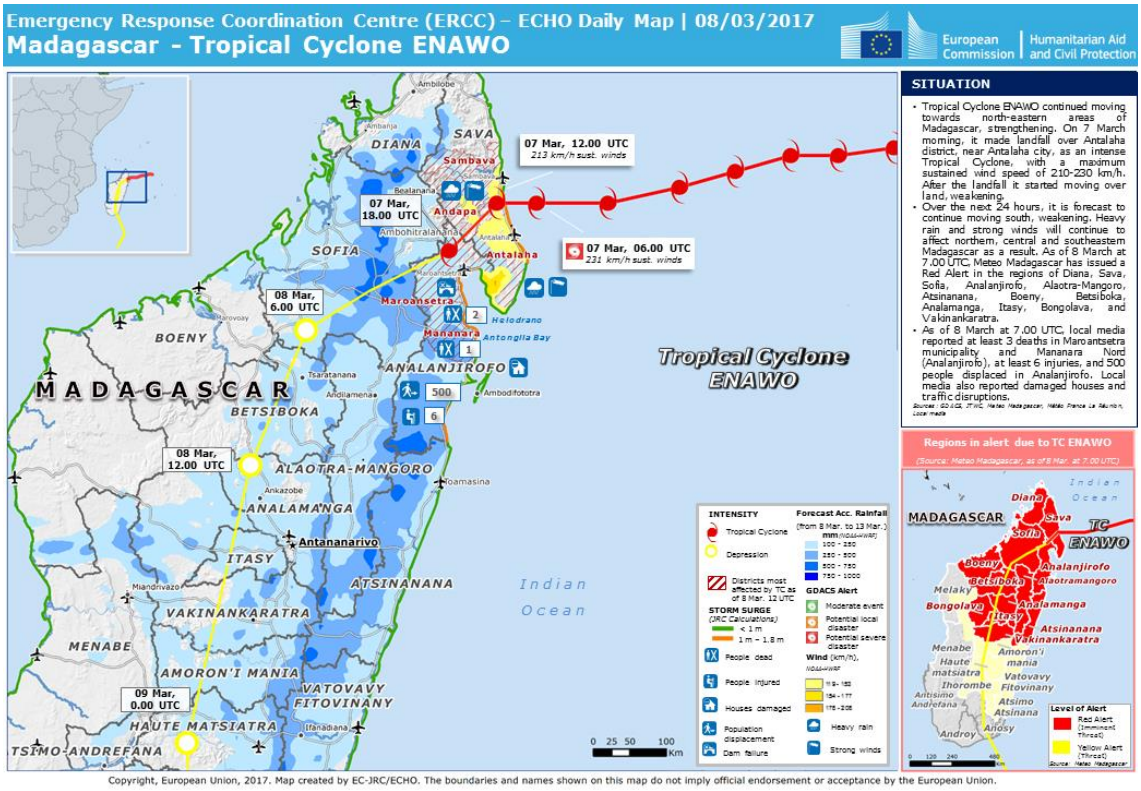
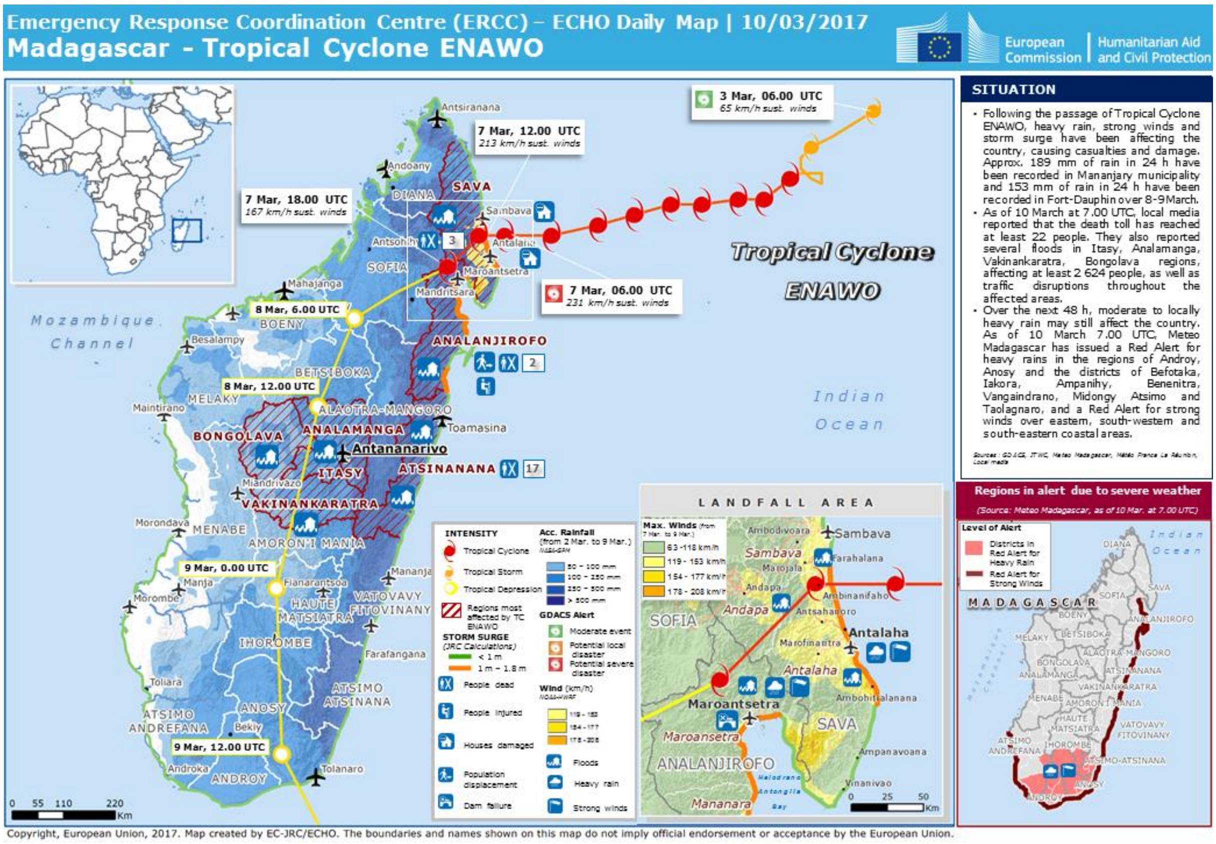
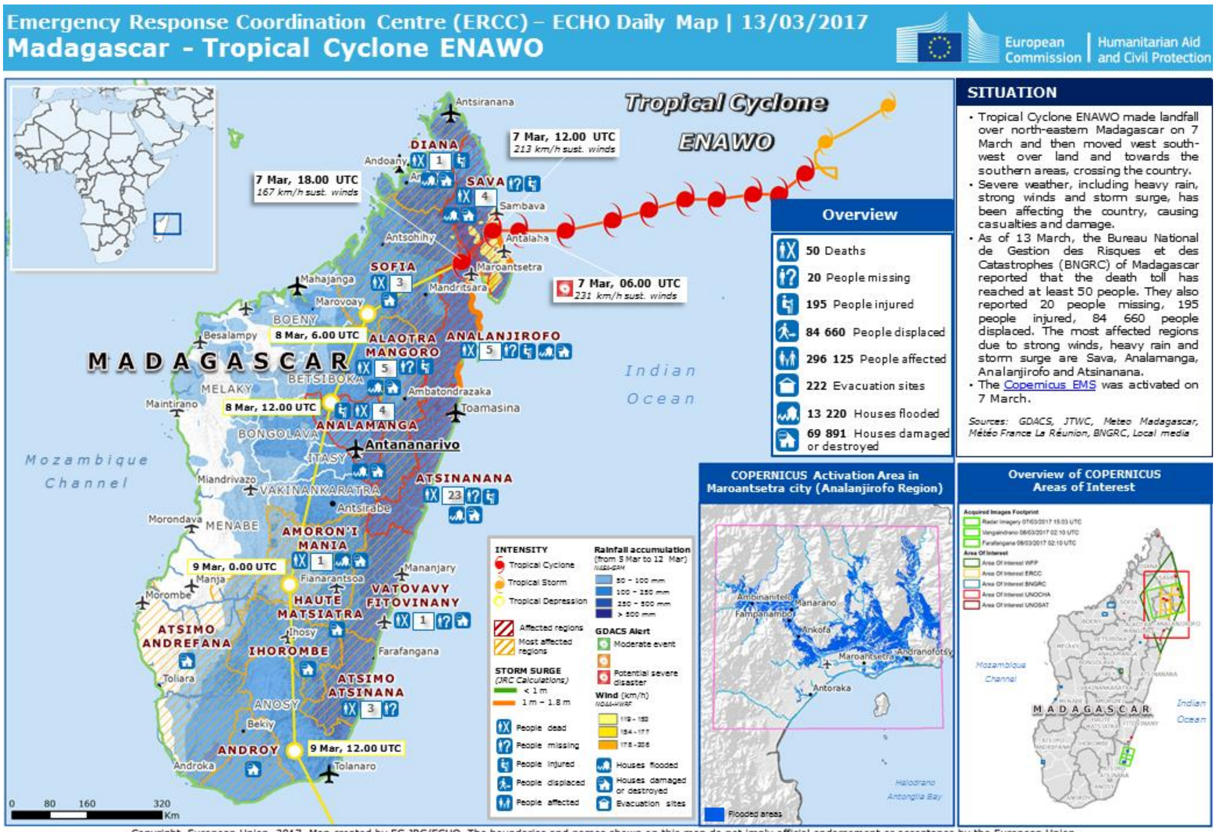
8 March 2017



10 March 2017



13 March 2017



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