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Tropical Cyclones and Storm Surge Modelling Activities

New systems developed for the Tropical Cyclones

Pamela Probst

Alessandro Annunziato

George Breyiannis

Thomas I. Petroliagkis

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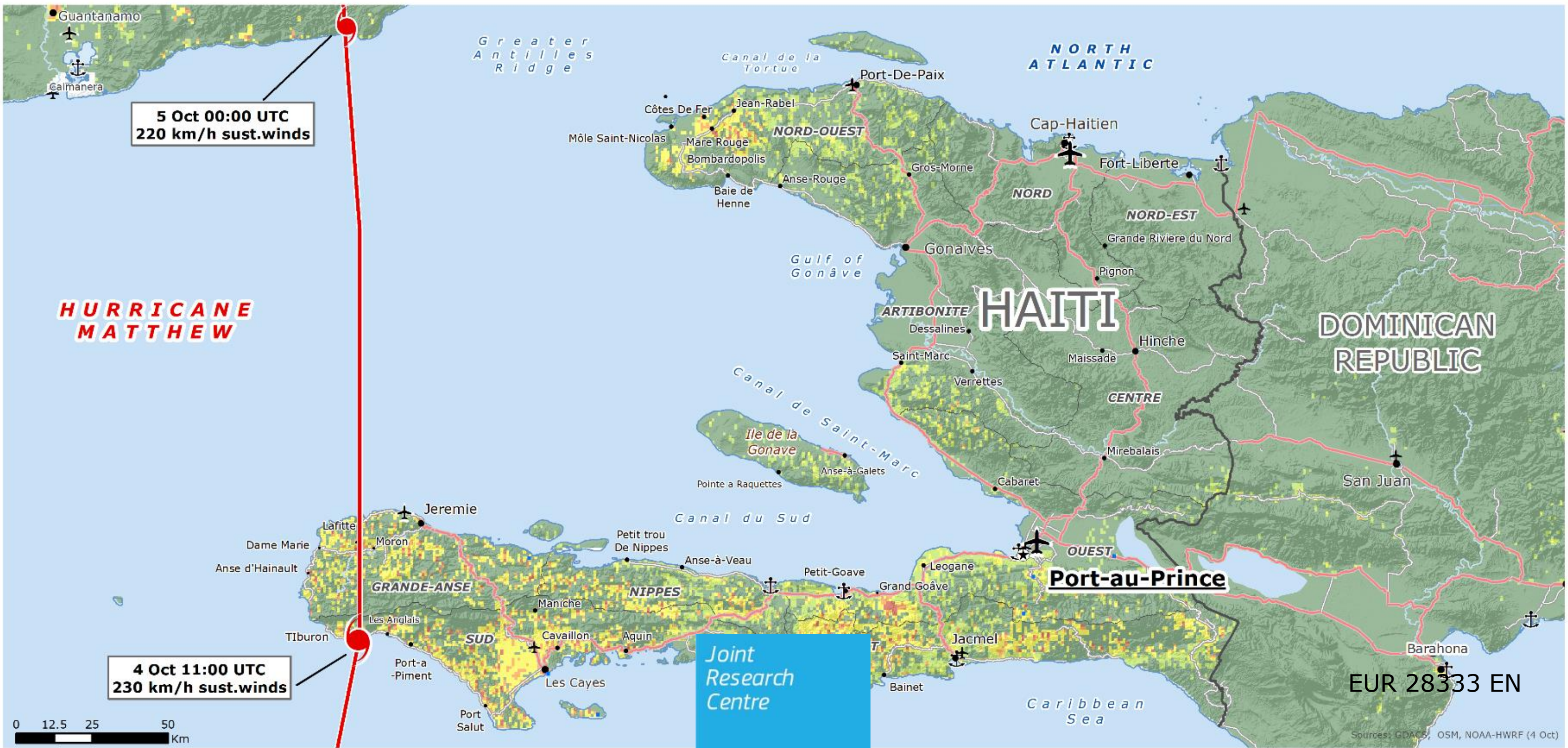

Joint Research Centre

EUR 28333 EN

Contact information
Name: Pamela Probst
Address: Via E. Fermi 2749, 21027 ISPRA (VA), Italy
Email: pamela.probst@ec.europa.eu
Tel.: +39 0332 789020

JRC Science Hub
https://ec.europa.eu/jrc

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Contents

Abstract

The Global Disasters Alert and Coordination System (GDACS) automatically invokes ad hoc numerical models to analyse the level of the hazard of natural disasters like earthquakes, tsunamis, tropical cyclones, floods and volcanoes. The Tropical Cyclones (TCs) are among the most damaging events, due to strong winds, heavy rains and storm surge. In order to estimate the area and the population affected, all three types of the above physical impacts must be taken into account. GDACS includes all these dangerous effects, using various sources of data.

The JRC set up an automatic routine that includes the TC information provided by the Joint Typhoon Warning Center (JTWC) and the National Oceanic and Atmospheric Administration (NOAA) into a single database, covering all TCs basins. This information is used in GDACS for the wind impact and as input for the JRC storm surge system. Recently the global numerical models and other TC models have notably improved their resolutions, therefore one of the first aim of this work is the assessment and implementation of new data sources for the wind, storm surge and rainfall impacts in GDACS. Moreover the TC modelling workflow has been revised in order to provide redundancy, transparency and efficiency while addressing issues of accuracy and incorporation of additional physical processes. The status of development is presented along with the outline of future steps.

1 Introduction

The Joint Research Centre has developed the Global Disasters Alert and Coordination System (GDACS, www.gdacs.org) in collaboration with the United Nations Office for Coordination of Humanitarian Support (UN-OCHA). The system processes automatically available information regarding natural disasters like earthquakes (including subsequent tsunamis), tropical cyclones, floods and volcanoes. The purpose of this analysis is to provide early awareness to relevant entities and authorities regarding potentially catastrophic consequences of such natural phenomena. More over the information is publicly available in the aforementioned website, which also serves as an aggregator of corresponding information and analysis from other institutions and agencies.

The Tropical Cyclones (TCs) are among the most damaging events, due to their three dangerous effects: strong winds, heavy rains and storm surge. In order to estimate the area and the population affected all the three types of physical impacts must be taken into account. GDACS includes all these dangerous effects, using various sources of data.

The JRC is currently using the information included in the TC bulletins (see Section 2.1.1) for the wind impact for the wind impact, while the heavy rain impact is obtained using the NOAA Ensemble Tropical Rainfall Potential (eTRaP) 6h accumulation rain. A more computational intensive analysis has been set up for the estimation of the expected storm surge due to the meteorological conditions imposed by the TC. This utilizes the pressure and wind field to compute the corresponding water level rise. An in-house procedure has been developed in order to define the necessary input for this calculation and the output includes the forecasting of the inundated areas along the path of the TC. A scheme of the current TC GDACS system is presented in **Figure 1**.

The current overall GDACS alert level for the TCs is based only on the wind impact and uses a risk formula that includes the TC wind speed, population affected and the vulnerability of the affected country. Depending on these parameters, the three types of alerts shown in **Table 1** are adopted. A specific alert level for the storm surge and rain impact is also created, but it is not yet included in the overall alert. More information can be found at: www.gdacs.org/model

GDACS TC ALERTS		
	GREEN ALERT	Moderate event, International Assistance not likely
	ORANGE ALERT	Potential local disasters, International Assistance might be required
	RED ALERT	Potentially severe disasters, International Assistance is expected to be required

Table 1 – GDACS TC alert levels

This report outlines the initiatives and progress of updating this simulation workflow carried out within 2016. A number of reasons suggested this revision including the availability of new models and data and the need to facilitate additional features and physical processes.

A brief description of the data sources and models available for the TCs is presented in Section 2, while the results of the tropical cyclones and storm surge activities are presented respectively in Section 3 and 4. Concluding remarks are in Section 5.

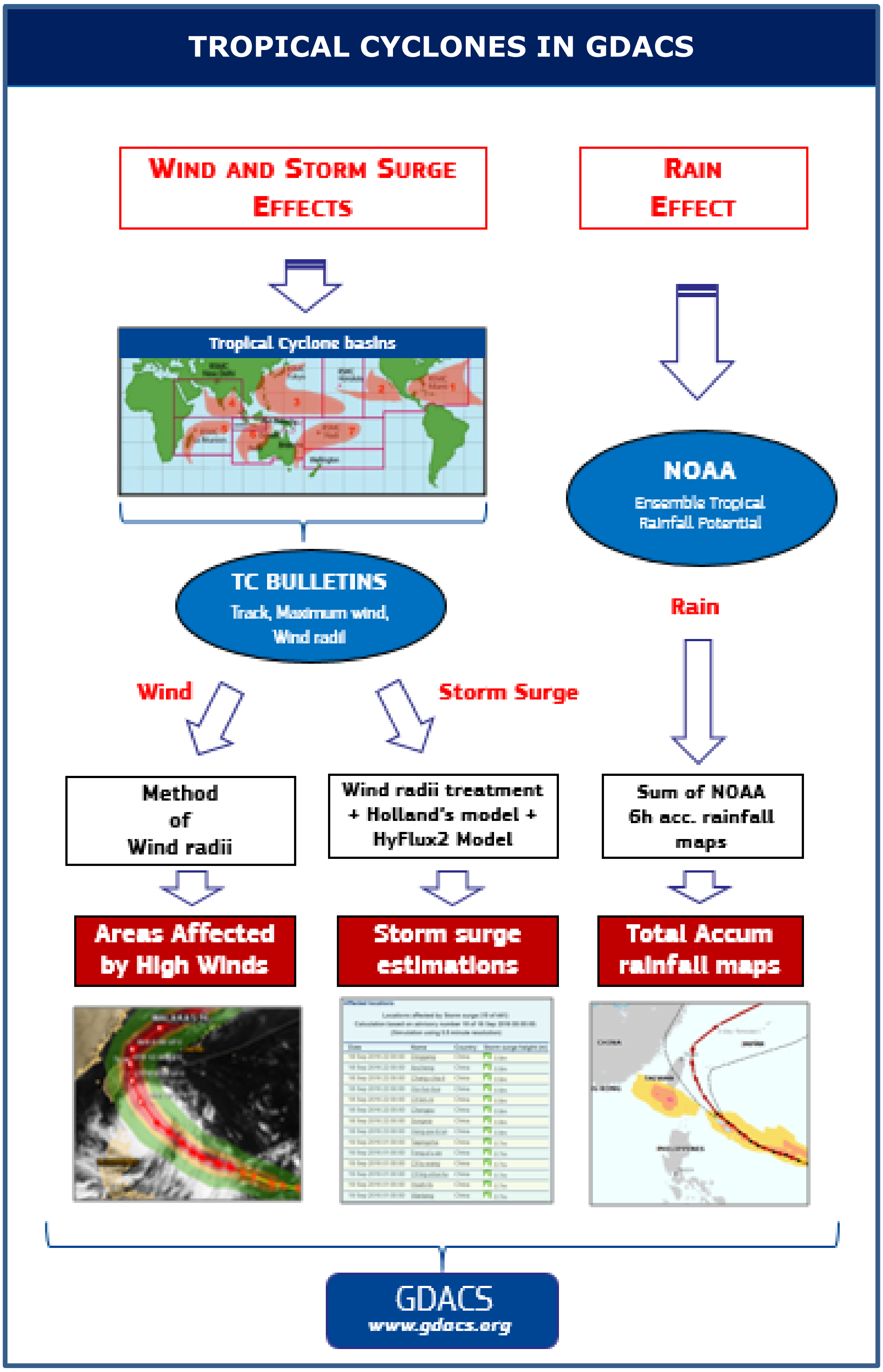

Figure 1 - Current TC system in GDACS.

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 these data and models is presented in this Section.

2.1.1 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 each 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 such 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.

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/.

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

2.1.2 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. 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 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

The JRC is currently testing these new sources of information, the first preliminary results are presented in Section 3.3 (HWRF) and in Section 4.2 (ECMWF).

2.1.3 Satellite data

Another source of TC data is the Satellite information. In this report two different products are presented:

- Multiplatform Tropical Cyclone Surface Winds Analysis' (MTCSWA) of NOAA - National Environmental Satellite, Data, and Information Service (NESDIS)
- e-surge project

NOAA-NESDIS: *Multiplatform Tropical Cyclone Surface Winds Analysis (MTCSWA)*

NOAA division that produces a composite product based on satellite information is the National Environmental Satellite, Data, and Information Service (NESDIS). Their product related to TCs is called Multiplatform Tropical Cyclone Surface Wind Analysis (MTCSWA), that provides six-hourly estimate of cyclone wind fields based on a variety of satellite based winds and wind proxies. Several data, text and graphical products are available.

— More information: http://rammb.cira.colostate.edu/products/tc_realtime/

— Data download: ftp://satepsanone.nesdis.noaa.gov/MTCSWA/

Note: the availability of data has an expiration date (roughly a month or so). It is envisioned that integration of similar information derived from satellite data analysis will provide additional feedback for validation/verification purposes in the future. This product has been used in the validation of the impact of TC GIOVANNA (see more information in Probst et al. 2012).

Another important satellite product for storm surge activities is coming from the e-surge project.

eSurge

The eSurge project, founded by the European Space Agency, was set up to create a service that will make earth observation data available to the storm surge community, both for historical surge events and as a demonstration of a near real time service.

The eSurge Project has run from 2011 to 2015, with an extension covering the first quarter of 2017, while a specific project for Venice (eSurge-Venice) has run from 2012 to 2015.

— eSurge: http://www.storm-surge.info/

— eSurge-Venice: http://www.esurge-venice.eu/

During this project, new techniques and methodologies have been developed and tested, utilising earth observations from satellites, in particular scatterometer (for wind components) and altimeter (for sea level height) data, for improving water level forecasts (storm surge) on coastal areas.

Moreover, for each TC GDACS red alert, a specific page for the eSurge data had been created in GDACS. An example of "e-Surge Live" in GDACS for TC NEPARTAK can be found at: http://www.gdacs.org/Cyclones/esurgeinfo.aspx?name=NEPARTAK-16

In the near future this product will be included in GDACS and could be used more frequently in the TC and storm surge modelling activities.

2.1.4 Discussion and next steps

The above wealth of information and modelling data provide however a range of contradicting information that stems from the inherit uncertainty regarding TC attributes. The various models produce a wide range of estimations in terms of TC location, intensity and characteristics.

Our current TC modelling is based on the location, transitional velocity and wind radii. These data can be seen to deviate significantly according to the source (**Table 2**).

Variable	JTWC	HWRF ATCF	NESDIS
RADIUS OF 064 KT WINDS [NM]	25, 25, 25, 25	101, 84, 59, 79	60, 55, 35, 45
RADIUS OF 050 KT WINDS [NM]	65, 65, 65, 65	135, 123, 97, 123	180, 135, 65, 155
RADIUS OF 034 KT WINDS [NM]	120, 140, 150, 125	262, 226, 187, 232	315, 315, 155, 225

Table 2 – Wind radii from various sources for TYPHOON 09W (CHAN-HOM) on 8 June 2015 00:00h

The disparity in the values of the wind radii is evident in the table above. The parametric profile given by NOAA-NESDIS suggests higher values for both the radius of maximum wind (R_{max}) and maximum wind value (V_{max}). It also retains higher values away from the centre. It has been seen that the profile produced by the JRC's model has a tendency to underestimate the R_{max}. Therefore, the possibility of incorporating the NOAA-NESDIS data is one option to enhance the current approach. Moreover, these data could be validated using the e-surge products.

In addition, the TC wind field can be far from symmetric around the centre. In **Figure 2**, this asymmetry is shown for the ECMWF and NESDIS data.

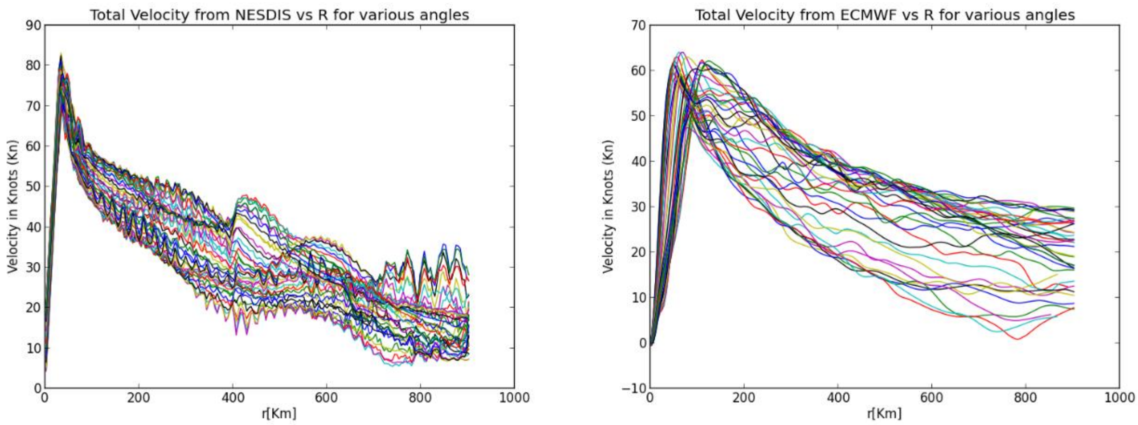

Figure 2- Wind profiles for various angles for TC CHAN-HOM, bulletin 31

Until recently the numerical simulations of ECMWF couldn’t resolve the high gradient near the radius of maximum wind due to their low resolution, and the HWRF data were not globally available. However this year, the ECMWF has upgraded their resolution to 9 km and even better, the HWRF data have also being upgraded to even higher resolution near the core and are now globally available (see Section 2.1.2). Therefore, the option to incorporate the data from numerical simulations (ECMWF, HWRF) or synthetic models such as the ones from NESDIS is being assessed within our operational constrains.

It is likely, however, that an ensemble set of runs will be required and such an option is foreseen during future development. The incorporation of direct satellite information is also under investigation.

Ultimately, the only way to assess the validity of the forecasting is by comparing with local measurements. The computed storm surge computations can be used as the control variable through comparisons with buoy measurements, where available. That way, a feedback to the TC model can provide corrections that will enhance the quality of the results.

3 Tropical Cyclones activities: wind and rain effects

3.1 New Tropical Cyclone Wind alert system

3.1.1 Current wind alert system

The GDACS alert levels for the TCs are based only on the Wind impact and uses a risk formula that includes:

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

This system calculates the areas along the track possibly affected by high winds and estimates the population and critical infrastructure included in these areas. For this calculation, the wind radii data provided in the TC bulletins are used and three different buffers are created. The thresholds of these buffers used in GDACS are shown in Table 3, while an example of the GDACS's wind buffers for the TC NEPARTAK is shown in Figure 3. More information on this system can be found in Vernaccini et al. (2007).

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

Table 3 - Wind buffers used in GDACS

3.1.2 Limitation of the current wind Alert System

Over the last few years this system has shown the following limitations:

(a) Impact of the most intense TCs

(b) Asymmetry of the TCs not included

(a) **<u>Impact of the most intense TCs</u>**

The current GDACS system calculates

- the number of people within the "red buffer", that represents the area possibly affected by Hurricane/Typhoon wind strengths (winds ≥ 119 km/h)
- the number of people within the "green and yellow buffers", that represents the area possibly affected by Tropical Storm winds.

In case of an intense TC, this system is not able to represent in detail the possible impact, because it uses only one single buffer for the winds ≥ 119 km/h (red buffer). This buffer could include winds from 119 km/h to over 252 km/h, without distinguishing the areas potentially affected by the very strong and destructive winds like Category 4 or 5 Hurricane from the areas potentially affected by only Category 1 winds. The wind field provided by GDACS is shown in Figure 3, while the one using the more detailed wind field of NOAA HWRF is shown in Figure 4.

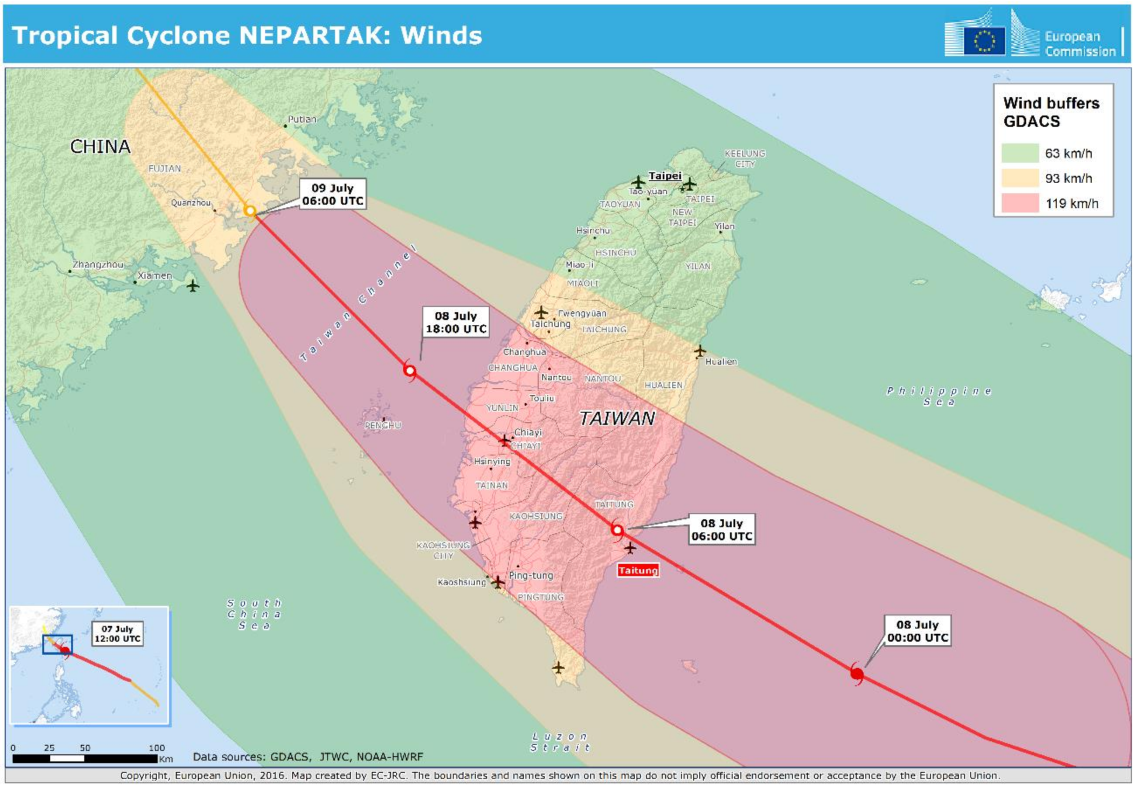

Figure 3 - TC NEPARTAK 2016 (source: GDACS, as of Adv. 17)
(wind buffer, green: 63-92 km/h, orange: 93-118 km/h, red: > 118 km/h)

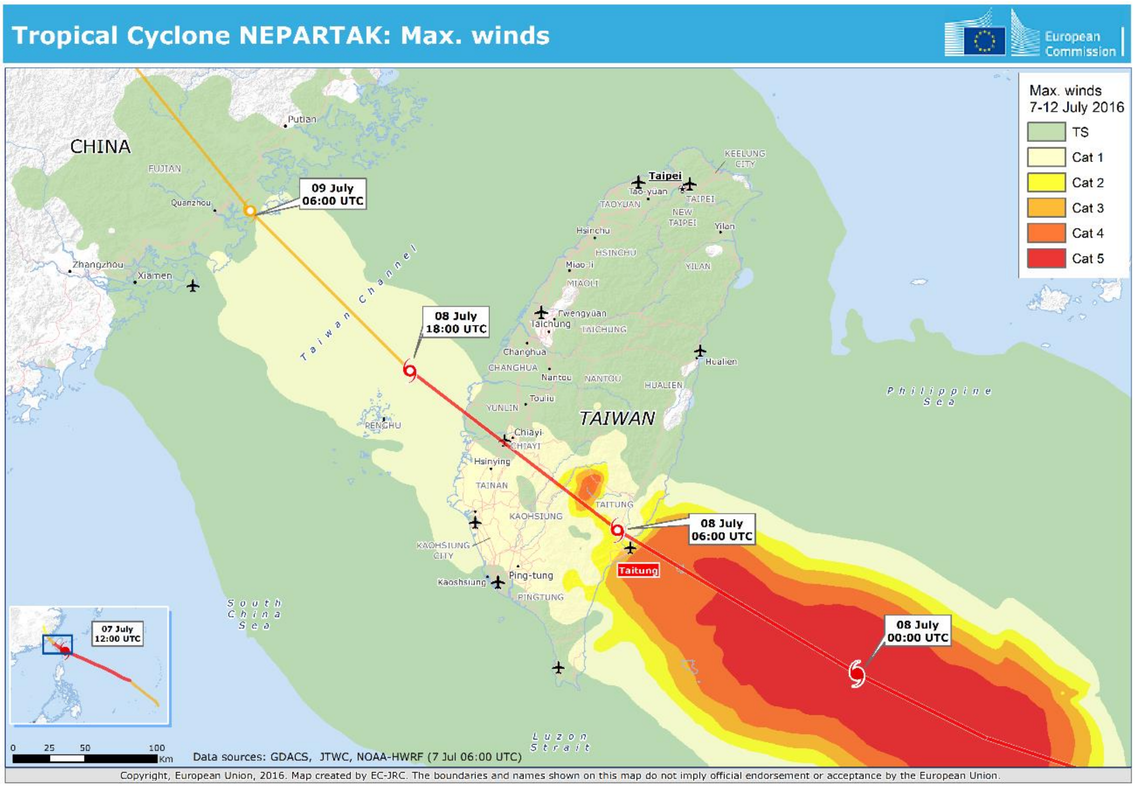

Figure 4 - TC NEPARTAK 2016 (source: NOAA-HWRF).
The colour classification is based on the Saffir Simpson Hurricane Scale (see **Table 4**)

(b) Asymmetry of the wind field not included

The wind field of a TC is not axis-symmetric, so several additional phenomena must be taken into account in order to model the real asymmetry of the wind field. One of the factors that can contribute to the asymmetric structure of a TC is its movement. In fact the strongest winds are on the right side[1] of the storm (left side in the southern hemisphere). For example, if a TC is moving towards north, the strongest winds will be on the right side (see the image below):

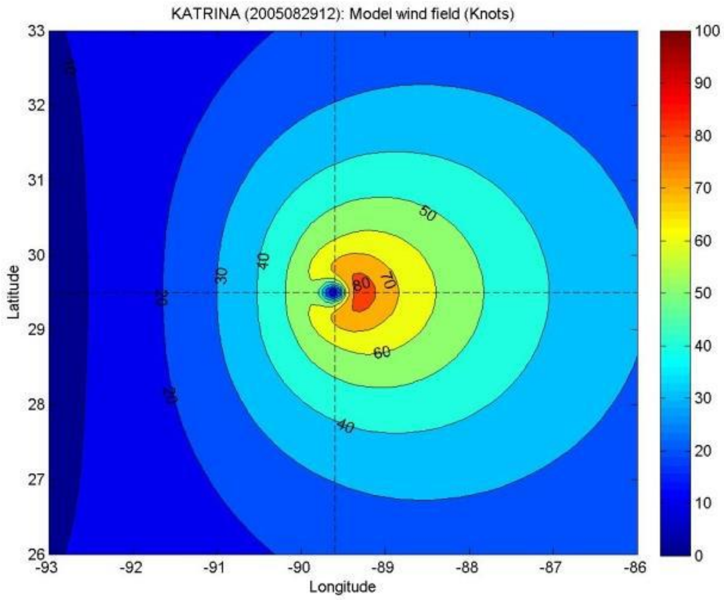

Figure 5 - HURRICANE KATRINA wind field, obtained using the Holland's parametric model.

A stationary TC has 140 km/h winds, but if it starts moving north at 10 km/h, the max. winds are up to 150 km/h on the right side and only 130 km/h on the left side. The TC bulletins already take this asymmetry into account and in this case the highest winds are 150 km/h (see http://www.aoml.noaa.gov/hrd/tcfaq/D6.html). Also the wind radii provided in the TC bulletins take into account the movement of the TC.

For example:

MAX SUSTAINED WINDS 90 KT WITH GUSTS TO 110 KT.

64 KT.......105NE 90SE 40SW 70NW.

50 KT.......140NE 140SE 60SW 90NW.

34 KT.......200NE 200SE 100SW 150NW.

Wind radii

64 KT. 105NE 90SE 40SW 70NW

means that winds of 64 kt are possible anywhere within that quadrant out to 105 nm NE, 90 nm SE, 40 nm SW, and 70 nm NW, of the estimated center of the storm.

[1] Right side of the storm" is defined with respect to the TC's motion: if the TC is moving to the north, the right side would be to the east of the TC, if it is moving to the west, the right side would be to the north of the TC.

However, in the current system used in GDACS, the max value of the wind radii is used. For example, for the red buffer the following values are used to create the buffer:

64 KT.......105NE 105SE 105SW 105NW

instead of

64 KT. 105NE   90SE   40SW   70NW

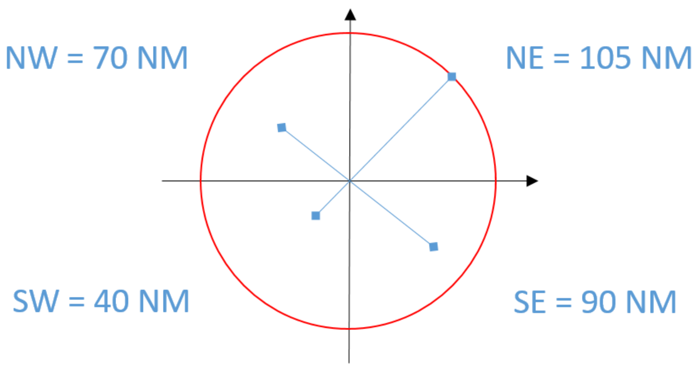

Figure 6 - System currently used in GDACS to create the wind buffer

Therefore, this system doesn't take into account the asymmetry of a TC, thus describing an area larger than the real one. This could generate a false GDACS Alert: e.g. a Red alert instead of Green Alerts, like for the Tropical Cyclone MALAKAS.

Example of a "False" GDACS Red Alert: Tropical Cyclone MALAKAS

TC MALAKAS was an intense Typhoon that formed over the Pacific Ocean in September 2016 and moved towards north-eastern Taiwan. Before passing Taiwan, a Red Alert was issued by GDACS for this TC, because the red buffer included part of NE Taiwan and it was a very intense Typhoon (max. sustained winds > 200 km/h), see bulletin 17 of 15 September 18:00 UTC[2]. According to this bulletin, 880 000 people were inside the red buffer and therefore possibly affected by Typhoon strength winds.

This alert level was not correct, because NE Taiwan was on the left side of the TC, where the winds were less intense, due to the movement of the TC (see description above). The strongest winds where on the right side of the TC and in this area there was only a small Japanese island (Yonaguni, pop: 1 645) and not an area with a large number of people. Comparing the GDACS buffers (**Figure 7**) with those created using the NOAA HWRF data (see **Figure 8**), it is clear that the GDACS RED alert was not correct: NE of Taiwan was affected only by Tropical Storm winds strength and not by Typhoon strength winds.

Note: after the TC bulletin nr. 19, the forecasted track changed (more towards east) and the NE areas of Taiwan were not anymore included in the red buffer and the GDACS alert level was reduced to Orange.

As described above, the current GDACS wind alert system has some limitations, therefore the JRC evaluated the possibility to implement a new system for the wind buffers to have a more correct TC wind impact and GDACS alert, especially when there is a very strong TC. This new system is based on the Holland parametric model currently used for the storm surge system and is described in the next section.

[2] See: http://www.gdacs.org/Cyclones/report.aspx?eventid=1000305&episodeid=17&eventtype=TC

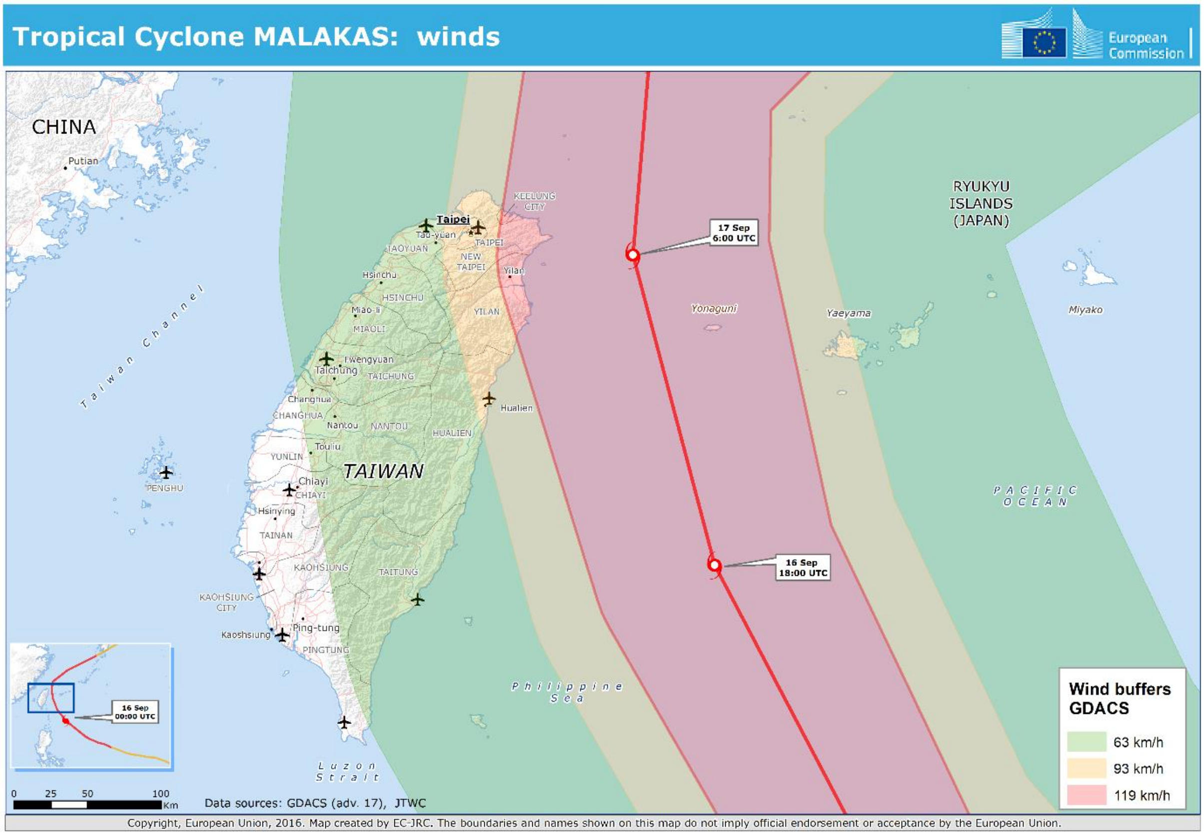

Figure 7 - GDACS wind buffers for TC MALAKAS (as of Adv. 17, 15 Sep. 18:00 UTC)

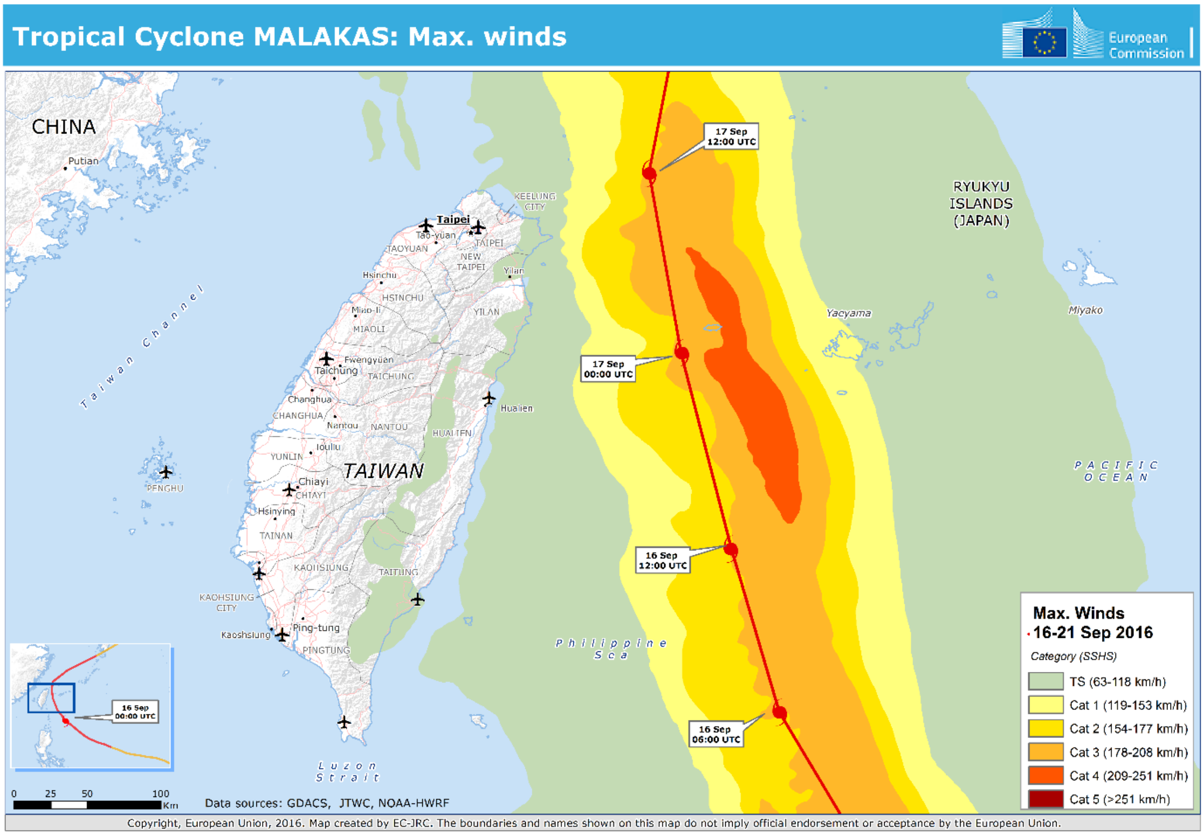

Figure 8 – NOAA-HWRF wind buffers for TC MALAKAS

3.1.3 Development of the new wind system

In order to have a better wind alert system, the JRC has developed the following procedure:

(a) Calculation of the new wind field, using the Holland parametric model

(b) Classification of the population affected using the SSHS

(a) Calculation of the new wind field, using the Holland's parametric model

A Python script based on the Holland's parametric model developed for the JRC storm surge system has been created in order to create the wind field. This system uses as input

- TC bulletins (*Track, Vmax, wind radii*)
- Other parameters (e.g R_{max}, *B*) calculated by the Monte Carlo method developed for the JRC storm surge system.

The Coriolis effect and the translational velocity (multiplied by a weight that decays exponentially with the distance from the TC eye) have been also included in this system.

The Holland's method currently used in the JRC storm surge system simulates the wind field only over the sea and not over land, because until 1 November 2016 the wind radii were provided only over the sea and not over the land. More information can be found in Probst and Franchello (2012).

(b) Classification of the population affected using the SSHS

The new system that the JRC is developing uses the Saffir-Simpson Hurricane Wind Scale (SSHS), instead of using one single class for the Hurricane/Typhoon winds (≥ 119 km/h, GDACS's red buffer). This new classification is shown in the table below.

CATEGORY		1-min Sustained Winds	
		knots	km/h
Hurricane	**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 4 - TC Classification (Saffir-Simpson Hurricane Wind Scale)
(see http://www.nhc.noaa.gov/aboutsshws.php)

An additional Python script is used to classify the population potentially affected by each Category winds strength (see thresholds in **Table 4**). The script:

- \# 0. read the characteristics of the input file
  - obtained using the Monte Carlo method and interpolated every 15 minutes
- \# 1. extract an area of Landscan population corresponding to the required bounding box
- \# 2. resample the vmax file to the resolution of Landscan
- \# 3. classify the vmax file creating another array of values classified
- \# 4. count the population in each cell and assign the corresponding class
- \# 5. print output

The results are then stored into a xml file in GDACS (see **Figure 9**).

Note: this code has been **parallelized**.

3.1.4 Test case

The results of this new method for TC MALAKAS (Adv. 17, 15 Sep. 18:00 UTC) is shown in **Figure 11**. As described on page 12, this was a "False" GDACS Red Alert.

Comparing these results with the current GDACS system (**Figure 10**), it is clearly visible that using the new method only the small Japanese island was affected by Typhoon-wind strength and not the NE areas of Taiwan. In the current GDACS system there were 880 000 people potentially affected by winds > 120 km/h, while using the new system only 1 645 people are affected by winds > 120 km/h. Therefore, the new system in this case was more correct than the current GDACS system. However, a more detailed validation of this system needs to be performed.


```
<popvalues>
  <!--  Cyclone: MALAKAS-16 BullNo: 17 cellSize=2.0   -->
  <class>
    <value>
      <![CDATA[ wind>0 and <=33 ]]>
    </value>
    <category>TS</category>
    <popValue>161141227.0</popValue>
  </class>
  <class>
    <value>
      <![CDATA[ wind>33 and <=43 ]]>
    </value>
    <category>CAT. 1</category>
    <popValue>1645.0</popValue>
  </class>
  <class>
    <value>
      <![CDATA[ wind>43 and <=50 ]]>
    </value>
    <category>CAT. 2</category>
    <popValue>0.0</popValue>
  </class>
  <class>
    <value>
      <![CDATA[ wind>50 and <=58 ]]>
    </value>
    <category>CAT. 3</category>
    <popValue>0.0</popValue>
  </class>
  <class>
    <value>
      <![CDATA[ wind>58 and <=70 ]]>
    </value>
    <category>CAT. 4</category>
    <popValue>0</popValue>
  </class>
  <class>
    <value>
      <![CDATA[ wind>70 and <=1000 ]]>
    </value>
    <category>CAT. 5</category>
    <popValue>0</popValue>
  </class>
</popvalues>
```


Figure 9 - Example of xml file obtained using the new classification system

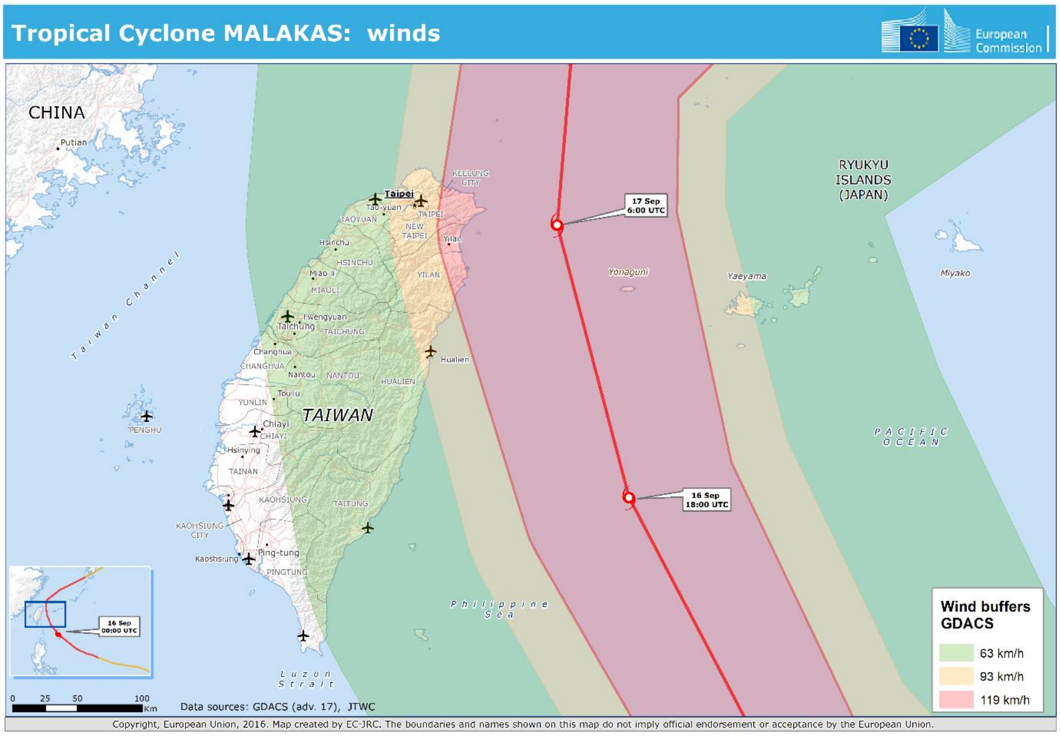

Figure 10 - GDACS wind buffers for TC MALAKAS (as of Adv. 17, 15 Sep. 18:00 UTC)

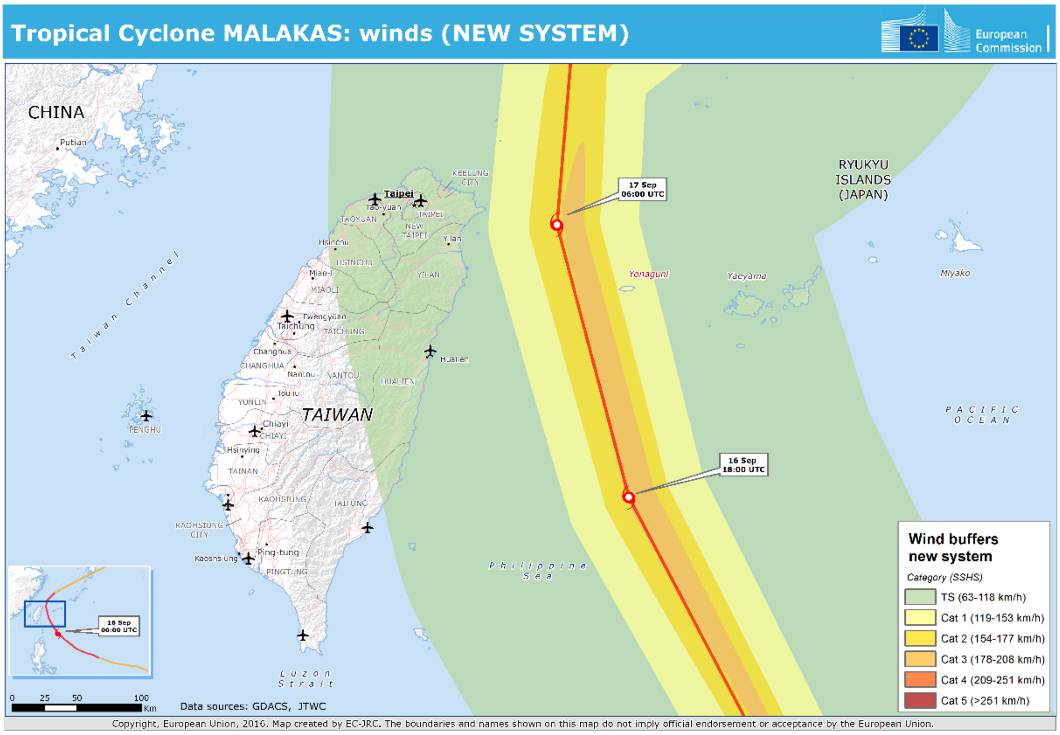

Figure 11 - GDACS new wind buffers for TC MALAKAS (as of Adv 17, 15 Sep. 18:00 UTC)

3.1.5 Future steps

(a) Assign the GDACS Alert level

This new system is being tested and a corresponding alert level will be set up. The alert level will consider the number of people possibly affected (for each SSHS Category) and the vulnerability of the country.

Currently, the JRC is analysing all GDACS TC alerts in order to validate the new procedure. Relevant information includes:

- TC information
- GDACS alert level
- Nr. of people affected Cat 1-5 (GDACS system)
- Number of dead (using the International Disaster Alert database EM-DAT CRED http://www.emdat.be/ , and official reports)
- international assistance
- Alert level in Reliefweb (http://reliefweb.int/)
- Glide number (http://glidenumber.net/)

These data will be used as a benchmark for the new wind system in the future.

Note:

- this system is **strongly dependent by the wind radii data** and these values could vary from source to source (as described in Section 2.1.4), therefore an ensemble method will be required and is foreseen during future development.
- This system is only for the wind impact, a **new specific alert system** for the **rainfall** and **storm surge** must be set up for the overall GDACS alert.
- JRC is also developing a new **Multi Risk Index** described in the next Section, that could be used for the alert level.
- Other wind field sources could be used (see the new HWRF implementation below).

(b) Implementation of the NOAA HWRF wind data

The JRC is also developing a method same as above, but using as input the HWRF data. As described in 2.1.2, this model provides a detailed wind field with a resolution of 2 km, including also the friction, that is not included in our implementation.

These TC products have been used for specific impact analysis and maps over the last year (see Section 3.3). Thus, a python script has been developed that read this data and calculate the population possibly affected by all the categories strengths winds of the SSHS (Table 4). More information on these utilizations are shown in Section 3.3.

The possibility to **utilize HWRF wind data** for the **wind and rainfall impacts** in GDACS, as well as **input** in the **JRC storm surge model**, will be assessed considering also on the time-availability of the data.

3.2 JRC TC Multi Risk Indicator

In October 2016, the JRC created a ***new multi risk indicator*** to identify the areas that were mostly affected by Hurricane MATTHEW. This index considers the wind speed, the rainfall and the population density in the area, as follows:

*Areas most affected: (Rain Class + Wind Class) * Population Class*

NOTE: This was only a **rapid preliminary evaluation** partially following the general definition of Risk, i.e.

*Risk = Hazard * Population Exposure * Vulnerability*

This analysis didn't include the hazard of storm surge, the vulnerability of the country and the climatological information. Work is under way for a more complete Combined Risk and Alert System.

3.2.1 Implementation

For this "multi risk indicator" the NOAA HWRF data have been used and the procedure has been tested for Hurricane MATTHEW, that hit Haiti on 4 October 2016 as a Category 4 Hurricane, and caused extensive damage and deaths.

Tropical Cyclone	Date	GDACS Alert	Country
MATTHEW	28 Sep – 9 Oct	RED	Haiti, Cuba, Bahamas, USA

Table 5 - TC used as a test for the Multi Risk Indicator

The first step was the classification of the Landscan™ **population** data, **HWRF winds**, using the Saffir Simpson Hurricane Scale, and the **HWRF rain,** using the total accumulation rainfall (see Tables below).

POPULATION	
Class	Pop (Landscan)
0	0 - 100
1	100 - 500
2	500 – 1'000
3	1'000 – 5'000
4	5'000 – 10'000
5	10'000 – 50'000
6	50'000 – 100'000

MAX. WINDS	
Class	Wind (SSHS)
0	TD
1	TS
2	Cat 1
3	Cat 2
4	Cat 3
5	Cat 4
6	Cat 5

RAINFALL	
Class	Rain
0	< 50 mm
1	50 – 100 mm
2	100 – 200 mm
3	200 – 300 mm
4	300 – 400 mm
5	400 – 500 mm
6	> 500 mm

Table 6 - Classification of the Population, winds and total accumulation rainfall

The HWRF data used, as well as the results of this preliminary analysis, are shown in the following maps.

Wind impact

MATTHEW affected Haiti with very strong winds. It made landfall near Les Anglais (south-western Haiti) on 4 October at 11:00 UTC, as very strong Category 4 Hurricane, with max. sustained winds of 230 km/h. Then it crossed over Grand'Anse (South-western Haiti) and moved towards Cuba, still as a Category 4 Hurricane.

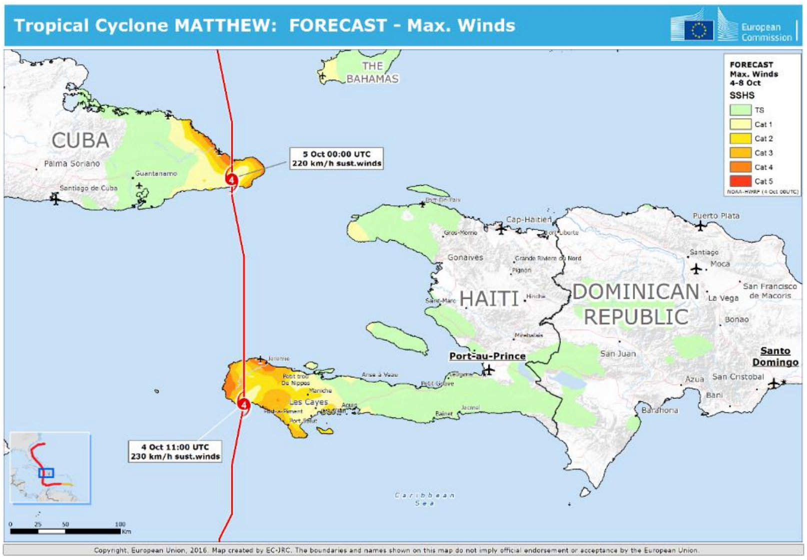

Figure 12 - Max winds over land on 4-8 Oct, (NOAA-HWRF, as of 4 Oct, 00:00 UTC)

Rain impact

MATTHEW caused also very heavy rainfall in Haiti, Dominican Republic, and Cuba during its passage. The total accumulated rainfall (shown only for land) over 4-9 October, according to NOAA-HWRF FORECAST, is shown in the map below. The amount of rainfall expected for southern and north-western Haiti was over 500 mm (see map below) with isolated amounts of 1000 mm (NOAA-NHC) in some areas of southern Haiti and south-western Dominican Republic. This amount of rainfall was <u>very high</u> compared to the monthly average of October (150-200 mm) and caused landslides and flash floods.

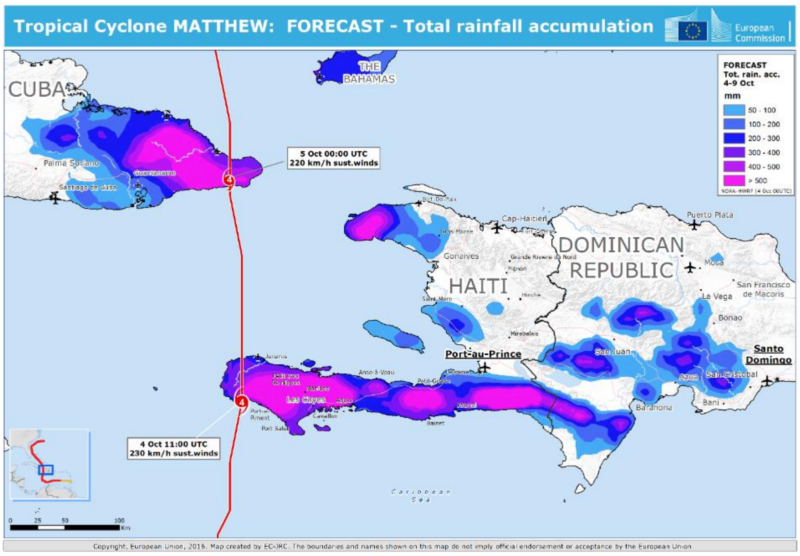

Figure 13 - Total Accum. rainfall forecast (over land) on 4-9 Oct (NOAA HWRF, 4 Oct, 00:00 UTC)

Population

The population density provided by Landscan™2014, is shown in the map below:

Figure 14 – Population density in the areas of the passage of MATTHEW.

Multi Risk Indicator

As described in the previous pages, the population density map, combined with the Wind and Rainfall maps produced the "Multi Risk Indicator" shown in **Figure 15**. According to this first preliminary analysis, the areas potentially most affected (Multi Risk Indicator: yellow, orange and red colours) were in:

- Southern Haiti: Grand'Anse, Sud, Nippes, Ouest and Sud-Est
- Central Haiti: Artibonite
- North-western Haiti: Nord-Ouest

As of 30 October 2016 (UN OCHA), the number of people affected by departments due to the passage of the Hurricane Matthew is shown in the table below.

DEPARTMENTS	PEOPLE AFFECTED (*As of 30 Oct 2016, UN OCHA*)	TOT. POPULATION (*GEOHIVE*)	% OF POP AFFECTED
Artibonite	69 000	1.7 million	4 %
Centre	-	746 000	-
Grand'Anse	468 000	468 000	100 %
Nippes	205 000	342 000	60 %
Nord	-	1.1 million	-
Nord-Est	-	394 000	-
Nord-Ouest	73 000	729 000	10 %
Ouest	221 000	4 million	6 %
Sud-Est	316 000	633 000	50 %
Sud	775 000	775000	100 %

Table 7 - Affected population by department

Sources: Total population, 2015 estimate (Geohive). Pop. Affected: UN OCHA: http://reliefweb.int/sites/reliefweb.int/files/resources/matthew_snapshot_31_oct_16.pdf

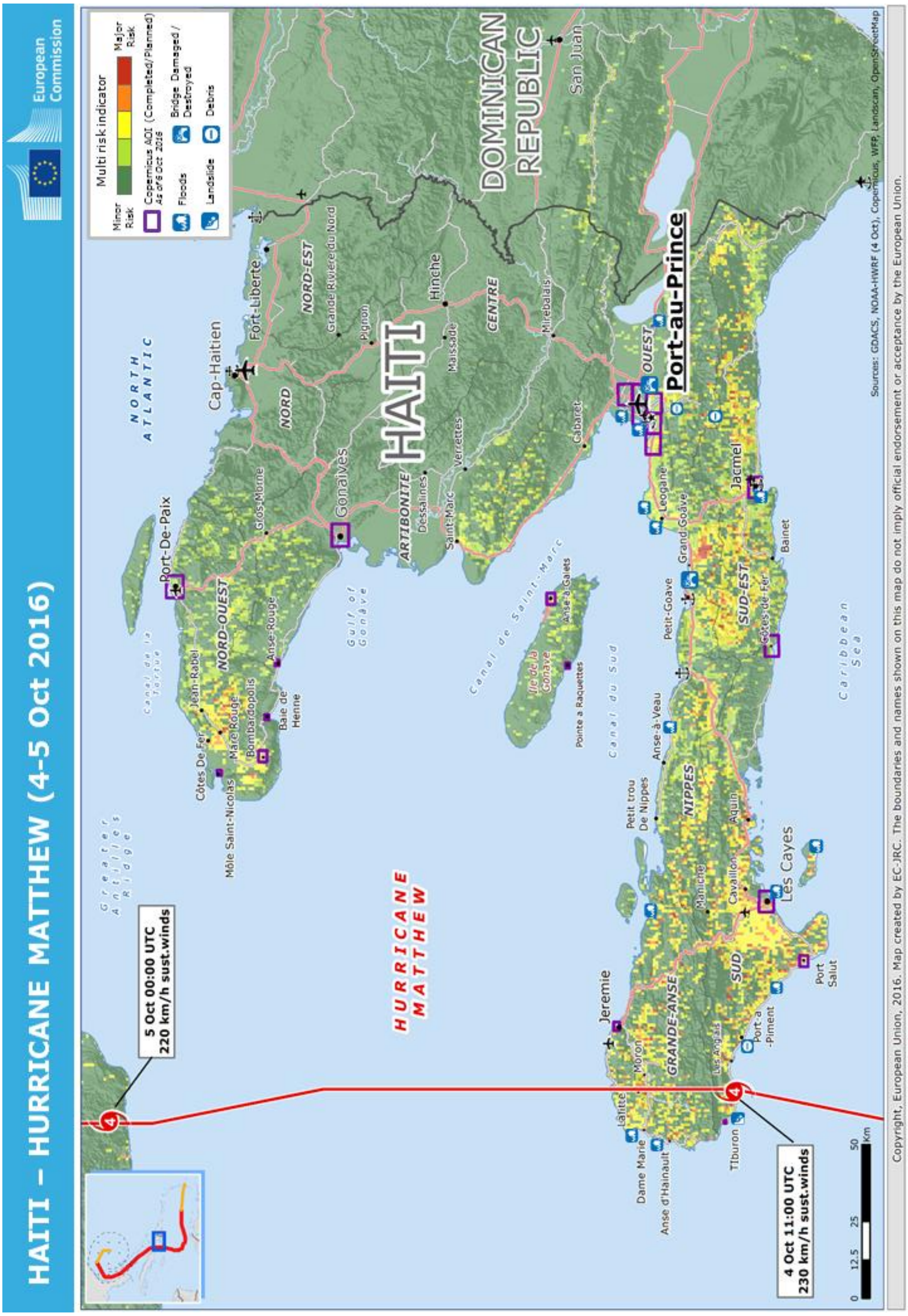

Figure 15 – JRC's Multi Risk Indicator: Areas possibly most affected (preliminary analysis)

The results of this preliminary analysis on the areas possibly most affected are in good agreement with the number of people affected, especially for the south-western areas. Only the risk index in the Nord-Ouest department seems overestimated (only 10% of population was affected). In this area, the NOAA HWRF model forecasted rainfall accumulation up to 600 mm while, the satellite measurements of NASA Global Precipitation Measurement (GPM) only up to 400 mm, as shown in Figure 16. Note: the total rainfall accumulated forecasted / measured by these two datasets is quite different also in other areas, therefore a more detailed analysis is required.

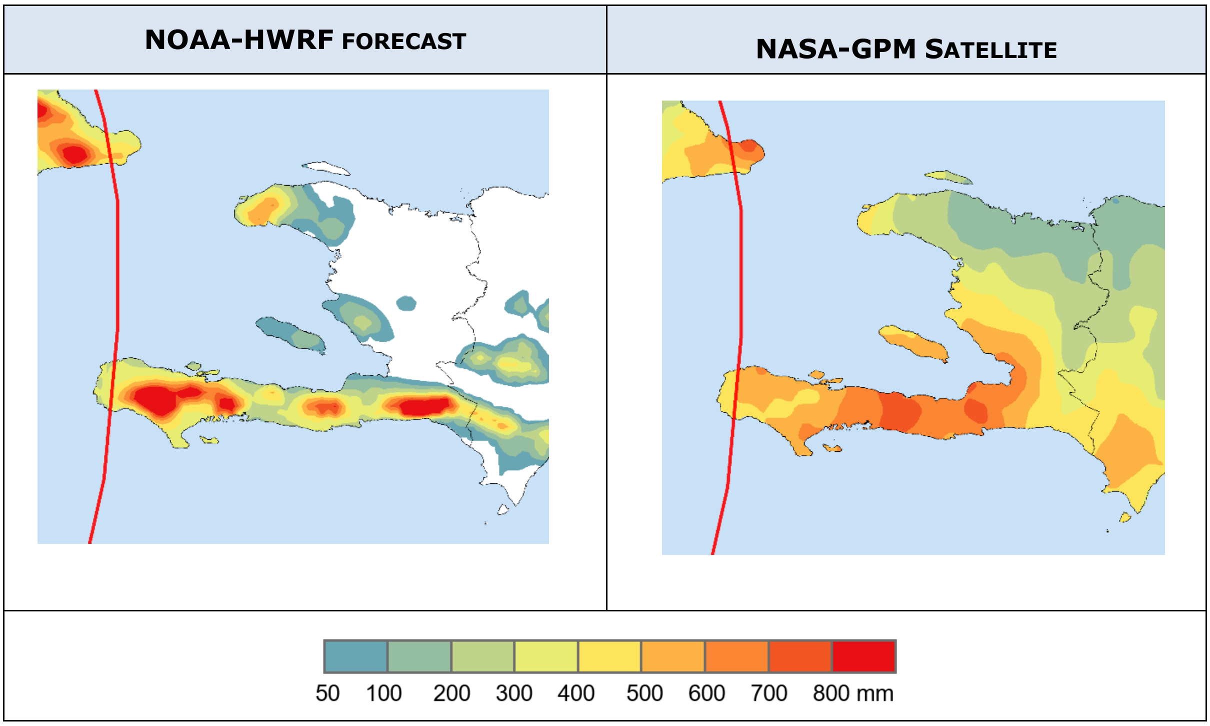

Figure 16 - Total Rainfall Accumulation over 4-9 Oct

3.2.2 Future steps

This study was only a **rapid preliminary evaluation** of the potentially most affected areas by Hurricane Matthew, therefore next steps can be:

- Validate the current multi-index for Hurricane Matthew with satellite data or more detailed impact assessment reports.
- Include in the risk formula: storm surge hazard, vulnerability of the country
- Develop a specific classification for the rainfall including climatological information
- Improve the risk formula (assign specific weights to the various hazards)
- Assessment of the new multi risk index for other TCs
- Use the JRC Global Human Settlement Layer (GHSL[3]) for the population

This "multi risk indicator" could be very useful also for the GDACS alert system described in the previous section.

[3] JRC GHSL: http://ghslsys.jrc.ec.europa.eu/

3.3 Implementation of HWRF data for wind and rain maps

Over the last few years the NOAA HWRF has been notably improved and several products are currently available for all TCs in all basins (see description below).

This product has a very high resolution and it could be able to simulate the wind and pressure fields of a TC. Thus, the JRC used this product in different studies:

- input for the new wind alert system (see Section 3.1)
- input for the new JRC multi risk index (see Section 3.2)
- in the tropical cyclone maps and reports (see description below).

3.3.1 Implementation

A procedure has been put in place to download and store the HWRF rainfall and wind swaths every day for each active TCs.

The HWRF rainfall and wind swaths are provided in ASCII format. A dedicated Python script is used to read these files and create a corresponding raster file. The procedure reads the provided file in a python array, reshapes it and exports it in geotiff format that offers an easy way of incorporating the graph to multiple products. Optionally, graphs can be created from within Python and there is also the possibility to export it in different formats.

The raster files created by this procedure have been used to create several TC maps (see the examples in **Figure 17 - Figure 20**) and reports (see GDACS website[4]), as well as within the ECHO Daily Maps (see ERCC portal[5] and the example in **Figure 21**).

3.3.2 Future steps

The HWRF products can be used for:

- rain and wind impact in GDACS
- atmospheric forcing for the JRC's storm surge code

The two points above have not been tested nor implemented yet. However an automatic routine has been set up to download and include the "HWRF TC bulletin" (i.e. track, max. sustained winds, central pressure and wind radii data) into a database (like for the NOAA and JTWC bulletins in GDACS) and the JRC is also testing these bulletins as input in the Monte Carlo method that creates the atmospheric input for the storm surge system and for the new wind alert system.

[4] GDACS website: www.gdacs.org

[5] Emergency Response Coordination Centre (ERCC) Daily Map: http://erccportal.jrc.ec.europa.eu/maps

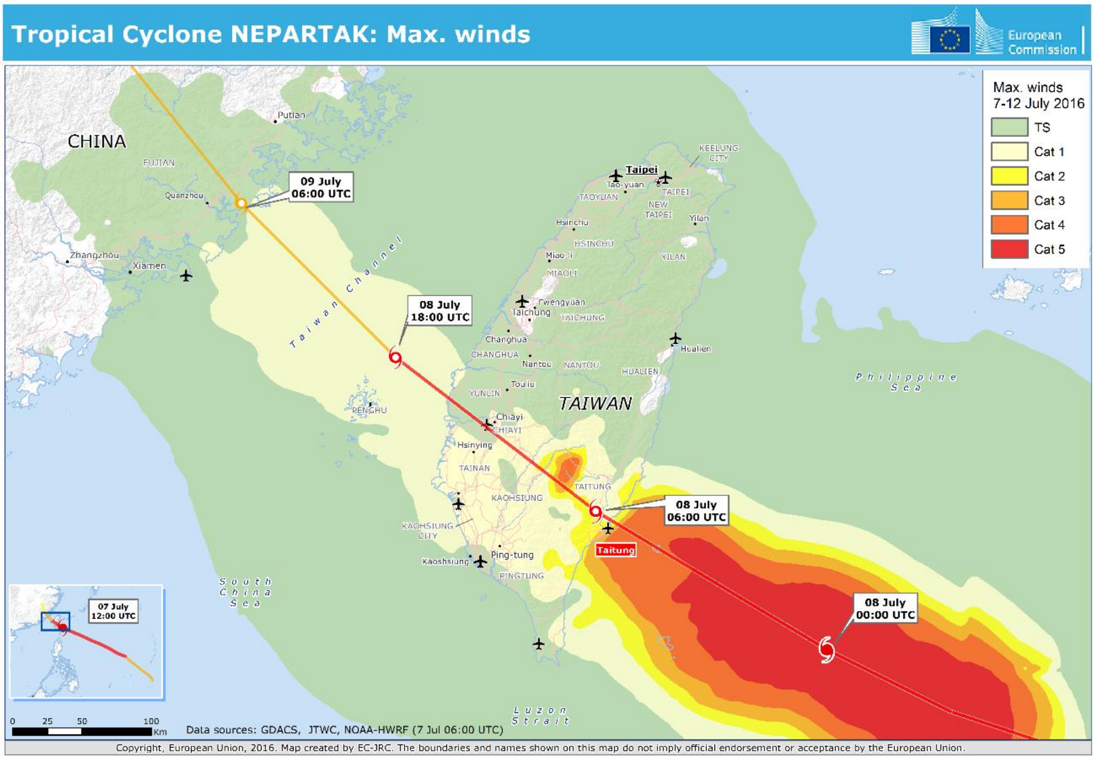

Figure 17 - Forecast of the maximum winds for TC NEPARTAK using the data of NOAA-HWRF (as of 7 Jul 2016, 6:00 UTC).

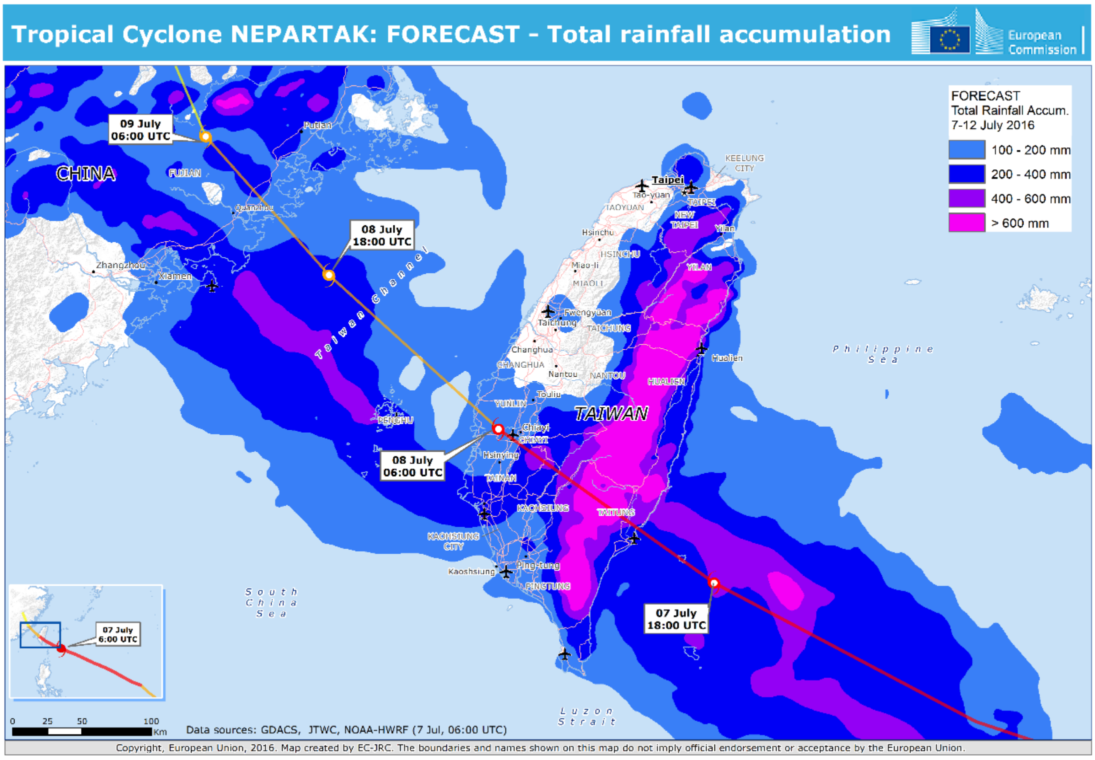

Figure 18 - Forecast of the total rainfall accumulation for the TC NEPARTAK using the data of NOAA HWRF (as of 7 Jul 2016, 6:00 UTC).

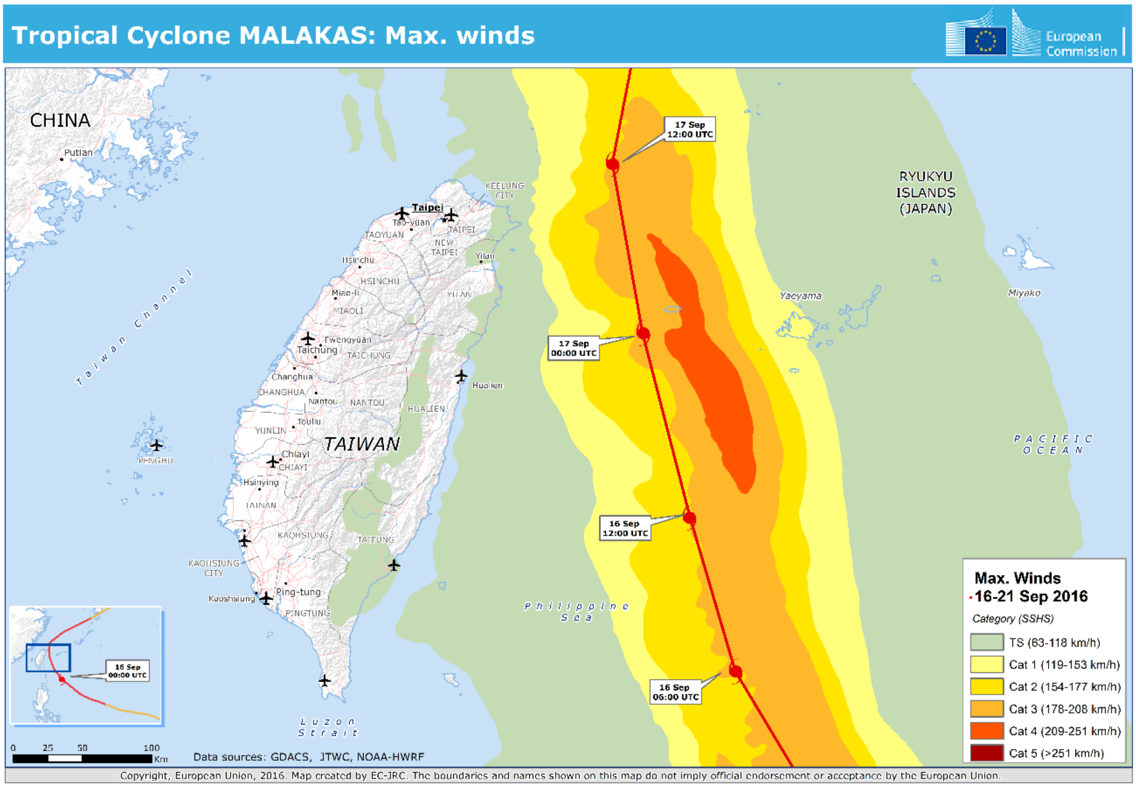

Figure 19 - Forecast of the maximum winds for TC MALAKAS using the data of NOAA-HWRF (as of 16 Sep 2016, 6:00 UTC).

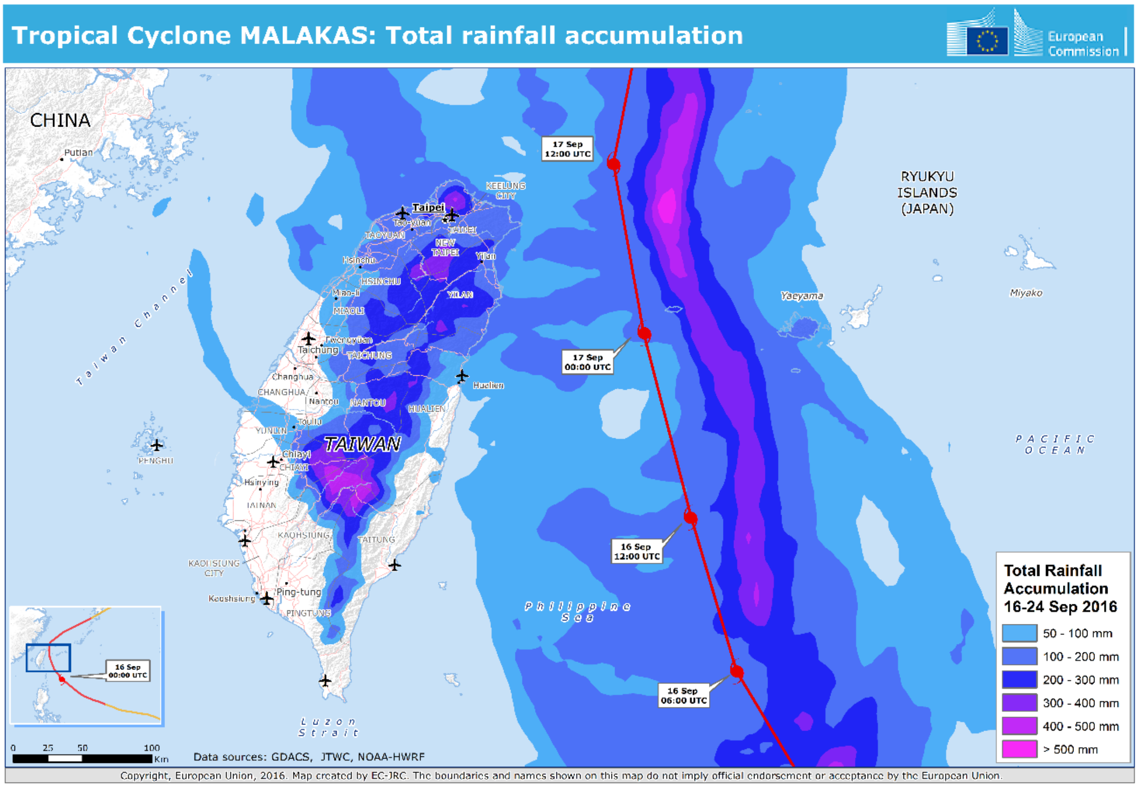

Figure 20 - Forecast of the total rainfall accumulation for TC MALAKAS using the data of NOAA HWRF (as of 16 Sep 2016, 6:00 UTC).

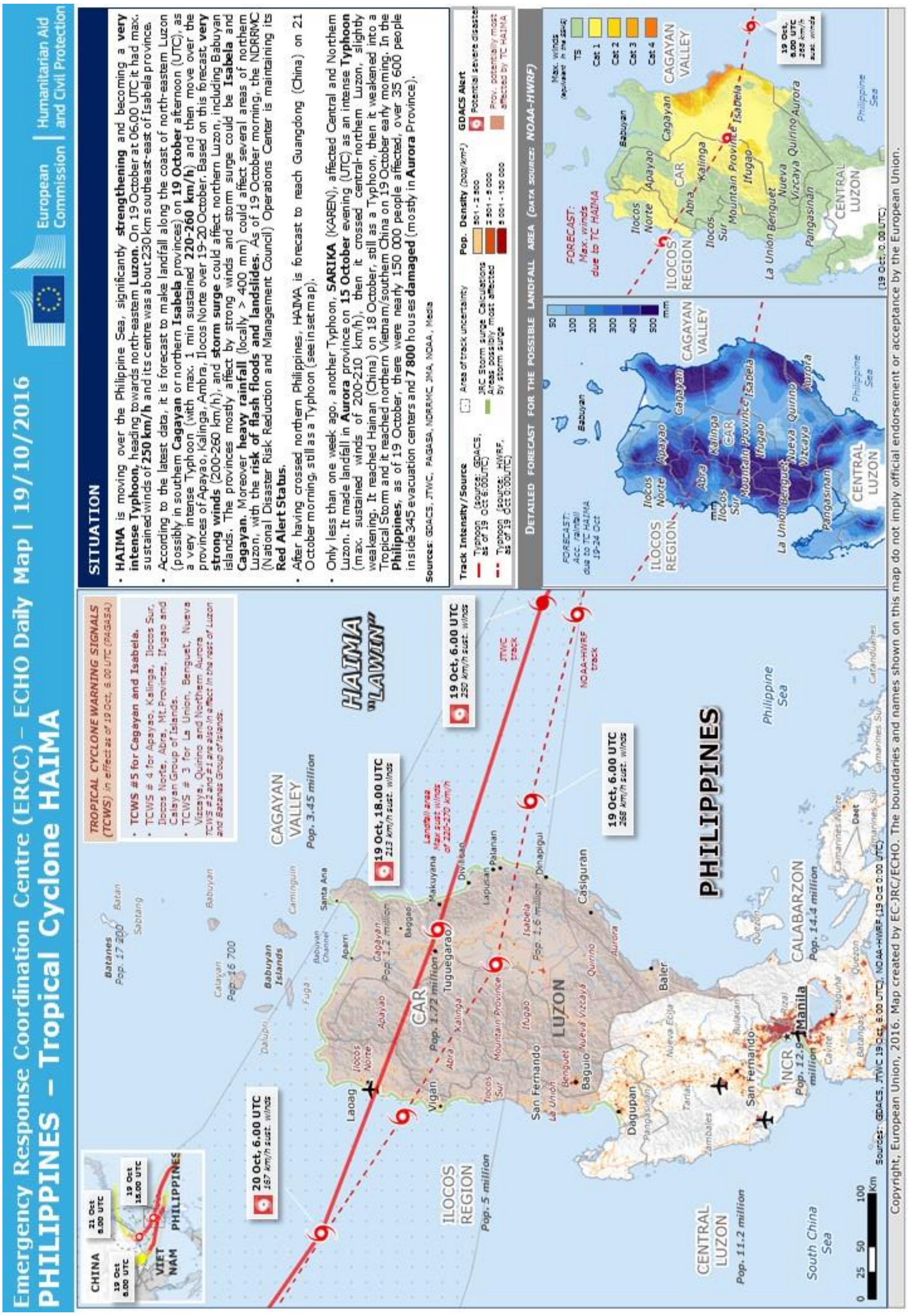

Figure 21 - ECHO Daily Map on Tropical Cyclone HAIMA (data source: GDACS, NOAA-HWRF)

4 Storm surge activities

4.1 New workflow in python

The operational workflow currently used in GDACS for the storm surge system is actually a combination of bash scripts, Fortran and C code. The executable script, written in bash controls the workflow. In addition, a lot of functionality is being carried out by an in-house graphics and analysis library written in Fortran and dubbed VPL. This creates a number of dependency and compatibility issues. The flow chart of the computation is so convoluted that inhibits transparency and efficiency. The statistical nature of the solver (Monte Carlo simulation) poses an additional hurdle in reproducibility and verification of the algorithm. The setup serves multiple purposes and is very difficult to streamline. To this end, a new setup based on virtual machines (VM) is established where development and testing can be carried out while providing redundancy and operability. In addition, a Git repository is setup in order to provide versioning and tracking control.

The current workflow utilizes the HyFlux code (Franchello and Krausmann, 2008) in order to compute the corresponding storm surge and post-processing is performed to provide relevant information. The data required for the workflow to function comes from bulletins issued by the relative agencies and organizations. The model used (Holland parameters approximation) is trading accuracy with simplicity. A number of new alternatives are becoming available which require a new approach (see Sections 2 and 3).

The steps undertaken to address the above issues are outlined and discussed below.

4.1.1 Code development

The currently functional workflow depends largely on VPL that manipulates graphics and tackles the pre-processing of the computation. In order to enhance the versatility of the process and to foster further development the workflow has been modified to use Python scripts instead of VPL routines. This way, the vast base of optimized Python modules can be put to use adding accuracy, portability and efficiency to the workflow.

In all, roughly 3600 lines of Python code replaced a similar number of Fortran code while deprecating some 90000 lines of code (that comprise VPL). It is foreseen that Python will eventually handle all the pre/post-processing while the solver itself will remain in Fortran in order to facilitate fast parallel computations and easy change of the solver itself.

The benefit of migrating to python can be seen in the simple case of spline interpolation presented in **Figure 22**.

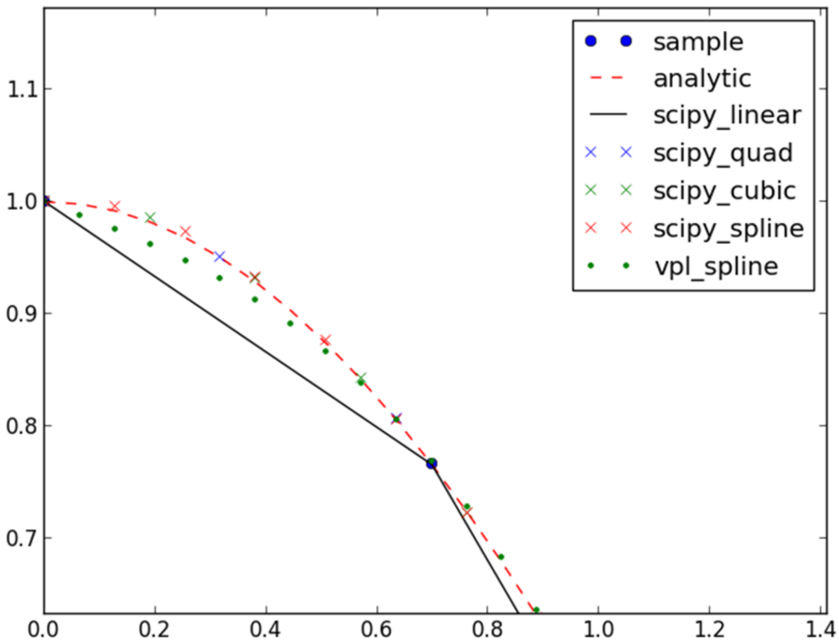

Figure 22 – Comparison between interpolation methods

The case of the Holland parameters derivation provides a more involved example. The current option is to use a Monte-Carlo (MC) algorithm to estimate the unknown parameters (see also Probst and Franchello, 2012).

The Holland expression used in the JRC storm surge system is defined as:

$$V_s(r) = \left[\frac{B_s}{\rho_{as}} \left(\frac{R_{maxs}}{r} \right)^{B_s} \Delta p_s \, e^{-\left(\frac{R_{max_s}}{r} \right)^{B_s}} \right]^x \qquad (1)$$

where ρ_{as} is the air density, R_{maxs} is radius of maximum wind (m), $\Delta p_s = Pn - Pc$ is the pressure drop (Pa) between the central pressure P_c and the environmental pressure (P_n) and r is the radius from the centre. The scaling factor B_s (peakness) defines the pressure and wind profile shape (1÷ 2.5). Note that the subscript s refers to the surface values at a nominal height of 10 m. The exponent x can be used to adjust (or fit) the profile accordingly.

Eq (1) has at least three unknowns R_{maxs}, B_s, x (P_c is also unknown most of the times but can be assigned a default value) and the MC process is trying to estimate these. **Table 8** shows a characteristic output of this process for various times.

time	b	k	rmax	deltap	bias	rmse
0.00000	0.811844	0.392771E-01	21089.9	4350.57	-0.616387E-01	0.896446
12.0000	0.999417	0.837338E-01	19468.7	4861.88	0.974545E-01	0.684370
24.0000	0.933550	0.585013E-01	15480.2	6388.26	-0.447391E-01	0.603154
36.0000	0.904220	0.748357E-01	11012.6	8051.07	0.251968	0.823728
48.0000	1.03422	0.105762	11457.4	7911.04	-0.318711	0.625298
72.0000	1.24700	0.125727	21034.7	4923.62	0.197630	1.17947

Table 8 – Estimation of Holland parameters for bulletin 31 of CHAN-HOM-15

It is seen from inspecting the data in table 1 that the bias and rms (root mean square) of the analysis attests to the discrepancies involved. The wind profile based on the above results for time=0. is depicted in **Figure 23** .

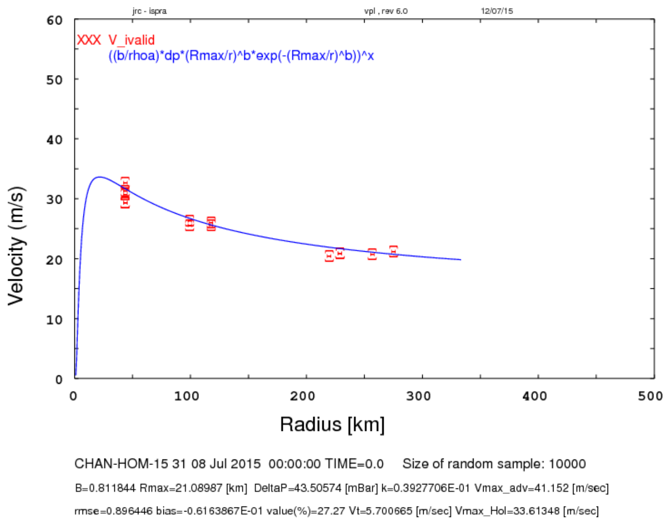

Figure 23 – The wind profile fitted to the wind radii for bulletin 31 of CHAN-HOM TC

The MC process adds a statistical component to the analysis, which combined with the sensitivity of the Holland expression to the values of the related parameters, inhibits the reproducibility of the computations.

However, Eq (1) can also be seen as an optimization problem with constrains set by the read-in values. A number of functions, available through the Scipy (http://www.scipy.org/) module in Python, can be utilized. The results of a corresponding test can be seen in **Figure 24**.

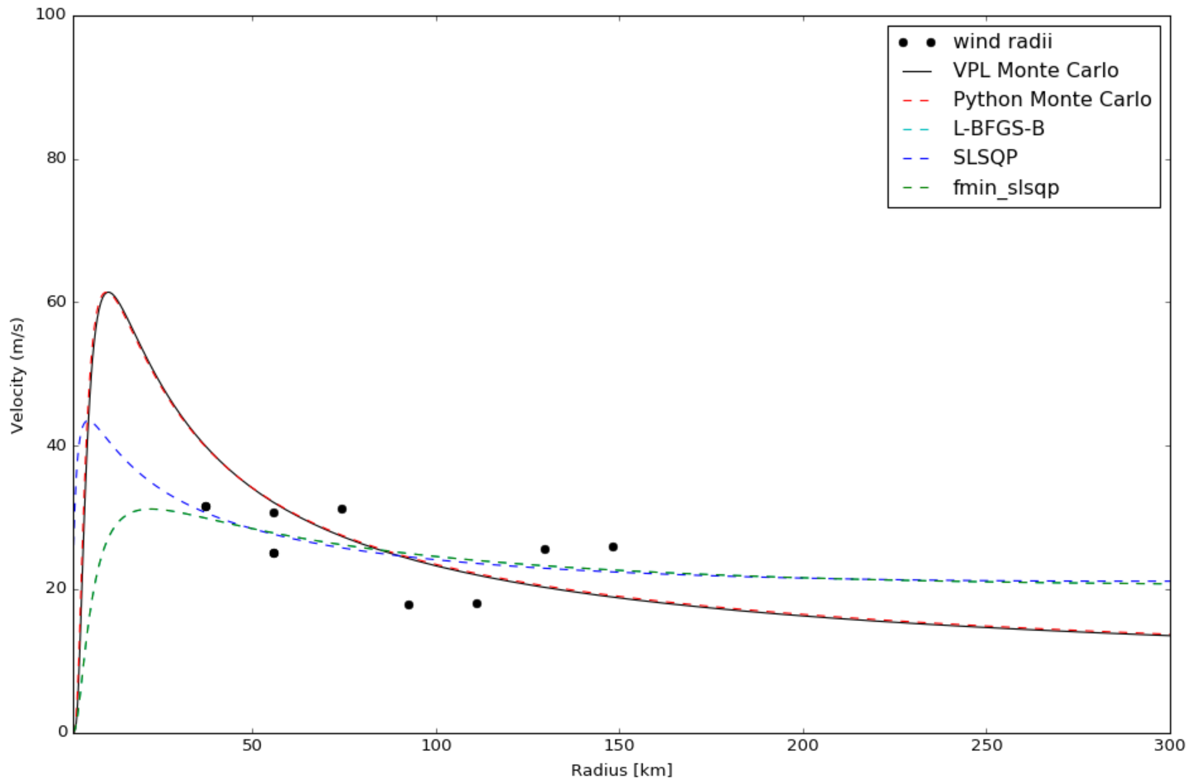

Figure 24 - Comparison of curve fitting between Monte-Carlo and optimization routines

Overall, the implementation of the MC method in Python compares well with the VPL equivalent. Included in the figure above are contours based on several available scipy routines. Analysis suggest that the maximum velocity as well as the spread of the wind radii data affect the performance of such functions. They seem to work better when the maximum velocity is lower. Note that additional information, when available, will reduce the number of uknowns making the analysis more amenable. In fact, the HWRF and other TC data providers are currently providing more info such as minimum pressure and radius of maximum wind which enhances the accuracy of the estimated wind profile. In any case, more research is needed before such functions can provide a viable alternative to the MC method.

4.1.2 Implementation

Substituting the VPL backbone of our workflow with a python based one required an extensive testing protocol and a variety of test cases. This testing bed was made available when the developmental shadow workflow was put into place earlier this year.

The python based workflow has been deployed for the past 6 months feeding into the internal dev-gdacs website and the benchmarking showed minor issues that were readily fixed. Based on the results so far it was decided to replace the VPL based one with the Python version providing more functionality and options for expansion.

4.2 Pilot study on ECMWF forcing

Based on the development done for the Coastal Risk exploratory project (see corresponding report) a new workflow has been setup using the DELFT3D code for simulating storm surge due to TCs.

4.2.1 Code development

The DELFT3D code requires bathymetry, grid, and atmospheric forcing in a specific format. However, the suite of codes is designed for a case by case analysis on a fixed grid setting up the simulation through a MATLAB based GUI. TCs provide a challenge since the location and lat/lon range of the storm's path is not known in advance. A number of python scripts were developed in order to automate the pre-processing steps of creating the required input for the simulations. These scripts include routines to read atmospheric data from grib files (the format that numerical simulation weather data are given in), extract the data for the Lat/Lon window required and then save these data in DELFT3D input data format. Additional scripts include the creation of the bathymetry grid based on GEBCO 2008 & 2014 grid data provided by experts in the field[6]. The process is automated and can be launched through command line with the required parameters without the dependency on MATLAB.

4.2.2 Implementation

The workflow starts with setting up the run by creating the input files for the simulation specifying lat/lon window, resolution, forecast range etc. The corresponding command looks like this

```
python setup.py -100. -50 5 35 'MATTHEW' '20160928.00' 72 .05 './MATTHEW' 'True'
```

which corresponds to *minlon, maxlon, minlat, maxlat, basename, date (YYYYMMDD.HH), number of forecasts, resolution (decimal degrees), path, compute uvp(T|F).*

After the first run has been concluded another scripts carries over the subsequent runs by copying the restart files from the previous run as well as the unmodified input files and creating the *u,v,p* files for the corresponding date stamp. A complete hincast simulation can be performed with the command line

```
python rerun.py 20131101.12 20131101.12 ./MATTHEW
```

which corresponds to *start_time*, *end_time* and *path*.

4.2.3 Test case

As a test case we selected TC MATTHEW that went through the Caribbean in Sep-Oct 2016. The lat/lon window used is shown in **Figure 25** where the interpolated bathymetric data on the simulation grid is presented.

[6] GEBCO: http://www.gebco.net/data_and_products/gridded_bathymetry_data/

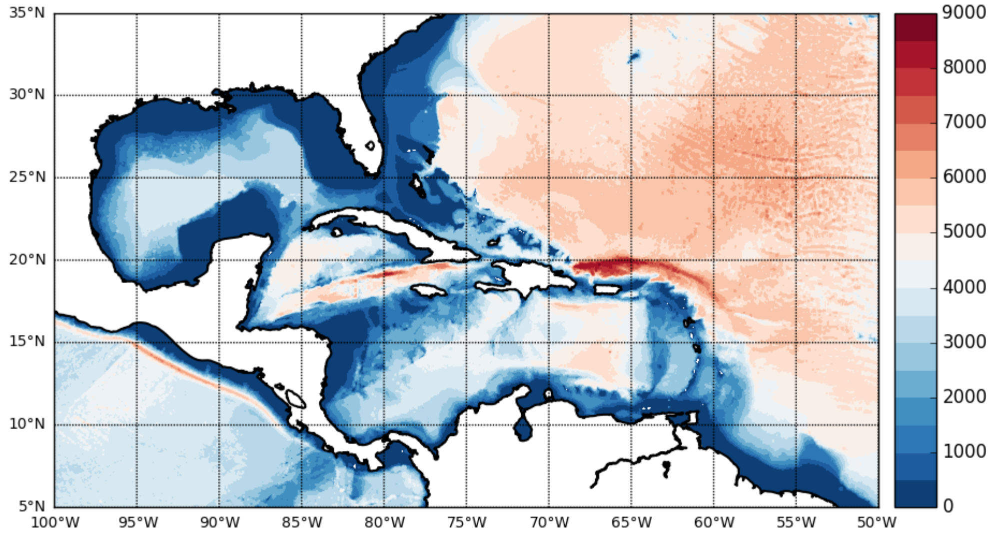

Figure 25 – Simulation window and corresponding bathymetry for TC MATTHEW

The resolution used is 0.05 decimal degrees (3 minutes) for a 2500 x 1500 grid. Each forecasting run took about 2 hours with 32 cores in parallel computation. An aggregation of the maximum storm surge computed is shown in **Figure 26** below. The image depicts in fact the path of the TC in terms of computed storm surge extreme.

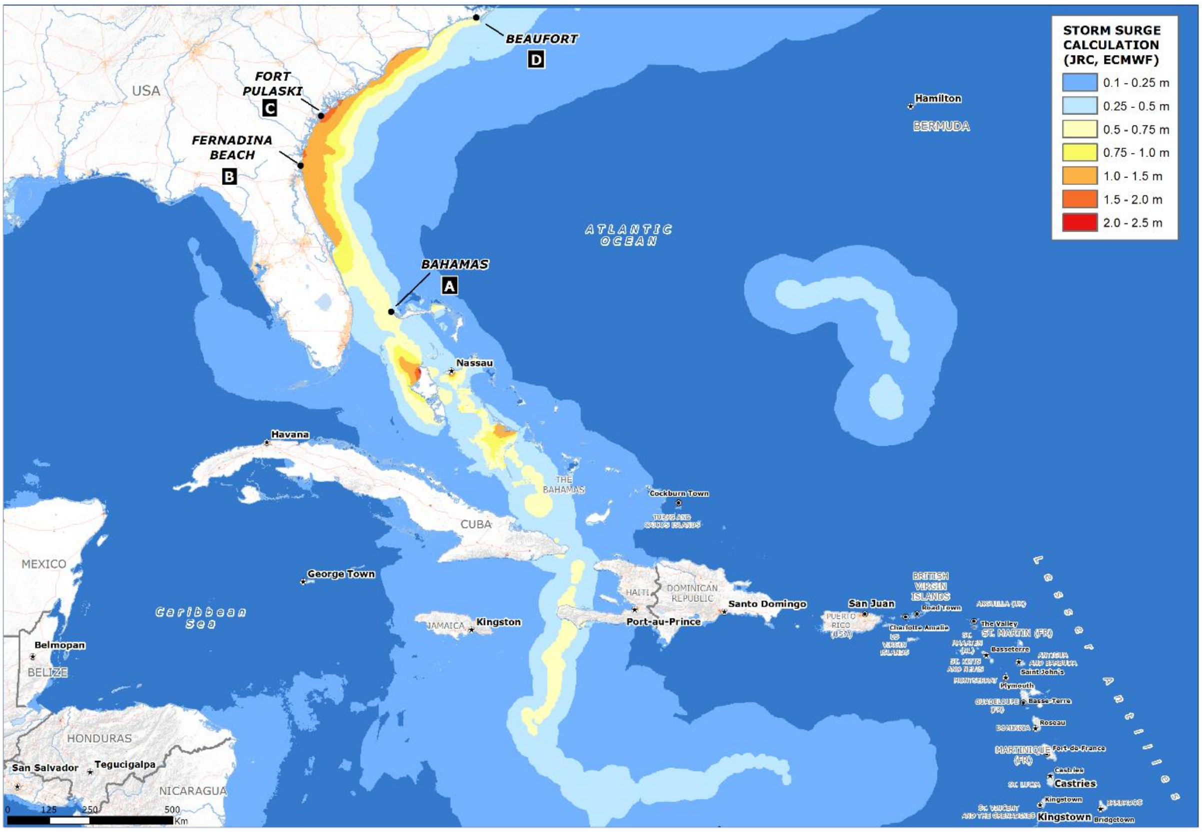

Figure 26 - Maximum storm surge values for TC MATTHEW

A more quantitative insight into the model can be seen by measuring with elevation data from local tide gauges or buoys that happen to be on the path of the TC and are indeed functional. From **Figure 26** above it is seen that the higher storm surge values manifest near the US coast and the Bahamas, where there are indeed some data available from direct measurements. A comparison between the estimated storm surge of Delft3D calculations (green lines), HyFlux2 calculations (red line) and measured data (blue lines) is given for the following 4 locations:

A) Bahamas – Settlment pt (**Figure 27 A**)
B) USA – Fernadina Beach (**Figure 27 B**)
C) USA – Fort Pulaski (**Figure 28 C**)
D) USA – Beaufort (**Figure 28 D**)

The HyFlux2 results are also included in theese figures (red lines). Note that the storm surge ”measured data” are obtained subtracting the tidal component from the sea level measurements (see Annunziato and Probst, 2016).

The comparison is seen to be promising in view of the inherent uncertainties but more analysis is needed in order to establish possible sources of error and ways to ameliorate them.

4.2.4 Future steps

The difference between hindcast and forecast mode is that the path of the cyclone is not known in advance. Dealing with this issue requires a combination of formulations. Options include a nested grid approach where a big basin-like low resolution grid provides initial/boundary conditions for a subsequent high resolution (HR) nested grid near the TC eye in order to more accurately estimate the storm surge, or a moving grid formulation where a HR moving grid is following the TC. Research is under way to develop and test such configurations. In addition, similar runs that use the even higher resolution HWRF data could be performed. It is foreseen that parallel workflows that utilize all numerical simulation atmospheric data can be executed forming an ensemble of runs that provide higher degree of confidence in our forecasting tools.

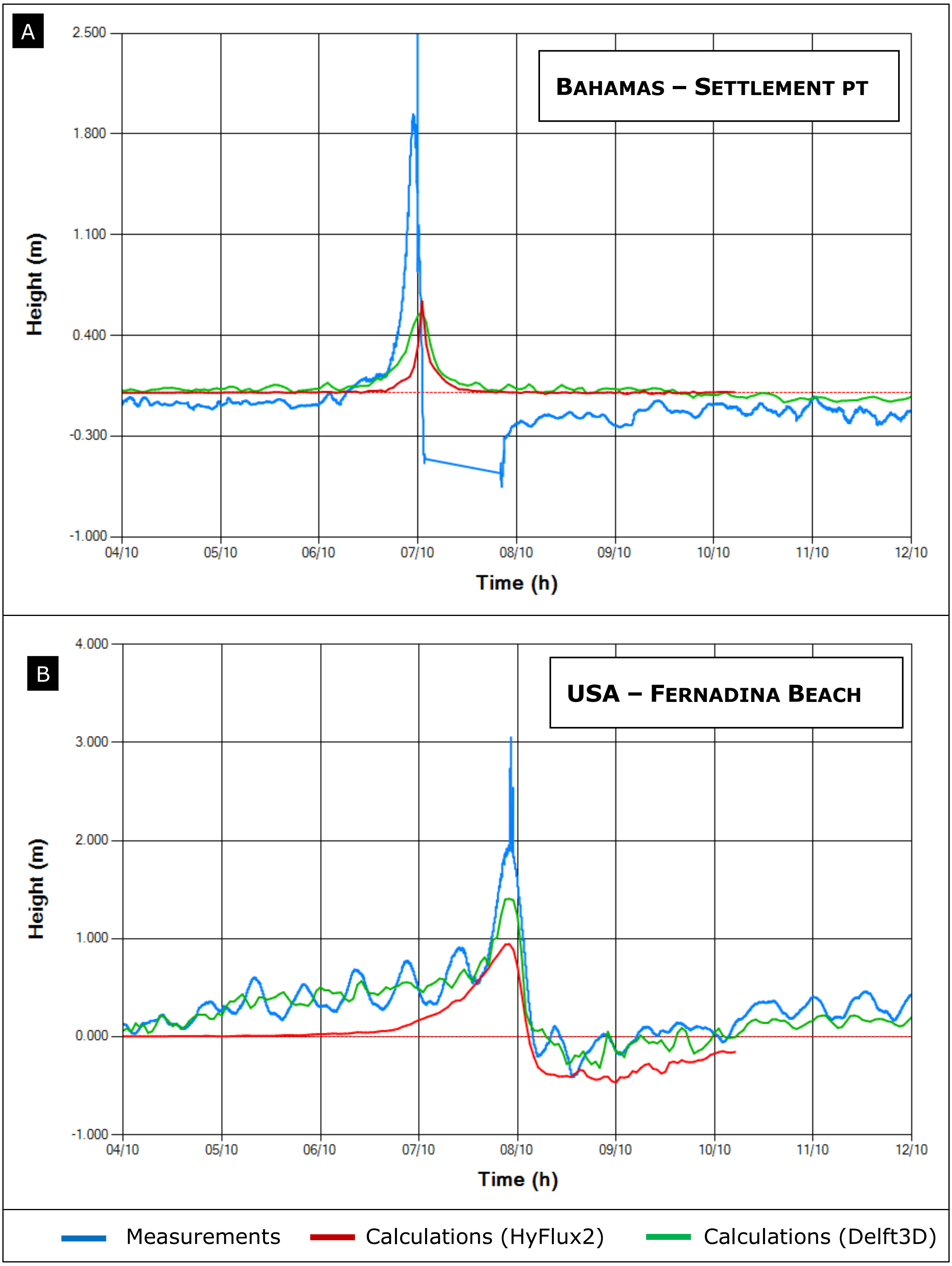

Figure 27 – Storm surge comparison between measurements (blue line) and calculations (Delf3D: green line, HyFlux2: red line) for two stations (Bahamas and USA – Fernadina Beach) due to the passage of TC MATTHEW.

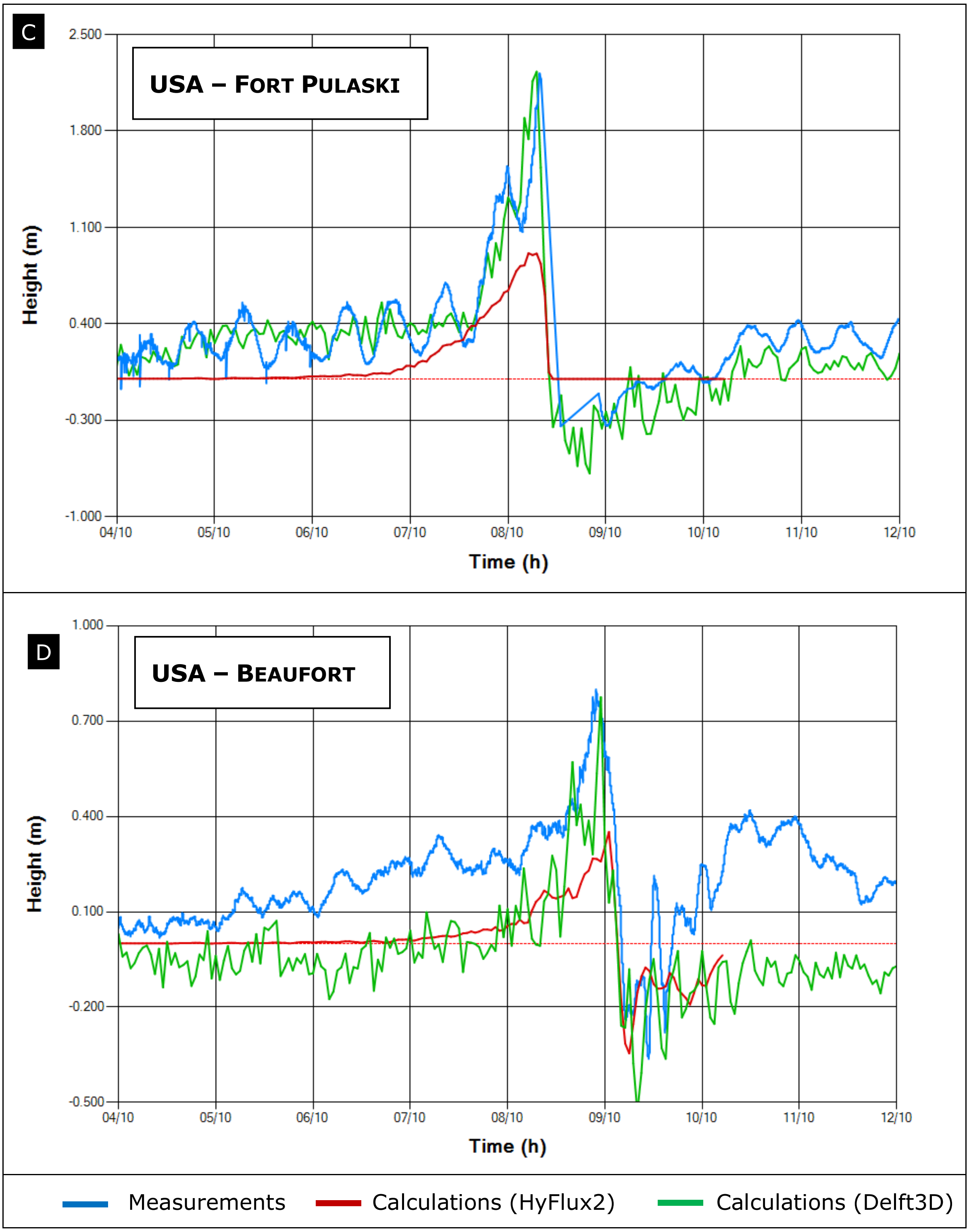

Figure 28 – As in **Figure 27**, but for the stations: USA – Fort Pulaski and USA – Beaufort.

5 Conclusions

The upgrade of the Tropical Cyclone analysis tools is underway including new data sources, rehashing the workflow in Python and assessing the pre/post-processing features. The development within 2016 included

- A developmental shadow workflow has been put into place providing redundancy and a test bed for testing all the new features without imposing on the production workflow.
- The VPL routines have been 'translated' to Python deprecating the VPL libraries.
- The bash scripts have been consolidated into a single execution script and further simplification is underway.
- A number of tools have been developed utilizing IPython (http://www.ipython.org/) for visualizing, manipulating and analysing available data.
- The assessment of various alternative sources for upgrading the analysis of the considered event. In particular, the JRC is testing the new products of NOAA-HWRF and ECMWF in order to improve the accuracy of the forecast and the GDACS alerts.
- The development of a new wind impact estimation, based on the Saffir Simpson Hurricane Scale, in order to give a more realistic alert, especially for the most intense tropical cyclones.
- New solvers (e.g. Delft3D-DELTARES) for the storm surge calculations including the ability to run in an operational mode (script based launch).

The above advances contribute to the establishment of a transparent, trackable and easy to disseminate test bed for further development.

The capability of parallel ensemble simulations with multiple configurations and subsequent analysis of the results will provide additional insight into the accuracy of the forecast and comparison with available measurements will be helpful in assessing the various models.

References

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Authors

Pamela Probst, Alessandro Annunziato, George Breyiannis, Thomas I. Petroliagkis

List of abbreviations and definitions

ECMWF	European Centre for Medium Weather Forecast
GDACS	Global Disasters Alerts and Coordination System
GFS	Global Forecasting System
GPM	Global Precipitation Measurement
HWRF	Hurricane Weather Research and Forecast System
JRC	Joint Research Centre
JTWC	Joint Typhoon Warning Center
MTCSW	Multiplatform Tropical Cyclone Surface Winds Analysis
NESDIS	National Environmental Satellite, Data, and Information Service
netCDF	Network Common Data Form
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
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting
Xml	Extensible Markup Language

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