European Commission

JRC TECHNICAL REPORTS

JRC storm surge system: *New developments*

Description of the new systems developed for SSCS & GDACS

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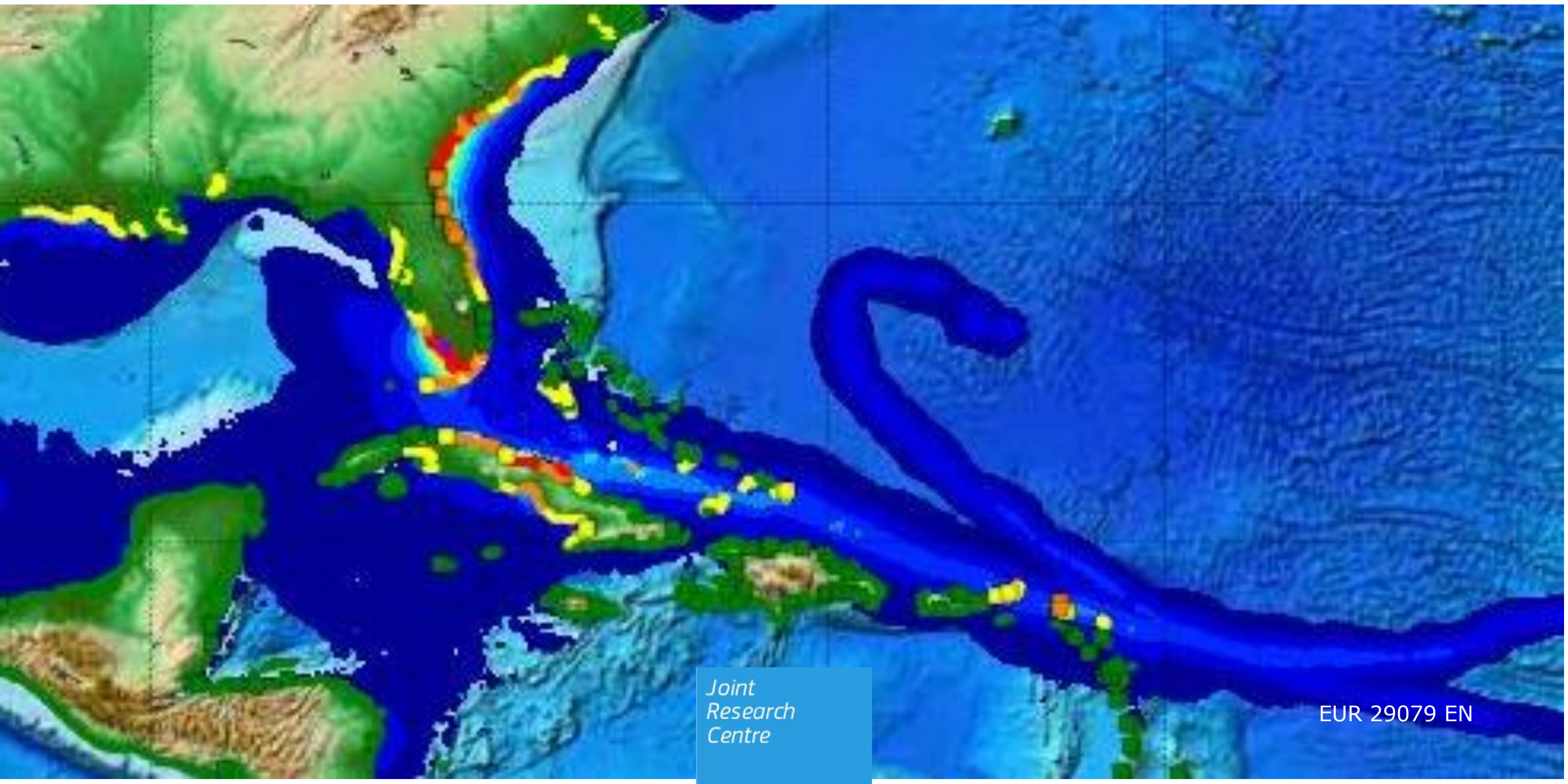
2017



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Contents

Abstract

JRC has developed the first storm surge calculation system for the Tropical Cyclones (TCs) included in the Global Disasters Alert and Coordination System (GDACS) in 2011. The TCs are not the only weather system that can generate a storm surge event, therefore a new Storm Surge Calculation System (SSCS) has been developed in 2013, to simulate the storm surge also in Europe.

JRC has recently developed and implemented a new storm surge system, using a new hydrodynamic code and new atmospheric forecasts, creating several new SSCS bulletins and TCs GDACS web pages. This report describes these new procedures developed.

1 Introduction

The **storm surge** is an abnormal rise of water above the astronomical tides, generated by strong winds and a drop in the atmospheric pressure, due to the passage of a Tropical Cyclone (TC) or an intense low pressure system in general.

JRC Operational Storm Surge System (HyFlux2)

The JRC Operational Storm Surge System calculates the storm surge for:

- **GDACS storm surge system for Tropical Cyclones (TCs):** In 2011, JRC has developed the first storm surge system for the TCs, including the atmospheric forcing in the JRC HyFlux2 code used for tsunami modelling. The results are included in the Global Disasters Alert and Coordination System (GDACS, www.gdacs.org). More information are available in Probst and Franchello (2012).

- **JRC Storm Surge Calculation System – SSCS:** The TCs are not the only weather system that can generate a storm surge, also the intense low pressure systems that affect Europe in winter could produce this phenomena. Therefore, the JRC has developed a new system in 2013 - JRC Storm Surge Calculation System (SSCS), using the JRC HyFlux2 code and the meteorological forecasts of several meteorological centers. This system has been used to produce every day the SSCS bulletins for different areas of Europe (see Annunziato and Probst, 2016) until March 2017. Then the JRC started using the new system described in this report.

In case of important events, the results of these two systems are included in the products (e.g. Daily Maps, Flash, Reports) prepared by the JRC for the Emergency Response and Coordination Center (ERCC) of the European Commission, as well for the other counterpart Meteorological Services with which JRC has collaboration Agreements.

New JRC Storm Surge System (Delf3D)

JRC has recently developed and implemented a new storm surge system that includes:

- new hydrodynamic code (Deltares Delft3D)
- new procedures in Python
- new atmospheric inputs (ECMWF, HWRF, GFS)
- new wind impact estimation
- new SSCS bulletins in PDF, using LaTeX

This new operational storm surge system is used for the SSCS and for the TCs in GDACS. The scheme of the new methodology is shown in *Figure 1*.

The main advantage of this new system is that it can use several different atmospheric sources in the same storm surge code, using the same procedures for the creation of the SSCS bulletins and for the TCs in GDACS.

A scheme of this new system is shown in *Figure 2*, while a complete description is presented in Section 2 (SSCS) and in Section 3 (TCs). Concluding remarks, limitations and future steps are in Section 4.

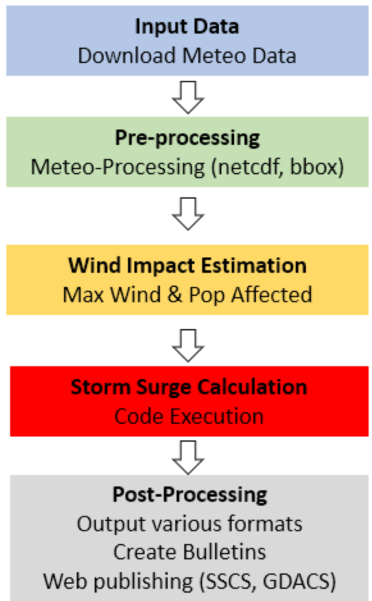

Figure 1 *– New Methodology*

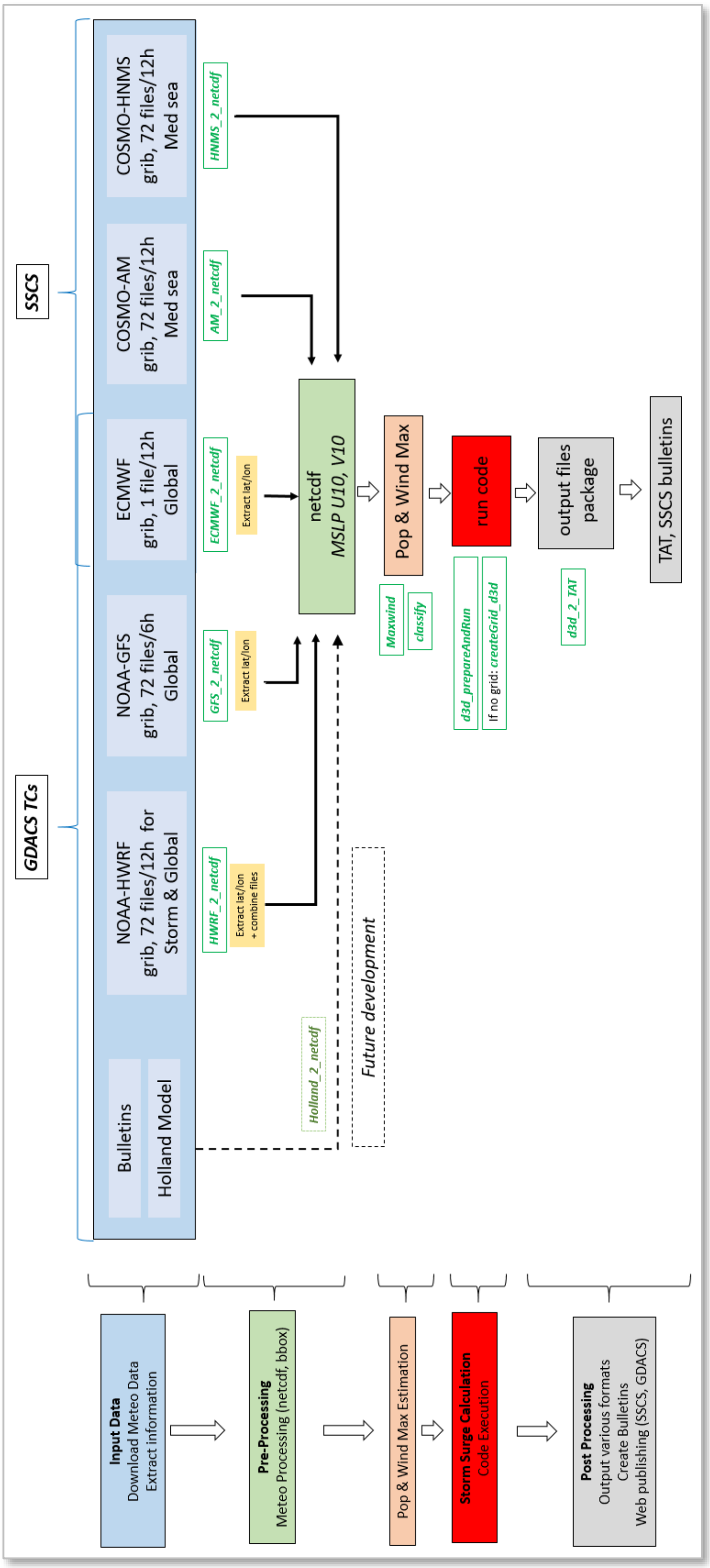

Figure 2 – *Detailed scheme of the New Storm Surge System*

2 JRC Storm Surge Calculation System (SSCS)

2.1 Overview

The new JRC Storm Surge System uses:

- Hydrodynamic code: **Deltares Delft3D**
- Meteorological forecasts[1] provided by the following meteorological centers:
  - European Centre for Medium Weather Forecast – ECMWF
  - Italian Air Force Meteorological Weather Service – AM
  - Hellenic National Meteorological Service – HNMS

A description of the code is in Annex 1, while the atmospheric forecasts in Annex 2.

Every day this system estimates the storm surge for the whole Europe and in particular for these different domains (see *Figure 3*):

- Whole Europe (ECMWF)
- Mediterranean Sea (AM, HNMS)

After having calculated the storm surge, the system creates the new SSCS bulletins. The new procedures developed for this new system are described in Section 2.2, while the new SSCS bulletins are in Section 2.3.

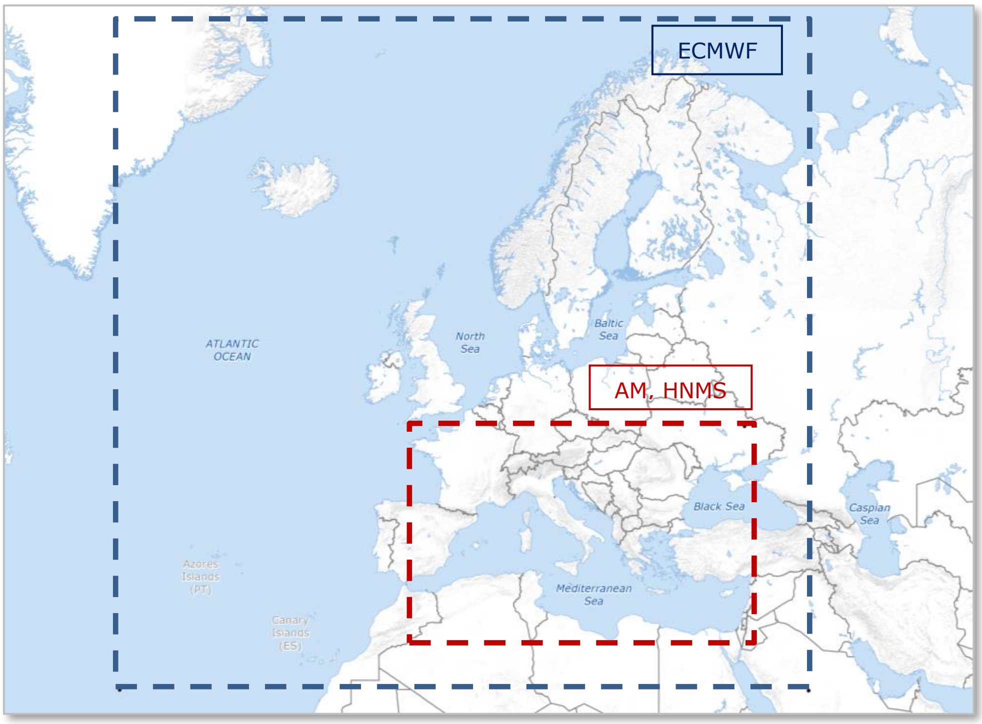

***Figure 3 -** JRC Storm Surge Calculation domains.*

[1] The following fields are used as atmospheric inputs for the JRC Storm surge model: Mean Sea Level Pressure (**MSLP**) in Pa, U component of wind (**10U**) at 10 meters in m/s, V component of wind (**10V**) at 10 meters in m/s

2.2 New Procedure

JRC set up the following new automatic procedures to estimate the storm surge and create the new SSCS bulletins. Most of the new procedures created are in Python.

1) **Input data**: Creation of new tasks (in parallel) for the download of the input data files (GRIB data) two times per day, as soon as the files become available.
2) **Pre-Processing**: Processing of the meteorological inputs to create one single netcdf file for pressure and wind speed components required by the storm surge calculations (see footnote 1).
3) **Impact Estimation:** Creation of the maximum wind file and calculation of the population potentially affected by different classes of winds.
4) **Storm surge Calculations**: Launch the calculations using Delft3D.
5) **Post-processing** of the results
    - Create output files in different formats (e.g. files for JRC Tsunami Analysis Tool- TAT, kmz, kml, tif).
    - Create bulletins for fixed windows (see Section 2.3).
    - Send the e-mail including the bulletins.

A brief description of these steps is presented over the next pages, while a scheme of these procedures is shown in *Figure 4*.

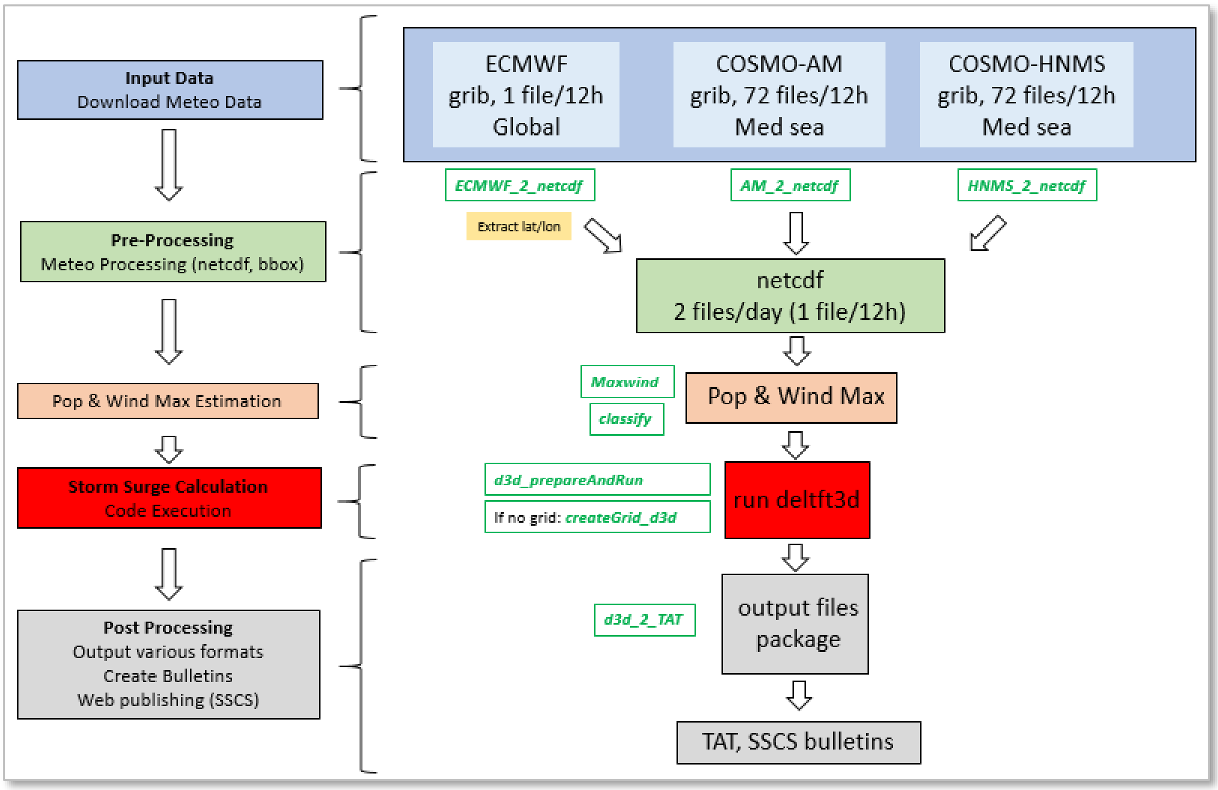

Figure 4 *– SSCS-Delft3D Procedure.*

1) **Input data:** *Download of the atmospheric forcing*

ECMWF, AM, HNMS produce every 12 hours a forecast for several parameters, including Mean Sea Level Pressure (MSLP) and 10m wind speed (U10, V10), for a 72h forecast period. The characteristics of each file and the domain are in the table below, while the descriptions of the models are in Annex 2.

Several new tasks have been set up to improve the download of these atmospheric inputs.

	ECMWF	AM	HNMS
Model	operational high-resolution (HRES)	COSMO-ME	COSMO-GR
Format	Grib	Grib, several files	Grib, several files
Domain	World	Southern Europe, Mediterranean Sea, Black Sea	Southern Europe, Mediterranean Sea, Black Sea
Horizontal Grid Size	≈ 9 km	≈ 7 km	≈ 7 km
Initial Time of Model runs	00, 12 UTC	00, 12 UTC	00, 12 UTC
Data Format	Grib (1 single file)	Grib (several files)	Grib (several files)
Nr files/day	2 files/day	146 files/day	146 files/day

***Table 1** – Atmospheric inputs used in the SSCS.*

2) **Pre-processing:** Processing of the meteorological inputs for the storm surge calculations

All the input files are in GRIB format, but they have a different domain, coordinate system, and are provided in a different "time-structure" (ECMWF: 1 file that includes all 72h forecasts, AM and HNMS: 1 file for each 1h forecasting time step).
One single procedure for each meteo source has been created, in order to:

- Extract a portion of the grib file for a number of areas of Europe (only for ECMWF data, see *Figure 3*)
- Create one single netcdf files that includes the 72 h time steps and the three variables: MSLP, U10, V10 (pressure and winds, see *Footnote 1*)

3) **Impact Estimation:** Classification of the population potentially affected by winds

A python script has been developed to create a tif file with maximum winds over the forecasting period of 72h and another one to classify the population potentially affected by different classes of wind strength.

The procedures:

```
# 0. read the input file and create the max tif file.
# 1. extract an area of the population dataset² corresponding to the required bounding box
# 2. resample the vmax file to the resolution of the population datataset
# 3. classify the vmax file creating another array of values classified
# 4. count the population in each cell and assign the corresponding wind class
# 5. print output
# 6. store the results into a xml file
```

Note: this wind impact estimation is inside the procedure of the storm surge system

[2] Two datasets of population are used: LandScan™ and the Global Human Settlement Layer (GHSL), see more information in Probst et al, 2017.

4) Calculations: *Storm surge calculations for several basins*

JRC has recently implemented a new solver: Deltares - Delft3D. As for the previous system, several calculations are performed every day using the previous forecast at -6 h and the forecasted values of the next 72 h (after the time 0 of the forecast). At the moment the calculations are performed using a 100 cores Linux workstation; however for each case only 30 cores for ECMWF and 20 for AM and HNMS are used in order to perform several calculations at the same time.

ECMWF		AM COSMO-ME		HNMS COSMO	
Europe	4 min	Mediterranean Sea	2 min	Mediterranean Sea	2 min

Table 2 - *Resolutions of the JRC calculations using the ECMWF, AM and HNMS data.*

5) Post processing: *Creation of maps, animations, bulletins*

After having calculated the storm surge, there are several post processing steps:

- Creation of the final calculation set
    - All the calculations performed contains forecast section of 72 h. The "final calculation" is composed merging all the calculation results between -10 days and + 72 h respect to the nominal time of the analysis (see more information in Annunziato and Probst, 2016).
- Create outputs in different formats (e.g. maximum wind and storm surge in tif format, maximum storm surge along the coast in kmz format)
- Create animations and maps: new detailed maps have been created (e.g. maximum winds over sea and over land, maximum storm surge)
- Create the bulletins for fixed windows: new SSCS bulletins created using LaTeX (see Section 2.3)
- Send the e-mail with the SSCS bulletin

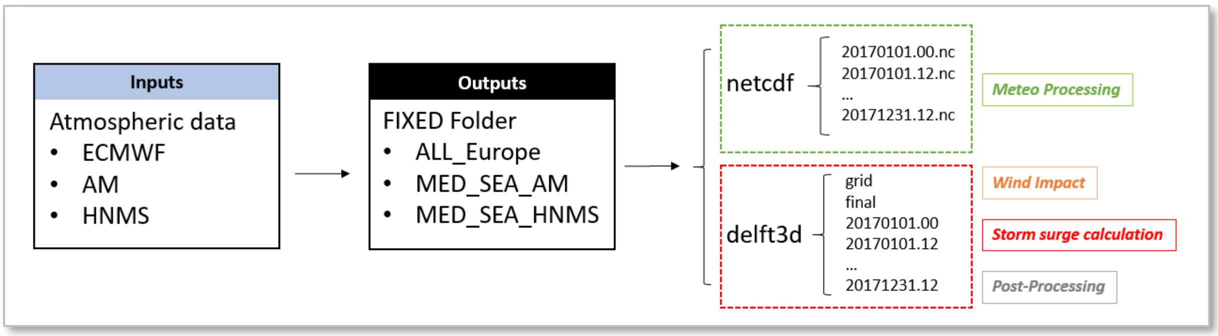

Figure 5 - *Inputs and Outputs*

Scheduled tasks: For all procedures described above, several different schedule tasks have been created, including a log file of the various calculations and webpages with the list of calculations completed and SSCS bulletins created.

Commands to run SSCS

Python or Bash:

python rerun.py *{start_date} {end_date} {code} {lonmin} {lonmax} {latmin} {latmax} {res} {atm_input} {dforecast} {timestep} {outputdir} {a} {b} {ncore} {listwin}*
./runcase.sh *{start_date} {end_date} delft3d {lonmin} {lonmax} {latmin} {latmax} {res} {atm_input} {dforecast} {timestep} {outputdir} {a} {b} {ncore} {listwin}*

Table 3 *- Command to run the new SSCS.*

where:

- *start_date*: yyyymmdd.hh
- *end_date*: yyyymmdd.hh
  → yyyy=year, mm=month, dd=day, hh=hour (e.g. 20171121.00)
  → Automatic: start_date=-1, end_date=5
- code: delft3d
- *lonmin*: lon min bounding box (bbox)
- *lonmax*: lon max bbox
- *latmin*: lat min bbox
- *latmax*: lat max bbox
- *res*: resolution of the calculation (see *Table 2*)
- *atm_input*: (ECMWF, COSMO-AM, COSMO-HNMS)
- *dforecast*: total hours forecast
- *timestep*: time step interpolation forecast
- *ncore*: number of cores
- *outputdir*: directory of the output
- *a* and *b* are used to force and perform specific run (see below)

ATMOSPHERIC INPUT	*COMMAND TO EXECUTE*
ECMWF	*python rerun.py -1 5 delft3d -40 43 25 75 4.0 ECMWF 72 60 FIXED/ALL_EUROPE 0 0 30 listWindows.txt*
AM	*python rerun.py -1 5 delft3d -4.0 35.0 30.7 49.7 2.0 COSMO-AM 72 60 FIXED/MED_SEA_AM_2m 0 0 20 listWindowsAM.txt*
HNMS	*python rerun.py -1 5 delft3d -5.2 36.613 30 46 2.0 COSMO-HNMS 72 60 FIXED/MED_SEA_HNMS_2m 0 0 20 listWindowsHNMS.txt*
Run all calculations	*allrun.sh*

Table 4 - *Commands to run SSCS*

Specific runs:

- *run a specific time period, creating calculations, figures, bulletins, …⇒* ***a=0, b=0***
- *create plots, figures + bulletins ⇒* ***a=0, b=2***
- *create only SSCS bulletins ⇒* ***a=0, b=3***
- *Restart Calculations and force results ⇒* ***a=0, b=1***

2.3 New SSCS bulletins

2.3.1 Main characteristics

JRC-SSCS creates every day several bulletins for different areas of Europe (see *Table 5*). These bulletins are created using many procedures in Python, Bash and a template in LaTeX (see *Figure 6* and Annex 3). The new methodology used is the following:

- **PreTeX**: A python script (extractXml) read a "PreTeX" file with the information and:
  - creates the plots (e.g. storm surge measured and calculated)
  - processes the images, downloading the figures (e.g. METEOSAT, webcams)
  - extractXml
  - processes the list of the locations affected and creates the tables (e.g. list of storm surge locations affected and max. storm surge)

  the output of the PreTeX process is a LaTeX file that includes the links for the images and plots, as well as the structures and lists for the tables.
- **CreatePDF**: The pdf file is created from the Pre-TeX file previously created using a bash script that run "pdflatex".
- **SendEmail**: the PDF versions of SSCS bulletins produced are sent by e-mail to the SSCS users, after their registration, when the bulletin is ready.

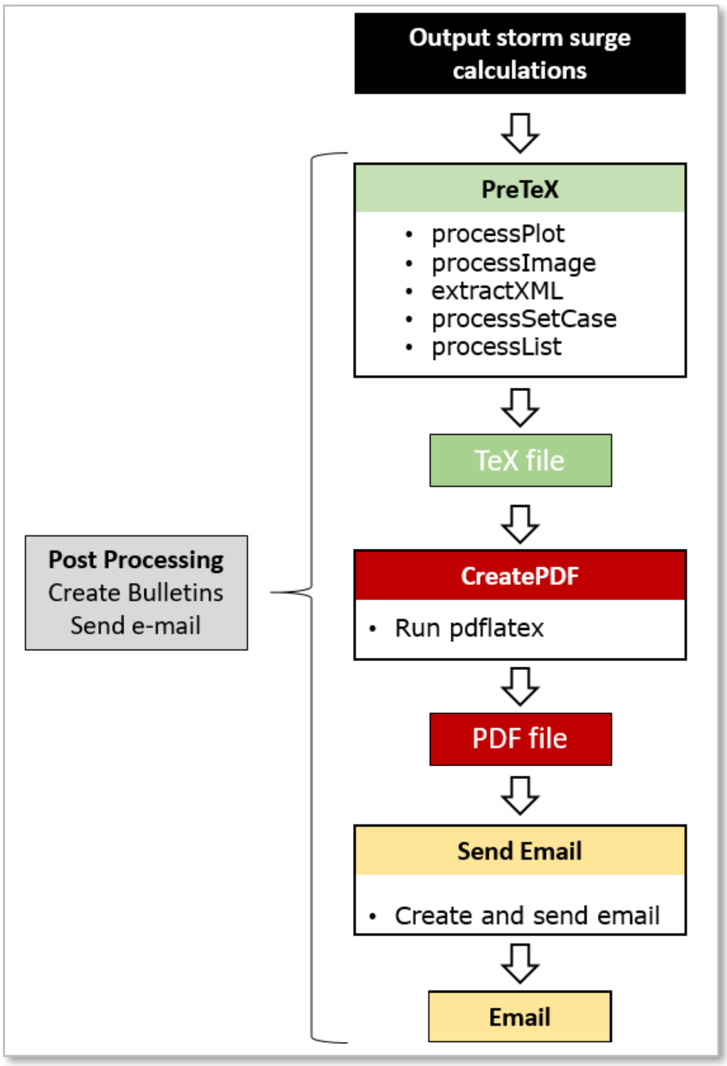

Figure 6 - *Procedures for the SSCS bulletins*

2.3.2 List of the SSCS bulletins

The list of the SSCS bulletins created are in *Table 5*, where the atmospheric inputs used are also shown.

SSCS BULLETINS	ATMOSPHERIC FORCING		
	ECMWF	AM	HNMS
UK & Ireland	●		
NORTH SEA	●		
N ATLANTIC	●		
MEDSEA	●		
IT (EN, IT)		●	
GREECE (EN, GR)			●

Table 5 – *List of the SSCS bulletins available.*

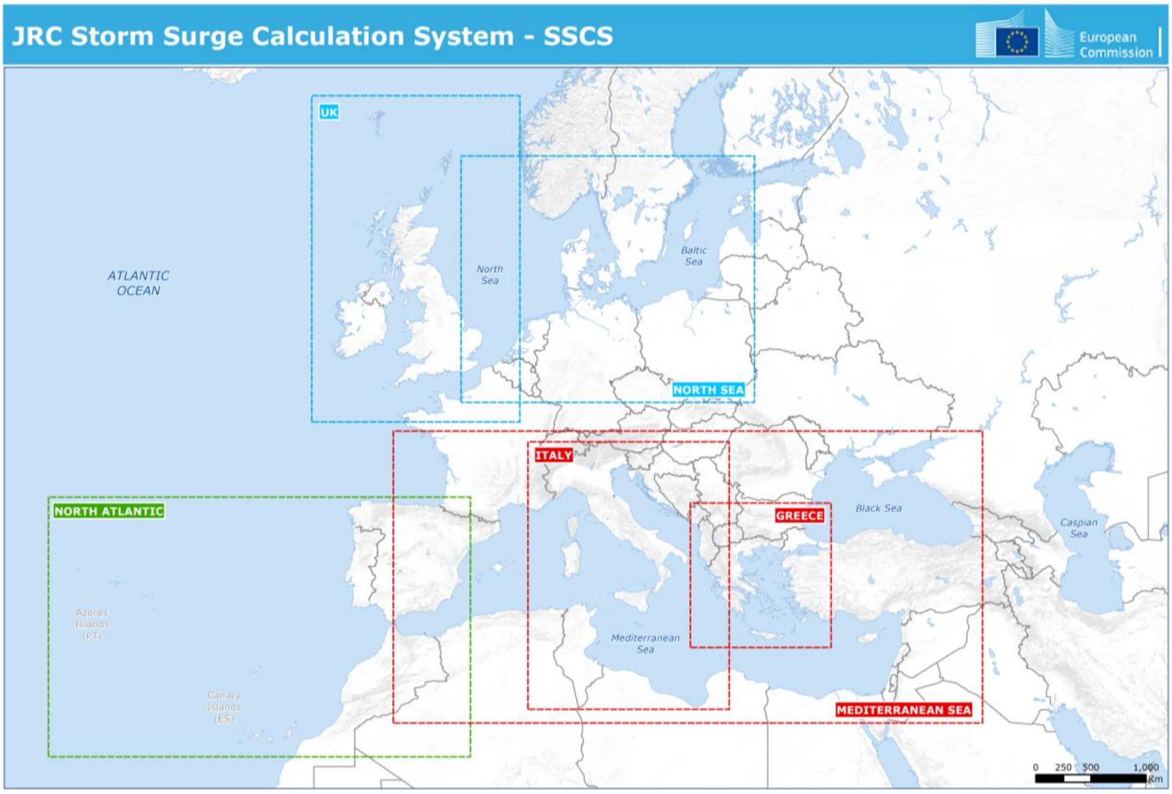

Figure 7 *- SSCS bulletins.*

2.3.3 LaTeX template

Every SSCS bulletin is created using the processes described in Section 2.3.1 and a specific "LaTeX template". The main characteristics of this template are presented below, while an example of the SSCS bulletin is in Annex 3.

Note: The final SSCS bulletin in pdf is created from the LaTeX file described here, but the list of locations affected, figures, tables, maps included in this latex file are created during the procedure "Pre-TeX", before running pdftatex (see *Figure 6*). For each SSCS bulletin a Pre-TeX file and a TeX file are created.

1 - Main Page

- *Title*:
  - type of bulletin (see list in *Table 5*)
  - time of the input data
  - time when the bulletin is issued

- *Table*:
  - list of the countries affected
  - alert level colour

- *Map*: the map includes the storm surge maximum height, values along the coasts (coastal impact line), and the locations affected according to a specific colour code (see Annunziato and Probst, 2016).

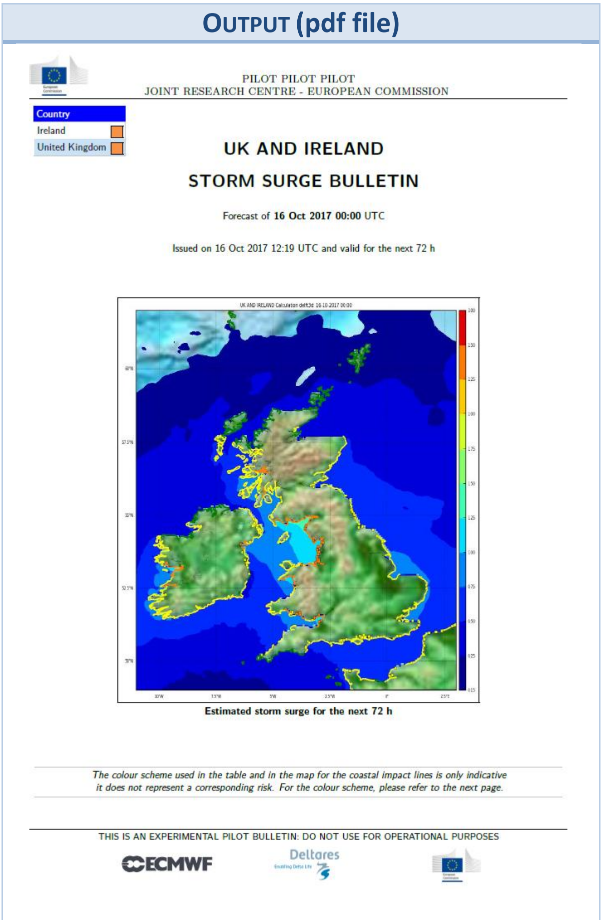

Figure 8 - *Example of the main page of the SSCS bulletin for UK/Ireland.*

2 - List of Locations

List of the locations affected by a storm surge greater than 0.5 m (North Sea, UK, Med Sea, North Atlantic), 0.3 m (Greece) and 0.3 m (Italy).
For each location affected:

- Maximum storm calculated
- Time of the maximum storm surge
- Colour code

OUTPUT (pdf file)

PILOT PILOT PILOT
JOINT RESEARCH CENTRE - EUROPEAN COMMISSION

LIST OF LOCATIONS

List of locations with height greater than **0.5 m**

Colour scheme
More than 3.00 m
2.00 - 3.00 m
1.00 - 2.00 m
0.50 - 1.00 m
0.05 - 0.50 m

Actual Time	Country	Location	Height	Lat	Lon
16 Oct 2017 11:00	Ireland	Dunquin	0.8	-10.467	52.133
16 Oct 2017 11:00	Ireland	Clynacartan	0.9	-10.400	51.900
16 Oct 2017 12:00	Ireland	An Daingean	0.9	-10.278	52.140
16 Oct 2017 11:00	Ireland	Cahirciveen	0.9	-10.237	51.947
16 Oct 2017 12:00	Ireland	Cloghane	0.9	-10.183	52.233
16 Oct 2017 11:00	Ireland	Waterville	0.9	-10.175	51.829
16 Oct 2017 16:00	Ireland	Aghleam	0.6	-10.100	54.117
16 Oct 2017 12:00	Ireland	Anascaul	0.8	-10.058	52.151
16 Oct 2017 11:00	Ireland	Allihies	0.9	-10.048	51.643
16 Oct 2017 14:00	Ireland	An Clochan	0.8	-10.025	53.489
16 Oct 2017 16:00	Ireland	Beal an Mhuirhead	0.6	-10.011	54.222
16 Oct 2017 11:00	Ireland	Sneem	0.9	-9.906	51.838
16 Oct 2017 14:00	Ireland	Ard	0.9	-9.883	53.317
16 Oct 2017 13:00	Ireland	Kilbaha	0.8	-9.877	52.569
16 Oct 2017 11:00	Ireland	Ballynakilla	0.8	-9.850	51.633
16 Oct 2017 15:00	Ireland	Louisburgh	0.7	-9.817	53.765
16 Oct 2017 14:00	Ireland	Killorglin	0.9	-9.792	52.106
16 Oct 2017 14:00	Ireland	Ardfert	0.9	-9.789	52.328
16 Oct 2017 11:00	Ireland	Adrigole	0.8	-9.717	51.683
16 Oct 2017 14:00	Ireland	Castlemaine	0.9	-9.709	52.168
16 Oct 2017 13:00	Ireland	Ballybunion	0.8	-9.675	52.512
16 Oct 2017 14:00	Ireland	Killeany	1.0	-9.667	53.100
16 Oct 2017 13:00	Ireland	Kilkee	0.8	-9.649	52.682
16 Oct 2017 16:00	Ireland	Belderg	0.5	-9.554	54.298
16 Oct 2017 14:00	Ireland	Doonbeg	0.8	-9.531	52.734
16 Oct 2017 14:00	Ireland	Kilrush	0.8	-9.489	52.640
16 Oct 2017 10:00	Ireland	Ballydehob	0.8	-9.477	51.563
16 Oct 2017 14:00	Ireland	Milltown Malbay	0.9	-9.410	52.859
16 Oct 2017 10:00	Ireland	Baltimore	0.8	-9.374	51.482
16 Oct 2017 16:00	Ireland	Ballycastle	0.5	-9.373	54.279
16 Oct 2017 11:00	Ireland	Skibbereen	0.8	-9.276	51.547
16 Oct 2017 14:00	Ireland	Ballyvaughan	1.1	-9.154	53.117
16 Oct 2017 11:00	Ireland	Ross Carberry	0.8	-9.044	51.579
16 Oct 2017 11:00	Ireland	Clonakilty	0.7	-8.889	51.624
16 Oct 2017 11:00	Ireland	Butlerstown	0.7	-8.717	51.600
16 Oct 2017 18:00	Ireland	An Charraig	0.5	-8.648	54.656
16 Oct 2017 18:00	Ireland	Grange	0.5	-8.530	54.393
16 Oct 2017 11:00	Ireland	Kinsale	0.7	-8.528	51.707
16 Oct 2017 18:00	Ireland	Killybegs	0.6	-8.460	54.639
16 Oct 2017 18:00	Ireland	Ardara	0.6	-8.420	54.764
16 Oct 2017 11:00	Ireland	Ballyfeard	0.8	-8.403	51.752
16 Oct 2017 11:00	Ireland	Passage West	0.8	-8.349	51.873
16 Oct 2017 11:00	Ireland	Knockraha	0.8	-8.333	51.950

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ECMWF Deltares

Figure 9 – *Example of the table of the list of the locations affected.*

3 – Meteosat Images (source: EUMETSAT)

Two Meteosat images (IR 10.8 Channels and EGB composite Natural Colours) are included in the SSCS bulletins (see *Figure 10*). Based on the area covered by the bulletin, three different images are included in the SSCS bulletin (see *Table 6*). More information are available at http://oiswww.eumetsat.org/IPPS/html/MSG/ .

Area	SSCS Bulletins
WESTERN EUROPE	North Atlantic
CENTRAL EUROPE	UK, North Sea, Med Sea, Italy
EASTERN EUROPE	Greece

Table 6 *- Meteosat areas.*

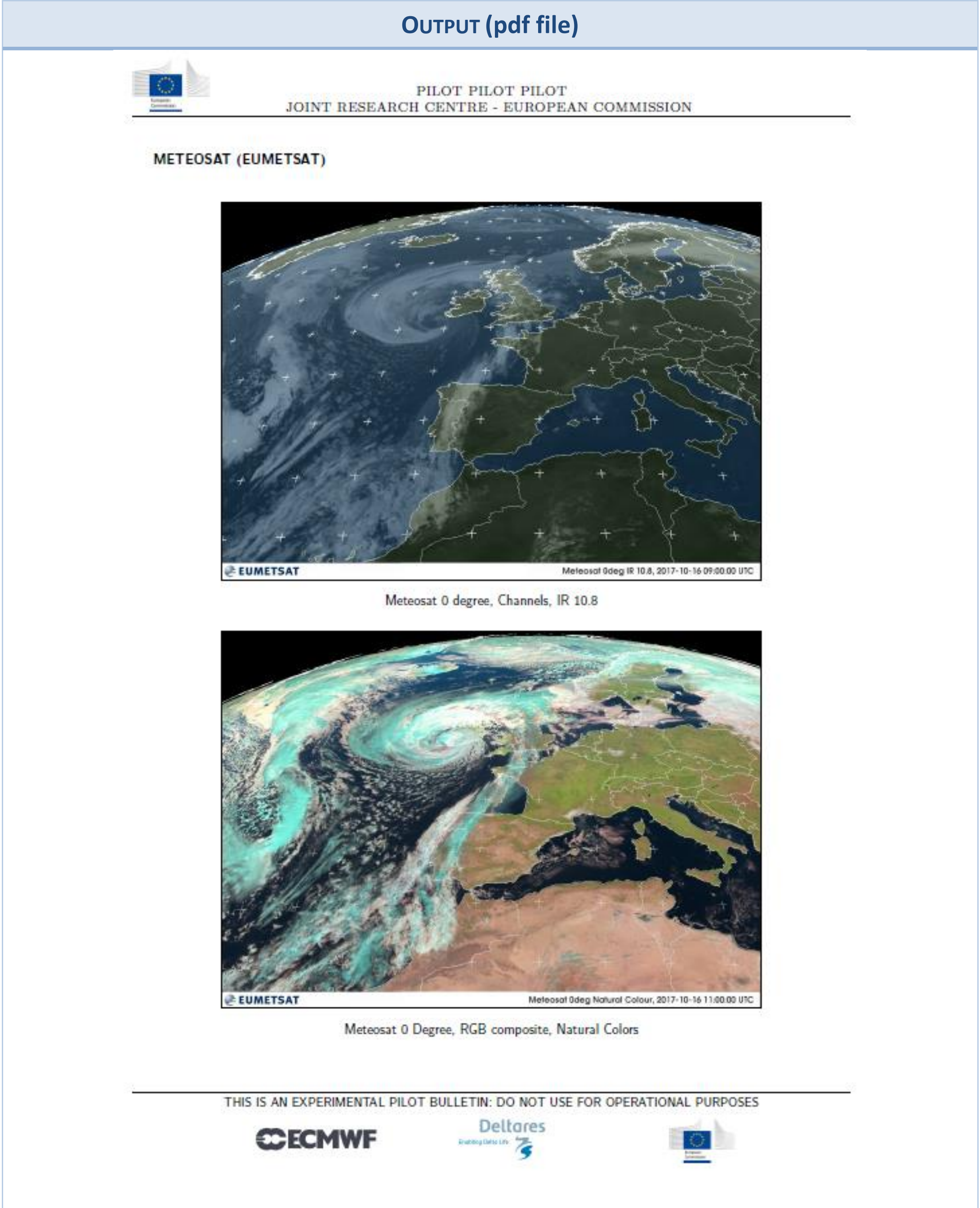

Figure 10 - *Meteosat images included in the SSCS bulletins.*

4 – JRC calculations: 10m Wind Speed and Sea Level Height

The maps of the Wind Speed at 10 m and the Sea Level Evolution obtained from the JRC calculations for the time: *t 0, t +24h, t + 48 h, t + 72 h* are included in this page.

OUTPUT (pdf file)

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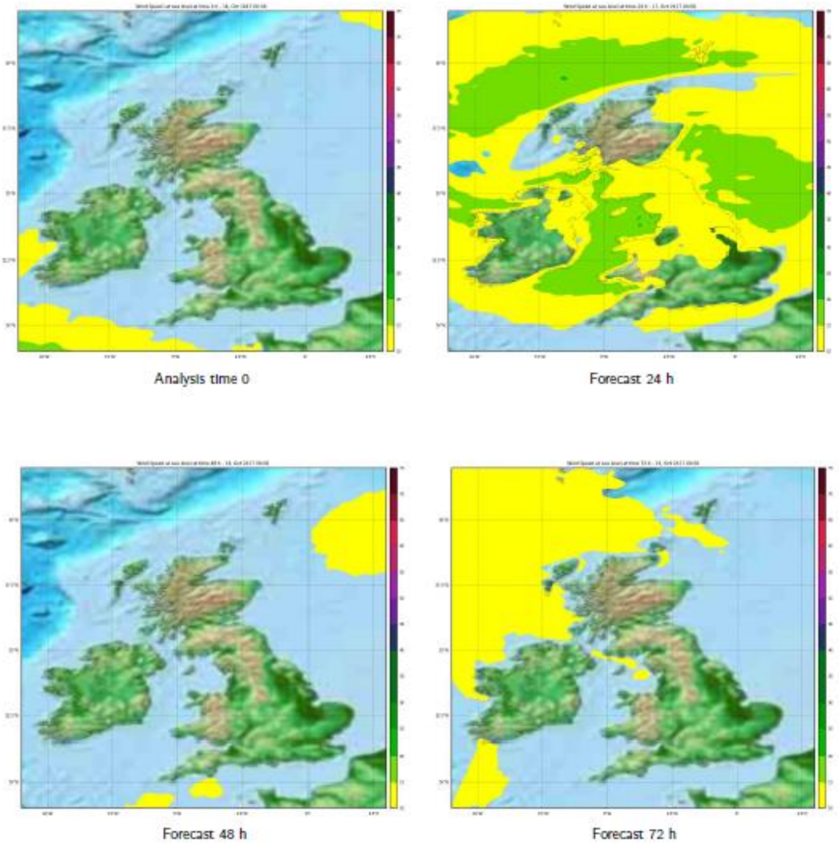
WIND IMPOSED



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ECMWF Deltares

Figure 11 - *Maps of the 10m Wind Speed*

OUTPUT (pdf file)

PILOT PILOT PILOT
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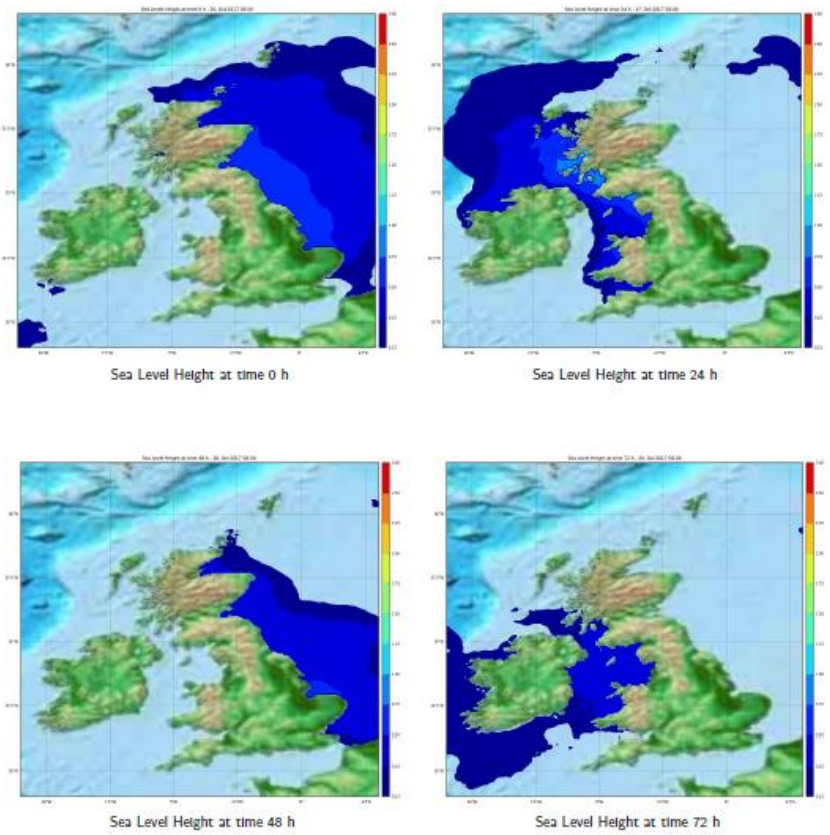
SEA LEVEL EVOLUTION



THIS IS AN EXPERIMENTAL PILOT BULLETIN: DO NOT USE FOR OPERATIONAL PURPOSES

ECMWF Deltares

***Figure 12** - Maps of the Sea Level Evolution.*

5 - Sea level comparisons between JRC calculations and measurements

In this section of the SSCS bulletin the JRC storm surge calculations are compared with the storm surge measured, obtained as:

Storm Surge (SS)	=	Sea level measured (TWL)	-	Tide level simulated (TD)

For each location, the storm surge measured and the one calculated are shown in the plot (see *Figure 13*), where the red line represents the storm surge measured, while the blue line represents the JRC storm surge calculations.

OUTPUT (pdf file)

SEA LEVEL STORM SURGE MEASUREMENTS AND MODELLING ESTIMATES

IRELAND and NORTHERN IRELAND (UK)

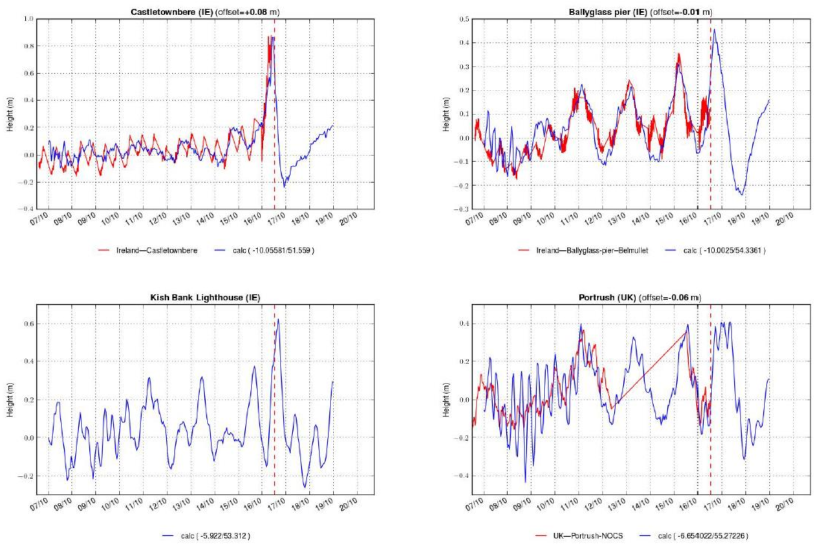


Figure 13 - *Example of the comparison between the storm surge measured (red line) and the storm surge calculated (blue line), where the values of the measured ones are obtained as: sea level measured (TWL) - tide level simulated (TD).*

In the bulletins of Italy and Greece this section is slightly different. For each location analysed there are two figures:

- LEFT Figure: Sea level measured (**TWL**): Storm Surge (SS) plus tide (TD)
- RIGHT Figure: Storm Surge (**SS**): Sea level measured (TWL) minus tide (TD)
  ➔ This figure is like the one included in the other SSCS bulletins.

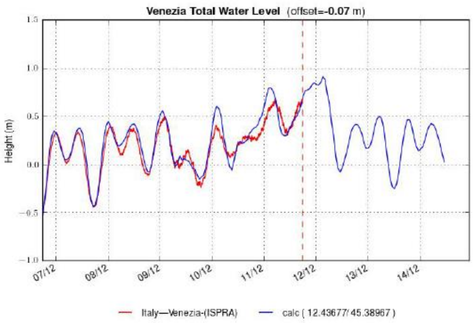
OUTPUT (pdf file)

Sea levels (TWL) on the left are the measured levels: Storm Surge (SS) plus tide (TD)

TWL= SS+TD

Sea levels on the right represent the Storm Surge (SS): Sea level (TWL) minus tide (TD) values

SS=TWL-TD



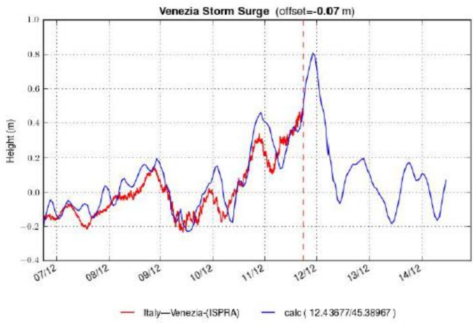


Figure 14 *-Left: Example of the comparison between the sea levels measured (red line) and the level calculated (blue line). Right: As for the left figure, but for the storm surge.*

The images of several webcams are also included in the SSCS bulletin (see *Figure 15*).

OUTPUT (pdf file)

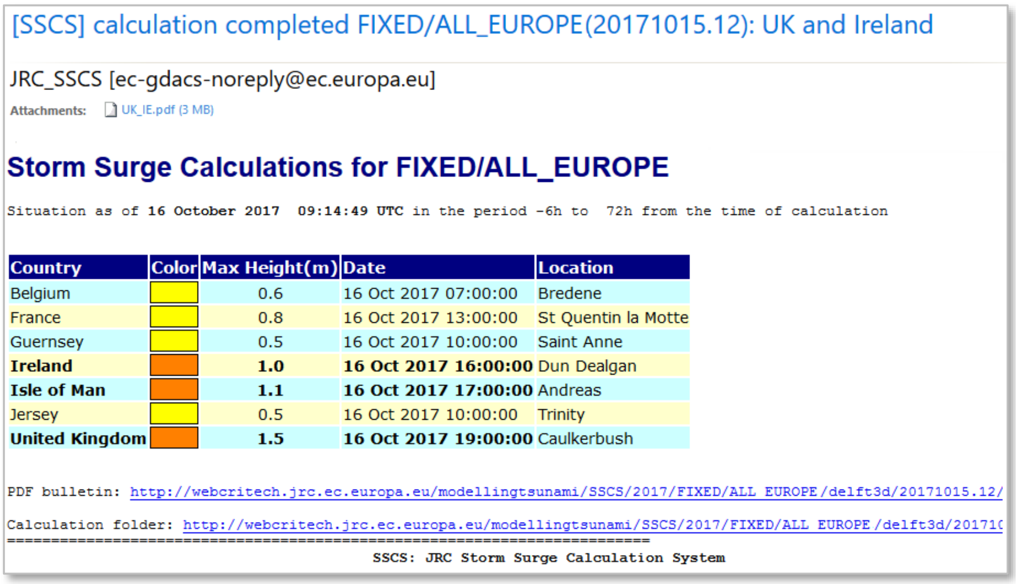
Webcam in Venezia, Piazza San Marco (ISPRA)

Webcam in Trieste (Protezione Civile FVG)

Figure 15 - *Example of the webcam in Venice (LEFT) and Trieste (RIGHT) included in the bulletin of Italy.*

2.3.4 SSCS email

The PDF versions of the SSCS bulletins produced are sent by e-mail to the SSCS users, when the bulletin is ready. The e-mail includes the pdf version of the bulletin and an overview table with the affected countries, maximum height of storm surge calculated, time of the maximum storm surge, location of the maximum storm surge, link to the pdf bulletin and to the calculation folder that includes all output files (see figure below).



[SSCS] calculation completed FIXED/ALL_EUROPE(20171015.12): UK and Ireland

JRC_SSCS [ec-gdacs-noreply@ec.europa.eu]

Attachments: UK_IE.pdf (3 MB)

Storm Surge Calculations for FIXED/ALL_EUROPE

Situation as of **16 October 2017 09:14:49 UTC** in the period -6h to 72h from the time of calculation

Country	Color	Max Height(m)	Date	Location
Belgium		0.6	16 Oct 2017 07:00:00	Bredene
France		0.8	16 Oct 2017 13:00:00	St Quentin la Motte
Guernsey		0.5	16 Oct 2017 10:00:00	Saint Anne
Ireland		**1.0**	**16 Oct 2017 16:00:00**	Dun Dealgan
Isle of Man		**1.1**	**16 Oct 2017 17:00:00**	Andreas
Jersey		0.5	16 Oct 2017 10:00:00	Trinity
United Kingdom		**1.5**	**16 Oct 2017 19:00:00**	Caulkerbush

PDF bulletin: http://webcritech.jrc.ec.europa.eu/modellingtsunami/SSCS/2017/FIXED/ALL_EUROPE/delft3d/20171015.12/

Calculation folder: http://webcritech.jrc.ec.europa.eu/modellingtsunami/SSCS/2017/FIXED/ALL_EUROPE/delft3d/20171(

SSCS: JRC Storm Surge Calculation System

Figure 16 - *Example of the new SSCS e-mail*

3 GDACS Storm surge system for TCs

3.1 Overview

The Tropical Cyclones (TCs) have three dangerous effects: strong winds, heavy rains and storm surge. In 2011, JRC has developed the first storm surge system for the TCs in GDACS[3], including the atmospheric forcing in the JRC HyFlux2 code used for tsunami modelling (see Probst and Franchello, 2012). For the atmospheric input, a specific Monte Carlo method based on the parametric model of Holland has been developed, using as input the wind radii data provided by the Joint Typhoon Warning Center (JTWC) and National Oceanic and Atmospheric Administration (NOAA) - National Hurricane Center (NHC), see Annex 2.2.
Over the last year, the JRC has developed several new tools to improve this operational storm surge system used in GDACS, based on the new:

- Hydrodynamic code: **Deltares Delft3D**
- Meteorological forecasts:
  - **ECMWF Operational high-resolution (HRES)**
  - **NOAA Hurricane Weather Research and Forecasting (HWRF)**
  - **NOAA Global Forecast System (GFS)**

A description of the code is in Annex 1, while the atmospheric forecasts are in Annex 2.2.

This new system estimates the storm surge for each TCs occurring worldwide (all TC basins are in *Figure 17*), using the three different atmospheric sources, and publishes the results in the new GDACS storm surge pages under development (not yet public). The new procedures are described in Section 3.2, while the new GDACS pages are in Section 3.3.

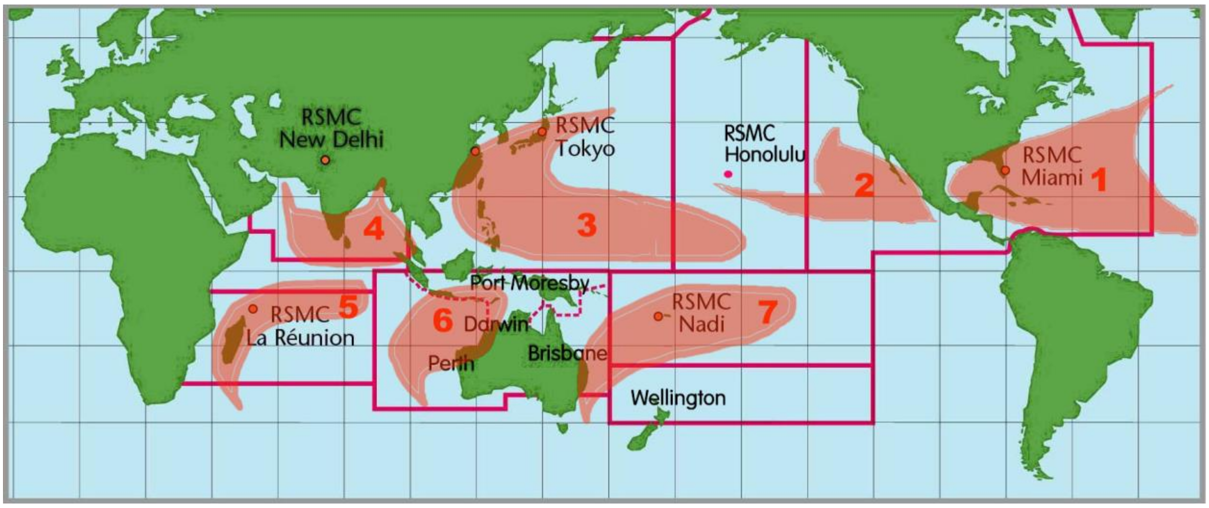


Figure 17 - *TC basins (source: WMO, NOAA http://www.aoml.noaa.gov/hrd/tcfaq/F1.html)*

[3] The Global Disaster Alert and Coordination System (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 (www.gdacs.org).

3.2 New Procedures

JRC set up the following new automatic procedures to download the new atmospheric data, estimate the storm surge and publish the results in GDACS.

1) **Input data**: Creation of several new tasks for:
   - 1.1) **download** (in parallel) of the input data files (GRIB data), as soon as the files become available
   - 1.2) **extract** the information required for the storm surge calculations and used for the estimation of the impact of the other two effects: wind and rainfall.
2) **Pre-Processing**: Processing of the meteorological inputs to create one single netcdf file that includes the atmospheric forcing (pressure and winds).
3) **Impact Estimation:** Creation of the maximum wind file and calculation of the population potentially affected by different class of winds (Note: this process will be included in the new impact assessment that the JRC is preparing for the TCs).
4) **Storm surge Calculations**: Launch the calculations using Delft3D (same code used for the SSCS).
5) **Post-processing** of the results
   - Create output files in different formats (e.g. files for JRC Tsunami Analysis Tool- TAT, kmz, kml, tif).
   - Publish the results in the new GDACS webpages under development (see Section 3.3).

A brief description of these steps is presented over the next pages, while a scheme of these procedures is shown in the figure below.

Note: Over the next months a new procedure will be created to include also the wind and pressure fields obtained using the Holland's model and the TC bulletins (method currently used in GDACS, see Probst and Franchello 2012).

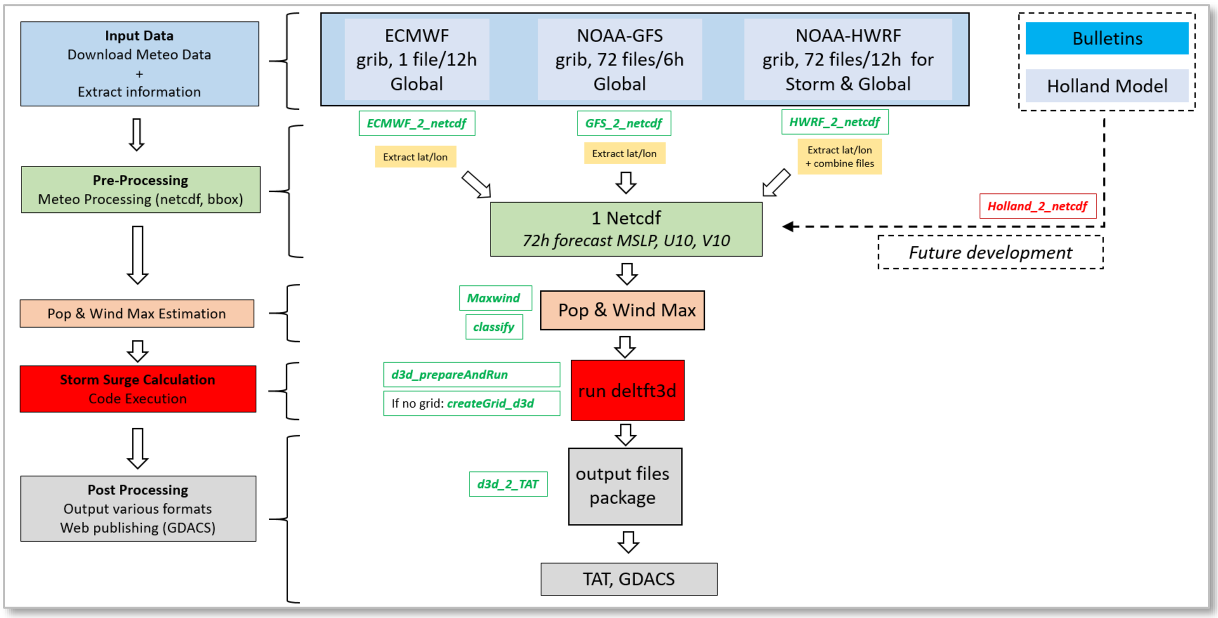


Figure 18 – *GDACS-Delft3D Procedure.*

1) Input data

The atmospheric input data used for the new storm surge calculations for TCs are:

- **ECMWF-HRES**,
- **NOAA-GFS**
- **NOAA-HWRF**

The procedure developed for ECMWF data is the same of the one used for SSCS, while for GFS and HWRF several new procedures have been developed. The characteristics of each file and the domain are in the table below, while the descriptions of the models are in Annex 2.2.

	ECMWF-HRES	NOAA-GFS	NOAA-HWRF
Model	operational high-resolution (HRES)	Global Forecast System (GFS)	Hurricane Weather Research and Forecasting (HWRF)
Format	Grib	Grib, several files	Grib, several files
Domain	Global	Global	All TC basins (3 domains: Global, Storm, Core)
Resolution	≈ 9 km	≈ 28 km	Combined 18/6/2 km
Initial Time of Model runs	00, 12 UTC	00, 06, 12, 18 UTC	00, 06, 12, 18 UTC
Data Format	Grib (1 file for model run including all forecasting time steps)	Grib (1 file for each forecasting time step)	Grib (1 file for each forecasting time step)
Parameters available	MSLP, u10,v10	Several parameters, including MSLP, u10,v10	Several parameters, including MSLP, u10,v10

Table 7- *Atmospheric inputs used in the storm surge calculations for GDACS TCs.*

1.1) Download of the atmospheric forcing

Several new tasks have been developed to download the NOAA data (GFS & HWRF):

NOAA-HWRF

There are several HWRF products (see Annex 2.2) and the new files are available every 6h. Currently we are downloading the following files used to prepare the JRC products for ERCC and in the new GDACS webpages (under development):

nr.	Product	Files	Variables
(a)	**GRIB2**	hwrfprs.global, hwrfprs.storm, hwrfprs.core	mslp (Pa), u10 (m/s), v10 (m/s), rainfall (mm), ...
(b)	**WRFDIAG**	wrfdiag_d01,wrfdiag_d02,wrfdiag_d03	mslp (Pa), u10 (m/s), v10 (m/s), rainfall (mm), ...
(c)	**ASCII**	winds10m.ascii, rainfall.ascii	wind swath (kt), rainfall swath (inch, inch2mm=25.4)
(d)	**TC track**	trak.hwrf.short6hr	track, vmax, pc, pn, rmax, wind radii

Table 8 – *NOAA-HWRF products*

All files are downloaded from the NOAA ftp website:
ftp://ftp.ncep.noaa.gov/pub/data/nccf/com/hur/prod/ (folder: hwrf.{yyyymmddhh})

(a) grib2 (for JRC Storm surge system)

- GLOBAL: irma11l.2017090700.hwrfprs.global.0p25.f000.grb2
- STORM: irma11l.2017090700.hwrfprs.storm.0p02.f000.grb2
- CORE: irma11l.2017090700.hwrfprs.core.0p02.f000.grb2

Timestep: 3h

Forecast: from 000 to 126 h (for the storm surge system we need only from 0 to 72 h)

(b) wrfdiag (for JRC Storm surge system)

- wrfdiag_d01 (GLOBAL): irma11l.2017090700.wrfdiag_d01
- wrfdiag_d02 (STORM): irma11l.2017090700.wrfdiag_d02
- wrfdiag_d03 (CORE): irma11l.2017090700.wrfdiag_d03

Timestep: 1h

Forecast: from 000 to 126 h (for the storm surge system we need only from 0 to 72 h)

(c) Files ASCII (wind & rainfall for new GDACS alerts under development, Daily Maps)

- Rainfall swath (inch): irma11l.2017090700.rainfall.ascii
- Wind swath (kt): irma11l.2017090700.wind10m.ascii

One single file every 6 h.

These two products include the accumulation over 126 h.

(d) Files TC track (for new GDACS alerts under development, Daily Maps)

- *.track.hwrf.short6hr

The TXT files include the forecast 0-126h for several variables (track, vmax, pc, pn, rmax, wind radii)

NOAA-GFS

There are several GFS products (see Annex 2.2) and the new files are available every 6h. Currently we are downloading the GFS - Global longitude-latitude grid 0.25° resolution (≈28 km)

	Files	Variables
GRIB2	gfs.tCCz.pgrb2.0p25.fFFF	mslp (Pa), u10 (m/s), v10 (m/s), rainfall (mm), snowdepthcover, tmin, tmax,...

Table 9 - *NOAA-GFS products*

All files are downloaded from the NOAA http website:
http://www.ftp.ncep.noaa.gov/data/nccf/com/gfs/prod/

GFS Files:

gfs.tCCz.pgrb2.0p25.fFFF
- CC is the model cycle runtime (i.e. 00, 06, 12, 18)
- FFF is the forecast hour of product from 000 - 384
- YYYYMMDD is the Year, Month and Day

Every day we are currently downloading these files:

- gfs.t00z.pgrb2.0p25.f000-72
- gfs.t06z.pgrb2.0p25.f000-72
- gfs.t12z.pgrb2.0p25.f000-72
- gfs.t18z.pgrb2.0p25.f000-72

Timestep: 3h

Forecast: from 000 to 384 h (but for the storm surge system we use only from 0 to 72h)

1.2) Extract atmospheric forcing

The HWRF and GFS forecasts contain several parameters for each forecast time, so we have developed some procedures in parallel to extract and saved only the information required for the new JRC GDACS Storm Surge System, as well as used in GDACS for the other TC effects (under development) and in the JRC products prepared for ERCC.

NOAA-HWRF

- Extract data used in the new JRC GDACS TC Storm Surge System under development (one grib file includes more than 700 bands; in the JRC storm surge system only MSLP, U10 and V10 are used).
- Extract data for the rainfall effect
- Convert ASCII files in tif file: rainfall and wind effects

→ 3 scripts: 1 for GRIB, 1 for WRFDIAG, 1 for ASCII files

a) *GRIB_extract_var.py*

python GRIB_extract_var.py -f {gribfile} -i {inputdir} -o {outputdir} -v {var} -t {dtype}

where:

- gribfile: input grib file (name of the file or "ALL" extract all files in the input folder)
- inpDir: input directory
- outDir: output directory
- var= var list file .txt or var1|var2| , see Default varlists(*)
- dtype=HWRF

(*)Default varlists: listGribHWRFsurge.txt (for storm surge) & listGribHWRFrain.txt (for rainfall)

listGribHWRFsurge.txt	Unit
Pressure reduced to MSL	Pa
10 metre U wind component	m/s
10 metre V wind component	m/s

listGribHWRFrain.txt	Unit
rainfall	mm

***Table 10 -** List of parameters extracted*

b) *WRFDIA_extract.py*

python WRFDIA_extract.py -f {hwrffile} -i {inputdir} -o {outputdir}

where:

- gribfile: input file (name of the file or "ALL" extract all files: 01,02,03)
- inpDir: input directory
- outDir: output directory

This script extracts the following parameters:

WRFDIA_extract	Unit
BEST_MSLP	Pa
U10	m/s
V10	m/s

Table 11 - *Parameters extracted*

b) *HWRF_ascii2tif.py*

python HWRF_ascii2tif.py -f {gribfile} -i {inputdir} -o {outputdir}

where:

- gribfile: input file (name of the file: rainfall.ascii, wind10m.ascii)
- inpDir: input directory
- outDir: output directory

outputfile: tif file (wind in m/s and rainfall in mm)

Variables	Unit
Wind swath	kt --> m/s
Rainfall	inch --> mm

Table 12 – *Parameters included in the tif files*

NOAA-GFS

- Extract data used in the new JRC GDACS Storm Surge System and for the other JRC products (meteo products: e.g. rainfall, temperatures)

GRIB_extract_var.py

python GRIB_extract_var.py -f {gribfile} -i {inputdir} -o {outputdir} -v {var} -t {dtype}

where:

- gribfile: input grib file (name of the file or "ALL" extract all files in the input folder)
- inpDir: input directory
- outDir: output directory
- var= var list file .txt or var1|var2| , see Default varlists(*)
- dtype=GFS

(*)Default varlists: listGribGFS.txt

listGribGFS.txt
Pressure reduced to MSL (Pa)
10 metre U wind component (m/s)
10 metre V wind component (m/s)
Minimum temperature
Maximum temperature
Snow depth
Total Precipitation (mm)

Table 13 - *NOAA-GFS parameters extracted*

Note: It is the same script used for HWRF, but using a different list of variables

2) **Pre-processing:** Processing of the meteorological inputs for the storm surge calculations

All the input files are in GRIB format, but they have a different domain, coordinate system and "time-structure". The scripts developed read the GRIB files and create the netCDF files used as input in the new JRC Storm surge system.
One single procedure for each meteo source has been created, in order to:

- Combine the various grids, superimposing the grid with a higher resolution to the global grid (only for HWRF files)
- Extract a portion of the grib file for a specific area based on the track of the TC for the three variables: MSLP, U10, V10
- Create one single netcdf files that includes the 72 h time steps and the three variables

3) **Impact Estimation:** Classification of the population potentially affected by winds

As for the SSCS, a Python script (parallelized) has been developed to create the maximum winds (ECMWF, GFS, HWRF) and another one to classify the population potentially affected (see Section 2.2.). For the wind thresholds, the TC system uses the Saffir-Simpson Hurricane Wind Scale (SSHS). 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 14 - *TC Classification (Saffir-Simpson Hurricane Wind Scale, SSHS) (see http://www.nhc.noaa.gov/aboutsshws.php)*

The number of people potentially affected by different classes of wind intensity obtained from these procedures are published in the new GDACS webpages under development (see Section 3.3).

Note: for the moment this classification is produced during the storm surge calculations, but over the next months a specific procedure only for the wind impact will be developed to improve the impact estimation in GDACS (see Probst et al, 2017).

4) **Calculations:** *Storm surge calculations for the three atmospheric sources*

As for the SSCS, the JRC has implemented the new solver: Deltares - Delft3D, but using a resolutions of 4 min for the three TCs storm surge calculations (ECMWF, HWRF and GFS). The calculations are performed using a 100 cores Linux workstation, but for each case only 10 cores (for each sources) are used since the three calculations are running on the same workstation of the SSCS.

The bounding box (bbox) of the calculations is automatically calculated considering the forecasted track of the TCs included in GDACS.

Note: A new procedure will be set up to create the new meteo files using the Holland's model and the TC bulletins, and will be used as input in these new calculations.

5) **Post processing:** *Creation of map, animations, bulletins*

After having calculated the storm surge, there are several post processing steps:

- Creation of the final calculation set
    - All the calculations performed contains forecast section of 72 h. The "final calculation" is composed merging all the calculation results between -10 days and + 72 h respect to the nominal time of the analysis (see more information in Annunziato and Probst, 2016).
- Create outputs in different formats (e.g. maximum wind and maximum storm surge in tif format, max storm surge along the coast in kmz format)
- Create animations and maps: new detailed maps have been created (e.g. maximum winds over sea and over land, maximum storm surge)
- Published the results in the new GDACS webpages (under development)

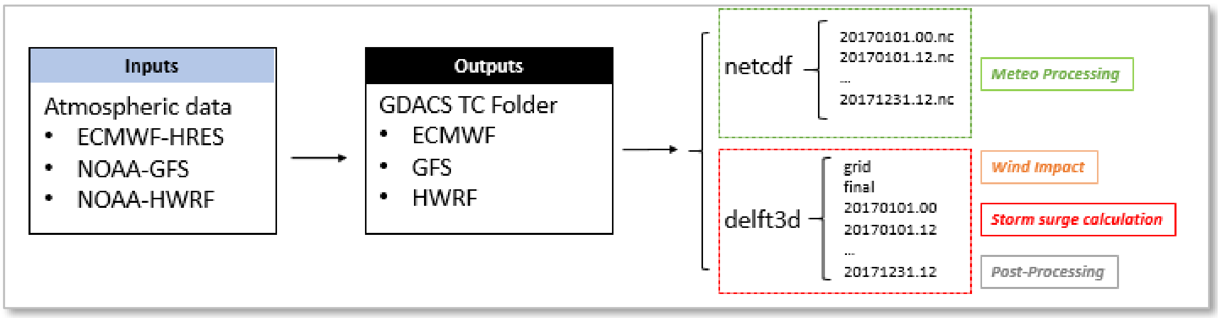


Table 15 - *Inputs and Outputs*

Note: For all procedures described above, several schedule tasks have been created, including a log file of the various calculations and a script that store only the final calculations after that a TC is finished.

Commands to run the new GDACS storm surge calculations

Python or Bash:

python rerun.py *{start_date} {end_date} {code} {lonmin} {lonmax} {latmin} {latmax} {res} {atm_input} {dforecast} {timestep} {outputdir} {a} {b} {ncore} {*}*
./runcase.sh *{start_date} {end_date} delft3d {lonmin} {lonmax} {latmin} {latmax} {res} {atm_input} {dforecast} {timestep} {outputdir} {a} {b} {ncore} {*}*
{}* For HWRF add: *"aa.txt" {gdacsid/hwrfid}*

***Table 16** - Command to run SSCS.*

where:

- *start_date*: yyyymmdd.hh
- *end_date*: yyyymmdd.hh
  → yyyy=year, mm=month, dd=day, hh=hour (e.g. 20171121.00)
- *code*: Delft3D (HyFlux2)
- *lonmin*: lon min bounding box (bbox)
- *lonmax*: lon max bbox
- *latmin*: lat min bbox
- *latmax*: lat max bbox
- *res*: resolution of the calculation (all calculations: 4)
- *atm_input*: (ECMWF, GFS, HWRF)
- *dforecast*: tot hours forecast (TC calculations: 72)
- *timestep*: time step interpolation forecast (all TC calculations: 15)
- *outputdir*: directory of the output
- *a* and *b:* parameters for calculations (all TC calculations: 1 1)
- *ncore*: number of cores (all TC calculations: 10)
- *gdacsid*: gdacs event id
- *hwrfid*: HWRF ID

ATMOSPHERIC INPUT	COMMAND TO EXECUTE
ECMWF-HRES	*python rerun.py 20170204.18 20170207.18 delft3d 39.995 64.269 -33.805 -3.5 4 ECMWF 72 15 GDACS/1000336/1_ECMWF 1 1 10*
NOAA-GFS	*python rerun.py 20170204.18 20170207.18 delft3d 39.995 64.269 -33.805 -3.5 4 GFS 72 15 GDACS/1000336/1_GFS 1 1 10*
NOAA-HWRF	*python rerun.py 20170204.18 20170207.18 delft3d 39.995 64.269 -33.805 -3.5 4 HWRF 72 15 GDACS/1000336/1_HWRF 1 1 10 "aa.txt" 1000336/04s*

***Table 17 –** Example of Commands to run TC storm surge calculations*

3.3 New GDACS webpages

For each TC and atmospheric sources (ECMWF, HWRF and GFS), JRC is preparing a new GDACS webpage to show the results of these new storm surge calculations (see description in Section 3.2), as well as for the new wind and rainfall impact estimations.

These new webpages will have the following structures:

- **GDACS alert**: overall alert level (wind, storm surge, rain).
- **Summary**: the most important information (e.g. maximum winds, population affected, time and maximum storm surge).
- **Wind**: Wind impact estimation: population potentially affected (total and per country) for each wind class based on the SSHS (see *Figure 19*), one map of the maximum winds and one for the time evolution.
- **Storm surge**: Storm surge impact estimation: a map with the maximum storm surge height and a table with the location potentially affected (as in the operational storm surge system).
- **Rainfall**: Rainfall impact estimation: population potentially affected (total and per country) for each rainfall class (see Probst et al. 2017), one map of the rainfall accumulation and one for the rainfall time evolution.

These pages are still **under development (rainfall part not yet implemented)** and are not public for the moment. The main characteristics of these new webpages are presented below showing the results for Hurricane IRMA.

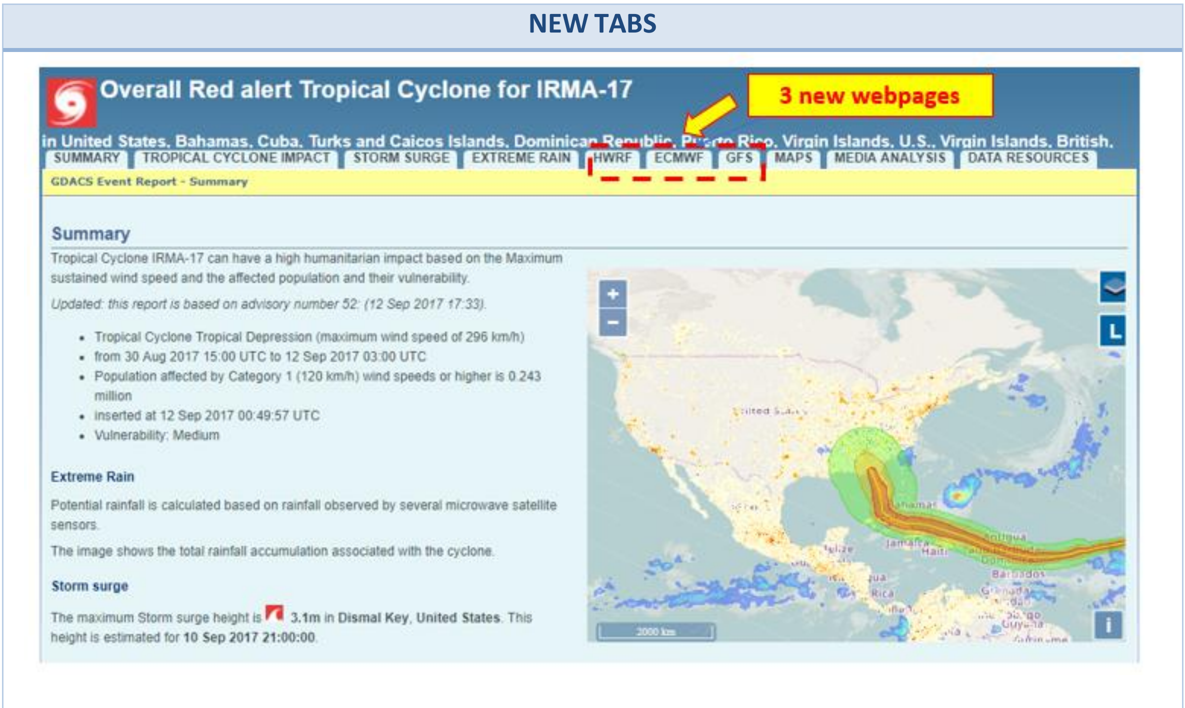
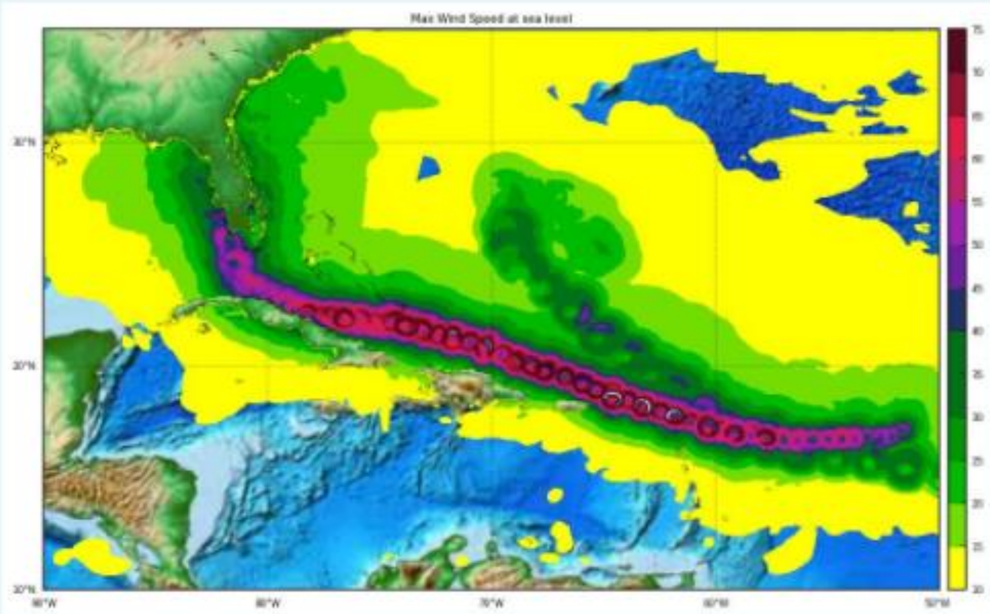


Figure 19 – *New GDACS webpages: New tabs ECMWF, HWRF, GFS (Hurricane IRMA).*

WIND



Max windspeed (*Source: HWRF*)

Legend
- · people affected <=10000
- • people affected >10000 and <100000
- ● people affected >100000

Calculation	Alert color	Date (UTC)	Wind speed	Population affected winds(>120km/h)	TS	CAT. 1	CAT. 2	CAT. 3	CAT. 4	CAT. 5	Countries
1		20170830.12	**69 km/h** (42 mph)	No people	·	×	×	×	×	×	Canada
2		20170904.06	**205 km/h** (127 mph)	130 thousand	●	●	·	·	×	×	Puerto Rico, Virgin Islands, British Virgin Islands, Saba (Netherlands), Sint Eustatius (Netherlands), Saint Kitts and Nevis, Antigua and Barbuda, Montserrat, Guadeloupe (France), British Virgin Islands, Saint Martin, Sint Maarten, Saint Barthelemy, Antigua and Barbuda, British Virgin Islands, Anguilla, Saint Martin, Antigua and Barbuda, British Virgin Islands, Anguilla, Antigua and Barbuda
3		20170904.12	**225 km/h** (139 mph)	90 thousand	●	•	·	·	•	×	Dominican Republic, Puerto Rico, Virgin Islands, Saint Martin, Sint Maarten, Saint Barthelemy, Antigua and Barbuda, Saba (Netherlands), Sint Eustatius (Netherlands), Saint Kitts and Nevis, British Virgin Islands, Saint Martin, Saint Barthelemy, Antigua and Barbuda, Anguilla, British Virgin Islands, Anguilla
4		20170904.18	**144 km/h** (89 mph)	30 thousand	●	•	×	×	×	×	Turks and Caicos Islands, Dominican Republic, British Virgin Islands, Puerto Rico, Anguilla, Saint Martin, Sint Maarten, Saint Barthelemy, Antigua and Barbuda, Saba (Netherlands), Sint Eustatius (Netherlands), Saint Kitts and Nevis, Turks and Caicos Islands, Anguilla
5		20170905.00	**148 km/h** (92 mph)	20 thousand	●	•	×	×	×	×	The Bahamas, Turks and Caicos Islands, British Virgin Islands, Anguilla, Saint Martin, Sint Maarten, Saint Barthelemy, Antigua and Barbuda, Saba (Netherlands), Sint Eustatius (Netherlands), Saint Kitts and Nevis
6		20170905.06	**218 km/h** (135 mph)	140 thousand	●	•	•	•	·	×	The Bahamas, Turks and Caicos Islands, Dominican Republic, British Virgin Islands, Puerto Rico, Saba (Netherlands), Antigua and Barbuda, Sint Eustatius (Netherlands), Saint Kitts and Nevis, Montserrat, Turks and Caicos Islands, The Bahamas, British Virgin Islands, Anguilla, Saint Martin, Sint Maarten, Saint Barthelemy, Antigua and Barbuda, The Bahamas, Turks and Caicos Islands, Anguilla
7		20170905.12	**245 km/h** (152 mph)	150 thousand	●	•	•	•	•	×	The Bahamas, Turks and Caicos Islands, Cuba, Dominican Republic, Haiti, Puerto Rico, British Virgin Islands, Saba (Netherlands), Sint Eustatius (Netherlands), Saint Kitts and Nevis, Antigua and Barbuda, Montserrat, Guadeloupe (France), The Bahamas, Turks and Caicos Islands, British Virgin Islands, Sint Maarten, Saint Barthelemy, Antigua and Barbuda, The Bahamas, Turks and Caicos Islands, British Virgin Islands, Saint Martin, Sint Maarten, Saint Barthelemy, Antigua and Barbuda, The Bahamas, Turks and Caicos Islands, British Virgin Islands, Anguilla, Turks and Caicos Islands, The Bahamas, British Virgin Islands, Anguilla, Antigua and Barbuda

Figure 20 - *New GDACS webpages: HWRF Winds (Hurricane IRMA).*

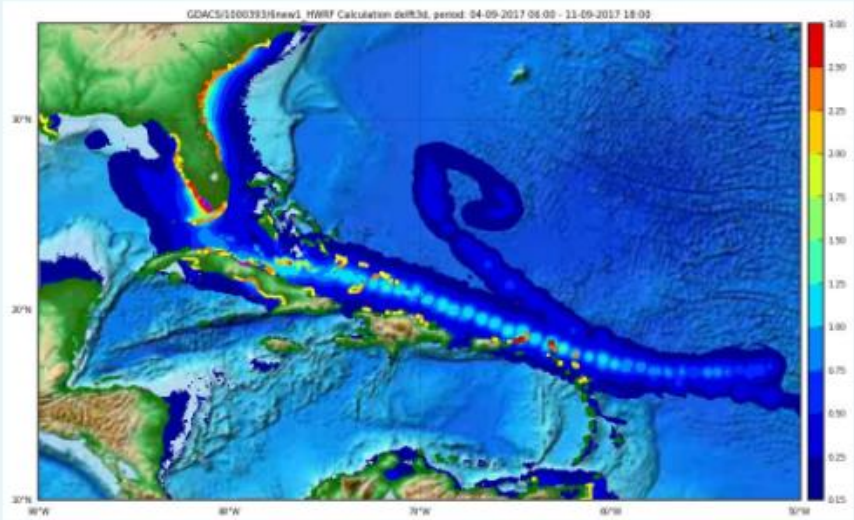
STORM SURGE

Orange alert for storm surge impact based on HWRF source

Summary

Current impact estimate:

- Population affected by cyclone-strength winds (>120km/h): **No People**
- Saffir-Simpson Category: Tropical storm
- Maximum sustained wind speed: **91** Km/h
- The maximum Storm surge height is **2.3m** in **Road Town**, **British Virgin Islands**. This height is estimated for **06 Sep 2017 19:00:00**.



Storm surge maximum height (*Source: JRC*)

Affected locations

Locations affected by Storm surge (15 of 2150)
Calculation based on advisory number of 12 Sep 2017 00:00.
(Simulation using minute resolution)

Date	Name	Country	Storm surge height (m)
06 Sep 2017 19:00:00	Road Town	British Virgin Islands	2.3m
06 Sep 2017 19:00:00	Pacham Town	British Virgin Islands	2.3m
06 Sep 2017 19:00:00	Spanish Town	British Virgin Islands	2.3m
06 Sep 2017 18:30:00	Adelphi	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Neltjeberg	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Cabritaberg	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Barrett	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Charlotte Amalie	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Enighed	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Bellevue	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Mandal	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Bolongo	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Donoe	Virgin Islands	2.3m
06 Sep 2017 18:30:00	Benner	Virgin Islands	2.3m

See full locations list (RSS)

Figure 21 - *New GDACS webpages: HWRF Storm Surge (Hurricane IRMA).*

4 Conclusions

The storm surge is an abnormal rise of water above the astronomical tides, generated by strong winds and a drop in the atmospheric pressure, due to the passage of a Tropical Cyclone (TC) or an intense low pressure system in general. JRC has developed the first storm surge calculation system for the Tropical Cyclones (TCs) included in the Global Disasters Alert and Coordination System (GDACS) in 2011 and the Storm Surge Calculation System (SSCS) for Europe in 2013.
Recently, the JRC has developed and implemented a new storm surge system for the SSCS and for the TCs in GDACS, using a new hydrodynamic code, atmospheric forecasts and creating new SSCS bulletins and GDACS web pages. This report has described all these new systems, showing the following:

Advantages:

- One single system for GDACS and SSCS, able to use several different atmospheric sources in the same code.
- Possibility to use different hydrodynamic codes (Delft3D, HyFlux2, other codes in the future: e.g. NAMI DANCE or HySEA)
- Run in parallel the calculations, using several cores
- Use one single calculation for the whole Europe

Limitations:

- Sometimes it is necessary to restart the calculations due to a problem related to the code and the bathymetry. For example there are some peaks on land, between islands and channels (i.e. Norway, Greece and Croatia)
    - ➔ Revise the bathymetry eliminating channels smaller than 1-2 cell sizes or increase the resolution
- Execution step is on multicore, but pre- and post-processing are still on a single core. For large computations, this is a limiting factor.
- There are still too many oscillations (i.e. Adriatic sea)
- No nested grid calculations
    - ➔ The ideal would be for example a Europe wide coarse calculation plus 3-4 nested calculations or a code with irregular grid nodding.

Future steps:

- Fix the problems related to the code and bathymetry
- Develop a new procedure that includes also the wind and pressure fields obtained using the Holland's model and the TC bulletins (method currently used in GDACS, see Probst and Franchello, 2012).

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List of abbreviations and definitions

AM	Italian Air Force Meteorological Weather Service
EC	European Commission
ECHO	European Civil Protection and Humanitarian Aid Operations
ECMWF	European Centre for Medium Weather Forecast
ERCC	Emergency Response Coordination Centre of DG ECHO
GDACS	Global Disasters Alerts and Coordination System
GFS	Global Forecasting System
GHSL	Global Human Settlement Layer
GPM	Global Precipitation Measurement
HNMS	Hellenic National Meteorological Service
HWRF	Hurricane Weather Research and Forecast System
JRC	Joint Research Centre
JTWC	Joint Typhoon Warning Center
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
SSCS	Storm Surge Calculation System
SSHS	Saffir Simpson Hurricane Scale
TC	Tropical Cyclone
TCWC	Tropical Cyclone Warning Centres
WMO	World Meteorological Organization
WRF	Weather Research and Forecasting

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Annexes

Annex 1 - Model Solvers

1.1 - HyFlux2

HyFlux2 model solves the shallow water equations using a finite volume method. The interface flux is computed by a Flux Vector Splitting method for shallow water equations based on a Godunov-type approach. A second-order scheme is applied to the water surface level and velocity, providing results with high accuracy and assuring the balance between fluxes and sources also for complex bathymetry and topography. Physical models are included to deal with bottom steps and shorelines. The second-order scheme together with the shorelinetracking method and the implicit source term treatment makes the model well balanced in respect to mass and momentum conservation laws, providing reliable and robust results.

HyFlux2 model uses uniform Cartesian grid and more detailed inundation simulations are performed by a nested grid approach. In the nest grid approach the boundary conditions of the simulations performed at finer grid size are taken from the simulation results at coarser grid size (see Franchello 2008, 2010).

In 2011, the atmospheric forcing has been included in the JRC tsunami HyFlux2 code in order to use it also for storm surge modelling (see Probst and Franchello, 2012).

1.2 - Delft3D

Delft3D of DELTARES is a flexible integrated 3D modelling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments.
The Delft3D suite has many modules that can be run independently or in coupled mode. The Delft3D-FLOW module can be used to evaluate the hydrodynamic response of a mass of water to various forcing components such as tides and winds. It can run on a rectilinear or curvilinear, boundary fitted grid in 2D or 3D mode. The 2D mode solves the depth-averaged hydrodynamic equations most applicable to storm surge computations while the 3D mode is required in dealing with transport processes.
The model solves the Navier Stokes equations for an incompressible fluid, under the shallow water and Boussinesq assumptions. This is coupled with a hydrostatic equation for pressure. The grid is staggered with the velocity computed on the vertices and the height of the water (pressure points) in the center of the grid cell. The numerical method is based on finite differences. The time integration is implicit, utilizing a variation of the ADI-method providing 2nd order accuracy both in space and time. The code is written in FORTRAN and is using MPICH to run in parallel mode. More information is available within the extensive collection of manuals provided by Deltares (http://oss.deltares.nl/web/delft3d/manuals).

Annex 2 - Atmospheric forcing

2.1 - SSCS

The SSCS uses meteorological forecasts produced by several meteorological centers in order to have the atmospheric input for the storm surge model and estimate the effect caused by the passage of an intense low pressure system.
The numerical weather forecasts of the following centers are used:

- **European Centre for Medium-Range Forecasts (ECMWF)**
- **Italian Air Force Meteorological Weather Service (AM)**
- **Hellenic National Meteorological Service (HNMS)**

The main characteristics of the forecasts used are shown in the table below, while a complete description is available in Annunziato and Probst (2016).

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.

The forecasts are produced every 12 hours (00, 12 UTC).

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

AM – COSMO-ME:

The COSMO[4]-ME model outputs are used as atmospheric input in the bulletin of Italy. This atmospheric input is provided by the Italian Air Force Meteorological Weather Service (AM). Two different configurations are available for deterministic forecast for Local Area Modelling: COSMO-ME and COSMO-IT. A probabilistic version (COSMO-ME EPS) is also available. COSMO-ME has a horizontal grid size of 5 km (before 7km), the following Domain: Central-southern Europe, Mediterranean Sea and Black Sea, and the forecasts are produced every 6 hours (00, 06, 12, 18 UTC).

— More information at: http://www.meteoam.it/modelli-di-previsione-numerica and at http://www.cosmo-model.org/content/tasks/operational/remet/default.htm.

HNME – COSMO-GR:

The HNMS COSMO model outputs are used as atmospheric input in the SSCS of Greece The Hellenic National Meteorological Service (HNMS) uses this model in operational mode. COSMO-GR has a horizontal grid size of 7 km, domain: Southern Europe, Mediterranean Sea and Black Sea, and the forecasts are produced every 12 hours (00, 12 UTC).

— More information at: and http://www.hnms.gr/emy/el/

[4] Consortium for Small-scale Modeling (**COSMO**) was formed in October 1998. Its general goal is to develop, improve and maintain a non-hydrostatic limited-area atmospheric model, to be used both for operational and for research applications by the members of the consortium. Moreover, within a licence agreement, the COSMO model may be used for operational and research applications by other national (hydro-)meteorological services, universities and research institutes (see http://www.cosmo-model.org/content/default.htm)

2.2 - GDACS

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 in GDACS are presented below, while more information can be found in the WMO - Global Guide to Tropical Cyclone Forecasting, 2017.

The atmospheric forcing of the operational storm surge system in GDACS is obtained using a Monte Carlo method based on the Holland parametric model and the information included in the TC bulletins provided by the JTWC and NOAA. Instead the new system developed uses as input the forecasts of ECMWF-HRES (as for SSCS), NOAA-GFS and NOAA-HWRF.

The main characteristics of these forecasts are shown below, while a complete description of these atmospheric inputs is available in Probst et al. (2016).

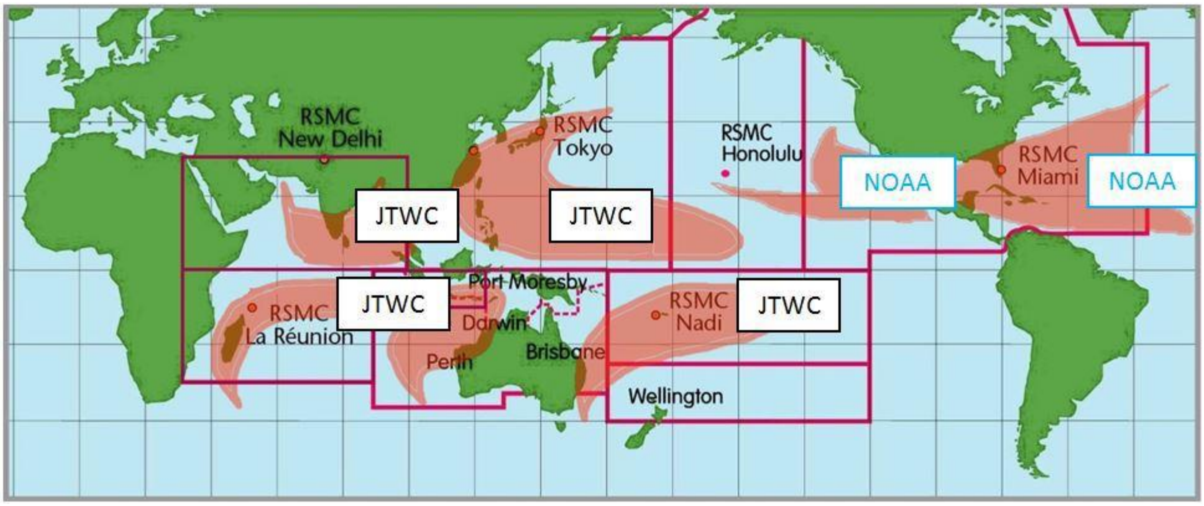
Tropical Cyclone bulletins

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. In addition to the RSMCs and TCWCs other organizations provides specific TC information (e.g. Joint Typhoon Warning Center - JTWC). Every 6-12 hours these centres publish a TC bulletin, including several TC information as: track, wind speed and wind radii[5]. The information and format included in each bulletin vary from center to center and it is not always in the same format, therefore the JRC set up an automatic routine that includes the TC bulletins produced by NOAA and JTWC into a single database, covering all TC basins. GDACS is currently using the wind radii data (34, 50 and 64 knots), provided in these bulletins, for the wind impact, as well as input in the Holland's Model used to infer the atmospheric forcing for the storm surge calculation in GDACS.

— 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/



TCs basins: data sources

[5] **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

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/

NOAA Global Forecast System (GFS) model

The Global Forecast System (GFS) is a weather forecast model produced by the National Centers for Environmental Prediction (NCEP) of NOAA. The entire globe is covered by the GFS at a base horizontal resolution of 28 kilometers between grid points, which is used by the operational forecasters who predict weather out to 16 days in the future. The GFS model is a coupled model, composed of four separate models. The forecasts are produced every six hours (00, 06, 12, and 18 UTC) and dozens of atmospheric and land-soil variables are available, from temperatures, winds, and precipitation to soil moisture and atmospheric ozone concentration.

— More information at: http://www.emc.ncep.noaa.gov/index.php?branch=GFS and https://www.ncdc.noaa.gov/data-access/model-data/model-datasets/global-forcast-system-gfs

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

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

Annex 3 – Example of the new SSCS bulletin

3.1 – PreTeX

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  \centerline{Forecast of \textbf{$BULLDATE} UTC}
  \vspace{7mm}
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  \hspace{2.0cm}\textit{it does not represent a corresponding risk. For the colour scheme, please refer to the next page.}\hspace{1.2cm}\\
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\hspace{10mm}List of locations with height greater than \textbf{$MAX m}
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            <h>276</h><w>460</w>
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         \caption*{Meteosat 0 Degree, RGB composite, Natural Colors}
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{\fontsize{13}{13}\textbf{\selectfont REFERENCES}}

Measured data from National Oceanographic Centre, Southampton (NOCS), Estimation from Joint Research Centre (JRC)
based on Meteorological Forecasts from European Centre for Medium Weather Forecast (ECMWF) and using the
DELTARES-DELFT3D Flow code.

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   \item DELTARES: \url{https://www.deltares.nl/en/}
   \item DELFT3D: \url{https://oss.deltares.nl/web/delft3d}
   \item EUMETSAT: \url{http://www.eumetsat.int/website/home/index.html}
   \item European Centre for Medium Weather Forecast  (ECMWF): \url{http://www.ecmwf.int}
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3.2 – PDF

PILOT PILOT PILOT
JOINT RESEARCH CENTRE - EUROPEAN COMMISSION

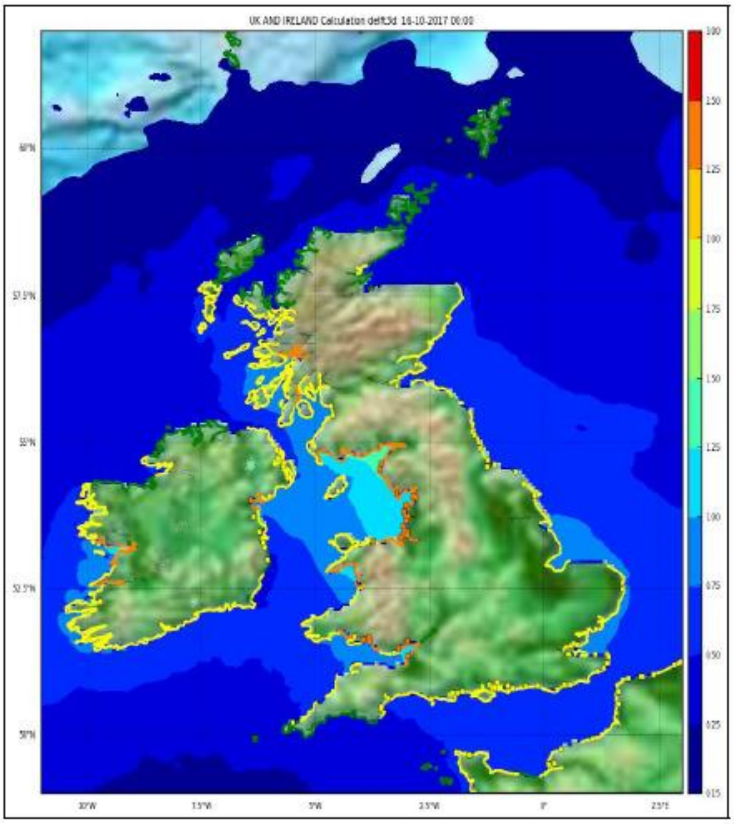
Country
Ireland
United Kingdom

UK AND IRELAND

STORM SURGE BULLETIN

Forecast of **16 Oct 2017 00:00** UTC

Issued on 16 Oct 2017 12:19 UTC and valid for the next 72 h



Estimated storm surge for the next 72 h

The colour scheme used in the table and in the map for the coastal impact lines is only indicative it does not represent a corresponding risk. For the colour scheme, please refer to the next page.

THIS IS AN EXPERIMENTAL PILOT BULLETIN: DO NOT USE FOR OPERATIONAL PURPOSES

LIST OF LOCATIONS

List of locations with height greater than **0.5 m**

Colour scheme
More than 3.00 m
2.00 - 3.00 m
1.00 - 2.00 m
0.50 - 1.00 m
0.05 - 0.50 m

Actual Time	Country	Location	Height	Lat	Lon
16 Oct 2017 11:00	Ireland	Dunquin	**0.8**	-10.467	52.133
16 Oct 2017 11:00	Ireland	Clynacartan	**0.9**	-10.400	51.900
16 Oct 2017 12:00	Ireland	An Daingean	**0.9**	-10.278	52.140
16 Oct 2017 11:00	Ireland	Cahirciveen	**0.9**	-10.237	51.947
16 Oct 2017 12:00	Ireland	Cloghane	**0.9**	-10.183	52.233
16 Oct 2017 11:00	Ireland	Waterville	**0.9**	-10.175	51.829
16 Oct 2017 16:00	Ireland	Aghleam	**0.6**	-10.100	54.117
16 Oct 2017 12:00	Ireland	Anascaul	**0.8**	-10.058	52.151
16 Oct 2017 11:00	Ireland	Allihies	**0.9**	-10.048	51.643
16 Oct 2017 14:00	Ireland	An Clochan	**0.8**	-10.025	53.489
16 Oct 2017 16:00	Ireland	Beal an Mhuirhead	**0.6**	-10.011	54.222
16 Oct 2017 11:00	Ireland	Sneem	**0.9**	-9.906	51.838
16 Oct 2017 14:00	Ireland	Ard	**0.9**	-9.883	53.317
16 Oct 2017 13:00	Ireland	Kilbaha	**0.8**	-9.877	52.569
16 Oct 2017 11:00	Ireland	Ballynakilla	**0.8**	-9.850	51.633
16 Oct 2017 15:00	Ireland	Louisburgh	**0.7**	-9.817	53.765
16 Oct 2017 14:00	Ireland	Killorglin	**0.9**	-9.792	52.106
16 Oct 2017 14:00	Ireland	Ardfert	**0.9**	-9.789	52.328
16 Oct 2017 11:00	Ireland	Adrigole	**0.8**	-9.717	51.683
16 Oct 2017 14:00	Ireland	Castlemaine	**0.9**	-9.709	52.168
16 Oct 2017 13:00	Ireland	Ballybunion	**0.8**	-9.675	52.512
16 Oct 2017 14:00	Ireland	Killeany	**1.0**	-9.667	53.100
16 Oct 2017 13:00	Ireland	Kilkee	**0.8**	-9.649	52.682
16 Oct 2017 16:00	Ireland	Belderg	**0.5**	-9.554	54.298
16 Oct 2017 14:00	Ireland	Doonbeg	**0.8**	-9.531	52.734
16 Oct 2017 14:00	Ireland	Kilrush	**0.8**	-9.489	52.640
16 Oct 2017 10:00	Ireland	Ballydehob	**0.8**	-9.477	51.563
16 Oct 2017 14:00	Ireland	Milltown Malbay	**0.9**	-9.410	52.859
16 Oct 2017 10:00	Ireland	Baltimore	**0.8**	-9.374	51.482
16 Oct 2017 16:00	Ireland	Ballycastle	**0.5**	-9.373	54.279
16 Oct 2017 11:00	Ireland	Skibbereen	**0.8**	-9.276	51.547
16 Oct 2017 14:00	Ireland	Ballyvaughan	**1.1**	-9.154	53.117
16 Oct 2017 11:00	Ireland	Ross Carberry	**0.8**	-9.044	51.579
16 Oct 2017 11:00	Ireland	Clonakilty	**0.7**	-8.889	51.624
16 Oct 2017 11:00	Ireland	Butlerstown	**0.7**	-8.717	51.600
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16 Oct 2017 11:00	Ireland	Ballyfeard	**0.8**	-8.403	51.752
16 Oct 2017 11:00	Ireland	Passage West	**0.8**	-8.349	51.873
16 Oct 2017 11:00	Ireland	Knockraha	**0.8**	-8.333	51.950

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16 Oct 2017 22:00	Ireland	Ballyshannon	**0.6**		-8.194	54.502
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17 Oct 2017 01:00	United Kingdom	Milovaig	**0.6**		-6.762	57.455
16 Oct 2017 12:00	Ireland	Wellington Bridge	**0.6**		-6.758	52.265
17 Oct 2017 01:00	United Kingdom	Dunvegan	**0.6**		-6.582	57.438
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16 Oct 2017 16:00	Ireland	Castlebellingham	**1.0**		-6.394	53.898
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17 Oct 2017 01:00	United Kingdom	Kilmory	**0.6**		-6.367	57.050
16 Oct 2017 23:00	United Kingdom	Bowmore	**0.8**		-6.290	55.759
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16 Oct 2017 17:00	United Kingdom	Carradale	**1.1**	-5.471	55.593
17 Oct 2017 00:00	United Kingdom	Oban	**1.4**	-5.467	56.411
16 Oct 2017 17:00	United Kingdom	Tarbert	**1.1**	-5.421	55.864
16 Oct 2017 13:00	United Kingdom	Hayle	**0.5**	-5.414	50.190
17 Oct 2017 00:00	United Kingdom	Portnacroish	**1.4**	-5.377	56.576
16 Oct 2017 17:00	United Kingdom	Blackwaterfoot	**1.0**	-5.328	55.503
16 Oct 2017 13:00	United Kingdom	Camborne	**0.5**	-5.299	50.217
17 Oct 2017 00:00	United Kingdom	Clovullin	**1.3**	-5.269	56.720
16 Oct 2017 13:00	United Kingdom	Saint Agnes	**0.7**	-5.206	50.314
16 Oct 2017 13:00	United Kingdom	Perranporth	**0.7**	-5.159	50.346
16 Oct 2017 18:00	United Kingdom	Brodick	**1.0**	-5.150	55.577
16 Oct 2017 17:00	United Kingdom	Portpatrick	**0.9**	-5.115	54.846
16 Oct 2017 13:00	United Kingdom	Goonhavern	**0.7**	-5.114	50.343
16 Oct 2017 13:00	United Kingdom	Penryn	**0.5**	-5.108	50.170
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16 Oct 2017 18:00	United Kingdom	Stranraer	**1.3**	-5.023	54.903
16 Oct 2017 18:00	United Kingdom	Ballantrae	**0.9**	-5.006	55.101
16 Oct 2017 16:00	United Kingdom	Goodwick	**0.7**	-4.991	52.000
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16 Oct 2017 19:00	United Kingdom	Dunoon	**1.0**		-4.926	55.954
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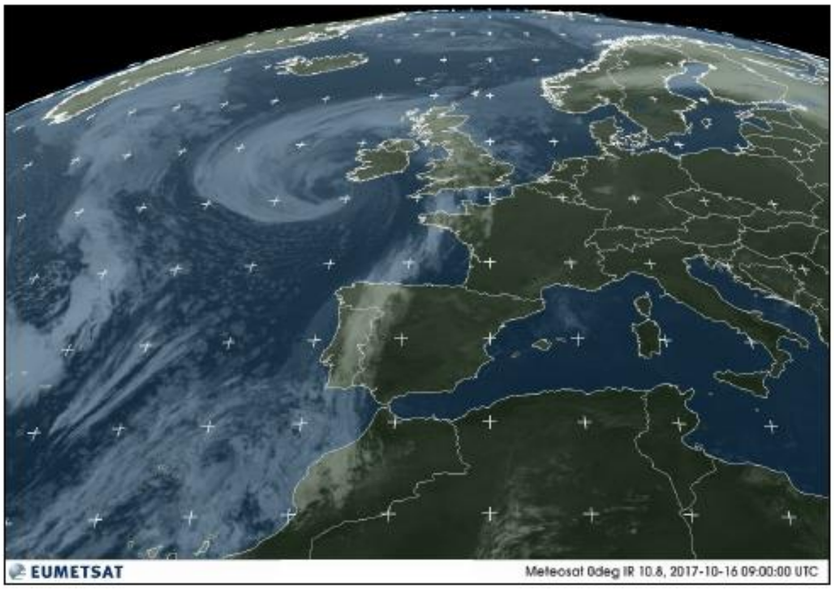
16 Oct 2017 19:00	United Kingdom	Largs	**1.0**		-4.861	55.793
16 Oct 2017 18:00	United Kingdom	Girvan	**0.9**		-4.854	55.239
16 Oct 2017 18:00	United Kingdom	Glenluce	**1.3**		-4.818	54.880
16 Oct 2017 18:00	United Kingdom	Ardrossan	**0.9**		-4.815	55.649
16 Oct 2017 19:00	United Kingdom	Gourock	**1.0**		-4.811	55.958
16 Oct 2017 18:00	United Kingdom	Saltcoats	**0.9**		-4.791	55.641
16 Oct 2017 15:00	United Kingdom	Tenby	**0.8**		-4.714	51.679
16 Oct 2017 16:00	United Kingdom	Aberdaron	**1.0**		-4.709	52.808
16 Oct 2017 15:00	United Kingdom	Saundersfoot	**0.8**		-4.706	51.711
16 Oct 2017 17:00	United Kingdom	Holyhead	**0.9**		-4.636	53.309
16 Oct 2017 18:00	United Kingdom	Prestwick	**0.9**		-4.617	55.498
16 Oct 2017 18:00	United Kingdom	Port William	**1.3**		-4.587	54.761
16 Oct 2017 17:00	United Kingdom	Valley	**0.9**		-4.566	53.284
16 Oct 2017 13:00	United Kingdom	Bude	**0.7**		-4.550	50.830
16 Oct 2017 13:00	United Kingdom	Poughill	**0.7**		-4.529	50.844
16 Oct 2017 16:00	United Kingdom	Nefyn	**1.1**		-4.526	52.936
16 Oct 2017 20:00	United Kingdom	Newton Stewart	**1.3**		-4.484	54.955
16 Oct 2017 20:00	United Kingdom	Wigtown	**1.3**		-4.452	54.868
16 Oct 2017 16:00	United Kingdom	Pwllheli	**1.2**		-4.421	52.889
16 Oct 2017 20:00	United Kingdom	Isle of Whithorn	**1.3**		-4.373	54.701
16 Oct 2017 18:00	United Kingdom	Amlwch	**1.0**		-4.343	53.407
16 Oct 2017 16:00	United Kingdom	Chwilog	**1.2**		-4.331	52.917
16 Oct 2017 17:00	United Kingdom	Caernarfon	**0.9**		-4.272	53.141
16 Oct 2017 15:00	United Kingdom	Aberaeron	**0.9**		-4.264	52.239
16 Oct 2017 18:00	United Kingdom	Benllech	**1.0**		-4.229	53.319
16 Oct 2017 16:00	United Kingdom	Criccieth	**1.2**		-4.224	52.921
16 Oct 2017 15:00	United Kingdom	Woolacombe	**0.8**		-4.209	51.175
16 Oct 2017 14:00	United Kingdom	Bideford	**0.8**		-4.205	51.019
16 Oct 2017 14:00	United Kingdom	Appledore	**0.8**		-4.198	51.052
16 Oct 2017 20:00	United Kingdom	Gatehouse of Fleet	**1.3**		-4.187	54.881
16 Oct 2017 17:00	United Kingdom	Menai Bridge	**0.9**		-4.180	53.230
16 Oct 2017 15:00	United Kingdom	Llanon	**0.9**		-4.180	52.277
16 Oct 2017 15:00	United Kingdom	Braunton	**0.9**		-4.165	51.112
16 Oct 2017 16:00	United Kingdom	Porthmadog	**1.2**		-4.136	52.929
16 Oct 2017 20:00	United Kingdom	Borgue	**1.3**		-4.134	54.812
16 Oct 2017 18:00	United Kingdom	Bangor	**1.0**		-4.131	53.228
16 Oct 2017 15:00	United Kingdom	Ilfracombe	**0.9**		-4.130	51.207
16 Oct 2017 15:00	United Kingdom	Llangelynin	**1.0**		-4.117	52.633
16 Oct 2017 18:00	United Kingdom	Beaumaris	**1.0**		-4.096	53.266
16 Oct 2017 15:00	United Kingdom	Aberystwyth	**1.0**		-4.085	52.416
16 Oct 2017 15:00	United Kingdom	Tywyn	**1.0**		-4.083	52.586
16 Oct 2017 16:00	United Kingdom	Penrhyndeudraeth	**1.2**		-4.074	52.930
16 Oct 2017 01:00	United Kingdom	Tain	**0.6**		-4.058	57.813
16 Oct 2017 16:00	United Kingdom	Barmouth	**1.2**		-4.057	52.726
16 Oct 2017 15:00	United Kingdom	Aberdovey	**1.0**		-4.039	52.547
16 Oct 2017 01:00	United Kingdom	Dornoch	**0.6**		-4.030	57.882

16 Oct 2017 01:00	United Kingdom	Golspie	**0.6**		-3.983	57.975
16 Oct 2017 19:00	United Kingdom	Llanfairfechan	**1.0**		-3.977	53.256
16 Oct 2017 01:00	United Kingdom	Balintore	**0.6**		-3.914	57.759
16 Oct 2017 20:00	United Kingdom	Auchencairn	**1.4**		-3.875	54.840
16 Oct 2017 01:00	United Kingdom	Brora	**0.6**		-3.857	58.013
16 Oct 2017 15:00	United Kingdom	Lynton	**1.0**		-3.838	51.228
16 Oct 2017 19:00	United Kingdom	Conwy	**1.0**		-3.833	53.282
16 Oct 2017 01:00	United Kingdom	Portmahomack	**0.5**		-3.828	57.835
16 Oct 2017 19:00	United Kingdom	Dalbeattie	**1.5**		-3.825	54.931
16 Oct 2017 15:00	United Kingdom	Porlock	**1.0**		-3.597	51.210
16 Oct 2017 19:00	United Kingdom	Abergele	**1.1**		-3.584	53.285
16 Oct 2017 10:00	United Kingdom	Galmpton	**0.5**		-3.560	50.399
16 Oct 2017 20:00	United Kingdom	Egremont	**1.3**		-3.532	54.484
16 Oct 2017 10:00	United Kingdom	Brixham	**0.5**		-3.519	50.397
16 Oct 2017 10:00	United Kingdom	Shaldon	**0.5**		-3.516	50.541
16 Oct 2017 10:00	United Kingdom	Teignmouth	**0.5**		-3.498	50.553
16 Oct 2017 19:00	United Kingdom	Maryport	**1.5**		-3.497	54.710
16 Oct 2017 10:00	United Kingdom	Countess Wear	**0.5**		-3.490	50.698
16 Oct 2017 15:00	United Kingdom	Llantwit Major	**1.0**		-3.489	51.407
16 Oct 2017 20:00	United Kingdom	Seascale	**1.3**		-3.479	54.398
16 Oct 2017 19:00	United Kingdom	Rhyl	**1.1**		-3.475	53.313
16 Oct 2017 15:00	United Kingdom	Minehead	**1.0**		-3.475	51.206
16 Oct 2017 10:00	United Kingdom	Dawlish	**0.5**		-3.471	50.583
16 Oct 2017 19:00	United Kingdom	Prestatyn	**1.1**		-3.415	53.335
16 Oct 2017 19:00	United Kingdom	Silloth	**1.5**		-3.385	54.865
16 Oct 2017 16:00	United Kingdom	Rhoose	**0.9**		-3.353	51.390
16 Oct 2017 16:00	United Kingdom	Watchet	**0.9**		-3.335	51.175
16 Oct 2017 16:00	United Kingdom	Williton	**0.9**		-3.322	51.161
16 Oct 2017 19:00	United Kingdom	Haverigg	**1.2**		-3.288	54.200
16 Oct 2017 19:00	United Kingdom	Vickerstown	**1.2**		-3.254	54.104
16 Oct 2017 10:00	United Kingdom	Sidmouth	**0.5**		-3.241	50.687
16 Oct 2017 02:00	United Kingdom	Burntisland	**0.6**		-3.236	56.063
16 Oct 2017 19:00	United Kingdom	Holywell	**1.1**		-3.224	53.277
16 Oct 2017 19:00	United Kingdom	Bowness-on-Solway	**1.5**		-3.217	54.950
16 Oct 2017 12:00	United Kingdom	Penarth	**1.0**		-3.177	51.437
16 Oct 2017 19:00	United Kingdom	Hoylake	**1.1**		-3.174	53.396
16 Oct 2017 02:00	United Kingdom	Thornton	**0.6**		-3.146	56.166
16 Oct 2017 02:00	United Kingdom	Craigmillar	**0.6**		-3.146	55.930
16 Oct 2017 10:00	United Kingdom	Branscombe	**0.6**		-3.136	50.691
16 Oct 2017 19:00	United Kingdom	Flint	**1.1**		-3.131	53.246
16 Oct 2017 12:00	United Kingdom	Llanrumney	**1.0**		-3.124	51.519
16 Oct 2017 02:00	United Kingdom	Niddrie	**0.6**		-3.115	55.932
16 Oct 2017 19:00	United Kingdom	Moreton	**1.1**		-3.112	53.403
16 Oct 2017 19:00	United Kingdom	Ulverston	**1.2**		-3.095	54.192
16 Oct 2017 10:00	United Kingdom	Seaton	**0.6**		-3.076	50.708
16 Oct 2017 02:00	United Kingdom	Musselburgh	**0.6**		-3.050	55.943
16 Oct 2017 19:00	United Kingdom	South Shore	**1.2**		-3.044	53.790
16 Oct 2017 02:00	United Kingdom	Buckhaven	**0.6**		-3.034	56.178
16 Oct 2017 19:00	United Kingdom	Cleveleys	**1.2**		-3.026	53.875
16 Oct 2017 19:00	United Kingdom	Thornton-Cleveleys	**1.2**		-3.021	53.874
16 Oct 2017 12:00	United Kingdom	Berrow	**1.0**		-3.017	51.267

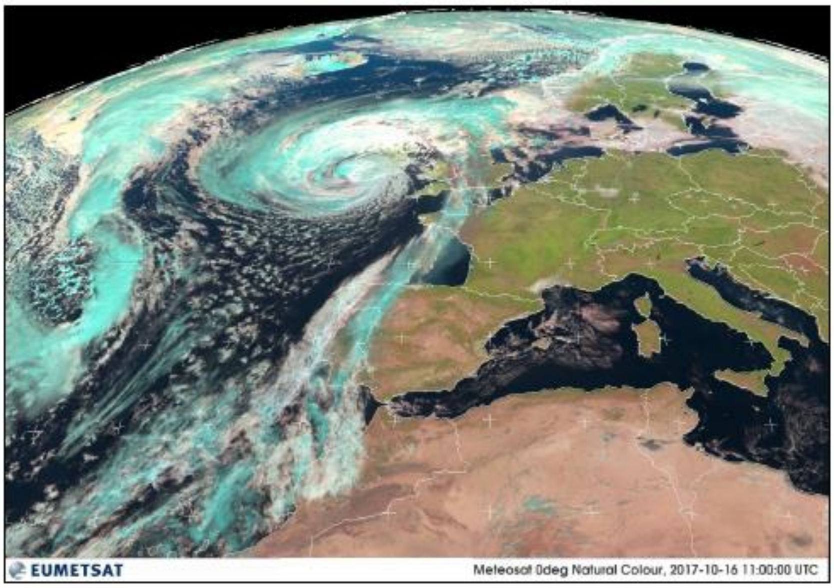
16 Oct 2017 19:00	United Kingdom	Thornton	**1.2**		-3.016	53.874
16 Oct 2017 02:00	United Kingdom	Leven	**0.6**		-2.999	56.197
16 Oct 2017 12:00	United Kingdom	Burnham-on-Sea	**1.0**		-2.997	51.238
16 Oct 2017 12:00	United Kingdom	Highbridge	**1.0**		-2.972	51.220
16 Oct 2017 19:00	United Kingdom	Poulton-le-Fylde	**1.2**		-2.968	53.862
16 Oct 2017 02:00	United Kingdom	Lundin Links	**0.6**		-2.960	56.214
16 Oct 2017 19:00	United Kingdom	Cartmel	**1.2**		-2.945	54.198
16 Oct 2017 10:00	United Kingdom	Lyme Regis	**0.6**		-2.944	50.730
16 Oct 2017 19:00	United Kingdom	Grange Over Sands	**1.2**		-2.922	54.184
16 Oct 2017 13:00	United Kingdom	Clevedon	**1.1**		-2.854	51.439
16 Oct 2017 02:00	United Kingdom	Gullane	**0.6**		-2.835	56.038
16 Oct 2017 01:00	United Kingdom	Elie	**0.6**		-2.822	56.192
16 Oct 2017 19:00	United Kingdom	Milnthorpe	**1.2**		-2.777	54.226
16 Oct 2017 13:00	United Kingdom	Portishead	**1.1**		-2.774	51.477
16 Oct 2017 19:00	United Kingdom	Carnforth	**1.2**		-2.772	54.126
16 Oct 2017 10:00	United Kingdom	Bridport	**0.6**		-2.762	50.736
16 Oct 2017 13:00	United Kingdom	Caldicot	**1.1**		-2.746	51.588
16 Oct 2017 01:00	United Kingdom	North Berwick	**0.6**		-2.724	56.058
16 Oct 2017 01:00	United Kingdom	Anstruther	**0.6**		-2.703	56.225
16 Oct 2017 13:00	United Kingdom	Avonmouth	**1.1**		-2.689	51.499
16 Oct 2017 13:00	United Kingdom	Chepstow	**1.1**		-2.682	51.639
16 Oct 2017 10:00	United Kingdom	Abbotsbury	**0.6**		-2.600	50.667
16 Oct 2017 02:00	United Kingdom	Arbroath	**0.6**		-2.595	56.563
16 Oct 2017 02:00	United Kingdom	Dunbar	**0.6**		-2.522	56.003
16 Oct 2017 02:00	United Kingdom	Montrose	**0.6**		-2.469	56.718
16 Oct 2017 10:00	United Kingdom	Easton	**0.6**		-2.444	50.543
16 Oct 2017 10:00	United Kingdom	Portland	**0.6**		-2.438	50.549
16 Oct 2017 00:00	United Kingdom	Inverbervie	**0.6**		-2.285	56.845
16 Oct 2017 00:00	United Kingdom	Stonehaven	**0.6**		-2.214	56.964
16 Oct 2017 10:00	United Kingdom	Wareham	**0.6**		-2.116	50.692
16 Oct 2017 02:00	United Kingdom	Eyemouth	**0.6**		-2.101	55.873
16 Oct 2017 00:00	United Kingdom	Balmedie	**0.5**		-2.050	57.250
16 Oct 2017 00:00	United Kingdom	Fraserburgh	**0.5**		-2.022	57.692
16 Oct 2017 02:00	United Kingdom	Berwick upon Tweed	**0.6**		-2.009	55.773
16 Oct 2017 11:00	United Kingdom	Swanage	**0.6**		-1.969	50.613
16 Oct 2017 11:00	United Kingdom	Newtown	**0.6**		-1.846	50.768
16 Oct 2017 00:00	United Kingdom	Peterhead	**0.5**		-1.794	57.510
16 Oct 2017 00:00	United Kingdom	North Sunderland	**0.6**		-1.657	55.581
16 Oct 2017 11:00	United Kingdom	Milford-on-Sea	**0.6**		-1.595	50.731
16 Oct 2017 01:00	United Kingdom	Amble	**0.6**		-1.583	55.333
16 Oct 2017 11:00	United Kingdom	Lymington	**0.7**		-1.543	50.760
16 Oct 2017 01:00	United Kingdom	Seaton Delaval	**0.6**		-1.524	55.072
16 Oct 2017 01:00	United Kingdom	Hebburn	**0.6**		-1.506	54.974
16 Oct 2017 01:00	United Kingdom	Seaton Sluice	**0.6**		-1.477	55.083
16 Oct 2017 01:00	United Kingdom	North Shields	**0.6**		-1.450	55.014
16 Oct 2017 01:00	United Kingdom	Tynemouth	**0.6**		-1.432	55.018
16 Oct 2017 11:00	United Kingdom	Cowes	**0.7**		-1.302	50.759
16 Oct 2017 12:00	United Kingdom	Newport	**0.7**		-1.299	50.701
16 Oct 2017 12:00	United Kingdom	Niton	**0.7**		-1.289	50.590
16 Oct 2017 12:00	United Kingdom	East Cowes	**0.7**		-1.287	50.758
16 Oct 2017 00:00	United Kingdom	Crimdon Park	**0.7**		-1.248	54.716

16 Oct 2017 12:00	United Kingdom	Ventnor	0.7		-1.205	50.599
16 Oct 2017 12:00	United Kingdom	Shanklin	0.7		-1.181	50.629
16 Oct 2017 12:00	United Kingdom	Ryde	0.7		-1.169	50.728
16 Oct 2017 12:00	United Kingdom	Sandown	0.7		-1.160	50.660
16 Oct 2017 00:00	United Kingdom	Eston	0.6		-1.149	54.560
16 Oct 2017 12:00	United Kingdom	Hardway	0.7		-1.141	50.815
16 Oct 2017 12:00	United Kingdom	Bembridge	0.7		-1.095	50.691
16 Oct 2017 12:00	United Kingdom	Havant	0.7		-0.987	50.858
16 Oct 2017 12:00	United Kingdom	Hayling Island	0.7		-0.978	50.829
16 Oct 2017 01:00	United Kingdom	Brotton	0.7		-0.944	54.570
16 Oct 2017 01:00	United Kingdom	Loftus	0.7		-0.892	54.555
16 Oct 2017 12:00	United Kingdom	Bosham	0.7		-0.856	50.836
16 Oct 2017 12:00	United Kingdom	Selsey	0.7		-0.786	50.740
16 Oct 2017 00:00	United Kingdom	Whitby	0.7		-0.620	54.482
16 Oct 2017 00:00	United Kingdom	Filey	0.7		-0.296	54.210
16 Oct 2017 12:00	United Kingdom	Shoreham-by-Sea	0.7		-0.275	50.834
16 Oct 2017 12:00	United Kingdom	Southwick	0.7		-0.240	50.837
16 Oct 2017 12:00	United Kingdom	Hove	0.7		-0.180	50.838
16 Oct 2017 02:00	United Kingdom	Flamborough	0.7		-0.129	54.115
16 Oct 2017 02:00	United Kingdom	Aldbrough	0.7		-0.116	53.825
16 Oct 2017 12:00	United Kingdom	Newhaven	0.7		0.039	50.795
16 Oct 2017 02:00	United Kingdom	North Somercotes	0.8		0.138	53.447
16 Oct 2017 03:00	United Kingdom	Friskney	1.0		0.180	53.075
16 Oct 2017 02:00	United Kingdom	Mablethorpe	0.9		0.261	53.338
16 Oct 2017 03:00	United Kingdom	Skegness	1.0		0.335	53.148
16 Oct 2017 03:00	United Kingdom	Hunstanton	1.0		0.493	52.939
16 Oct 2017 08:00	United Kingdom	North Benfleet	0.9		0.540	51.584
16 Oct 2017 13:00	United Kingdom	Saint Leonards	0.7		0.546	50.855
16 Oct 2017 08:00	United Kingdom	Allhallows	0.9		0.646	51.467
16 Oct 2017 13:00	United Kingdom	Fairlight	0.7		0.652	50.879
16 Oct 2017 08:00	United Kingdom	Westcliff-on-Sea	0.9		0.686	51.543
16 Oct 2017 13:00	United Kingdom	Rye	0.7		0.732	50.953
16 Oct 2017 08:00	United Kingdom	Queenborough	0.9		0.749	51.416
16 Oct 2017 08:00	United Kingdom	Sheerness	0.9		0.759	51.439
16 Oct 2017 13:00	United Kingdom	Camber	0.7		0.790	50.936
16 Oct 2017 08:00	United Kingdom	Southminster	0.9		0.824	51.663
16 Oct 2017 08:00	United Kingdom	Faversham	0.9		0.884	51.314
16 Oct 2017 13:00	United Kingdom	Lydd	0.7		0.899	50.952
16 Oct 2017 08:00	United Kingdom	Leysdown-on-Sea	0.9		0.909	51.397
16 Oct 2017 13:00	United Kingdom	New Romney	0.7		0.943	50.988
16 Oct 2017 13:00	United Kingdom	Littlestone-on-Sea	0.7		0.960	50.984
16 Oct 2017 13:00	United Kingdom	Dymchurch	0.7		0.992	51.026
16 Oct 2017 13:00	United Kingdom	Hythe	0.7		1.080	51.071
16 Oct 2017 04:00	United Kingdom	Cromer	0.8		1.299	52.929
16 Oct 2017 07:00	United Kingdom	Sandwich	0.7		1.338	51.276
16 Oct 2017 07:00	United Kingdom	Felixstowe	0.8		1.341	51.966
16 Oct 2017 08:00	United Kingdom	Kingsdown	0.7		1.392	51.187
16 Oct 2017 04:00	United Kingdom	Mundesley	0.8		1.430	52.879
16 Oct 2017 07:00	United Kingdom	Broadstairs	0.8		1.436	51.360
16 Oct 2017 06:00	United Kingdom	Wrentham	0.8		1.665	52.388
16 Oct 2017 06:00	United Kingdom	Corton	0.8		1.744	52.517

METEOSAT (EUMETSAT)



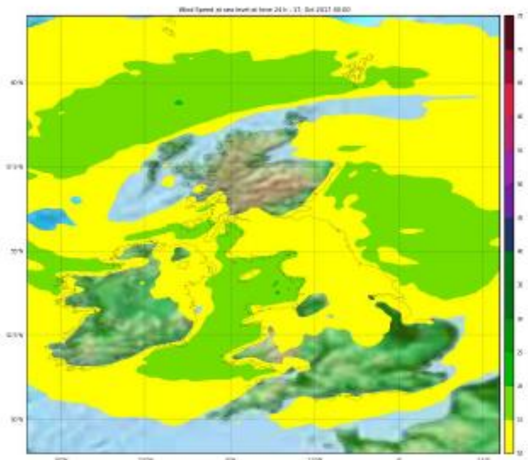
Meteosat 0 degree, Channels, IR 10.8



Meteosat 0 Degree, RGB composite, Natural Colors

WIND IMPOSED

Analysis time 0

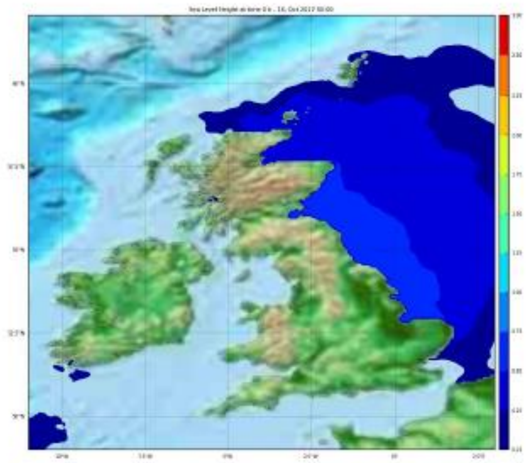


Forecast 24 h

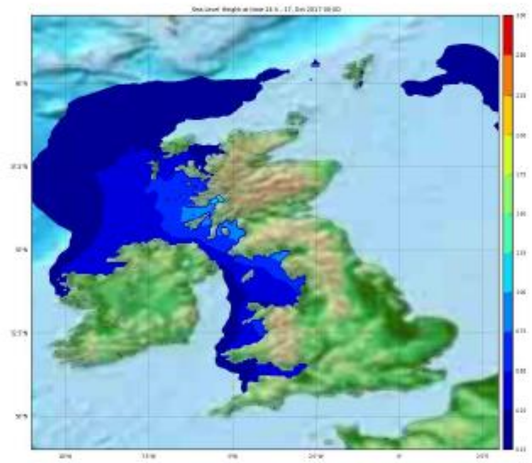
Forecast 48 h

Forecast 72 h

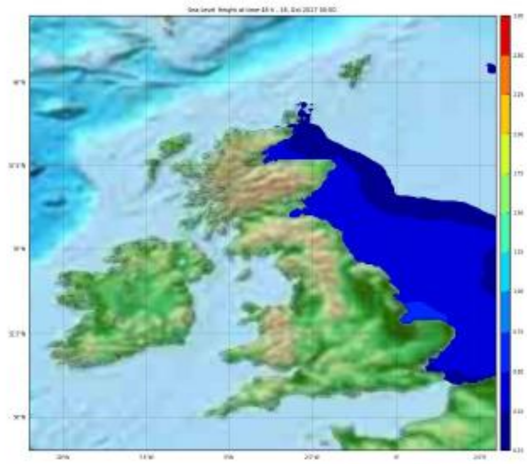
SEA LEVEL EVOLUTION



Sea Level Height at time 0 h



Sea Level Height at time 24 h

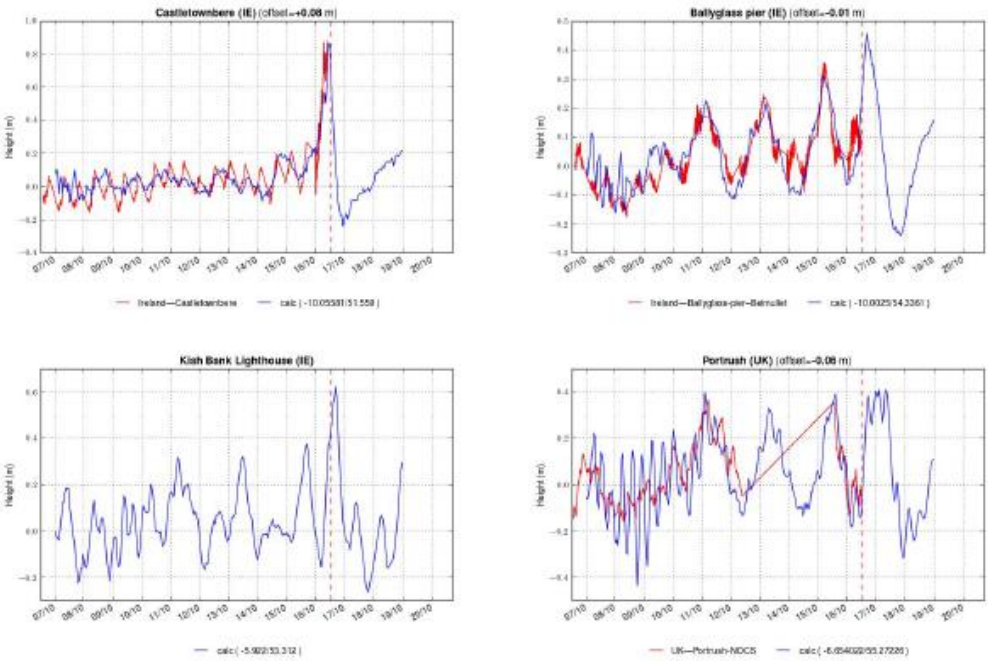


Sea Level Height at time 48 h

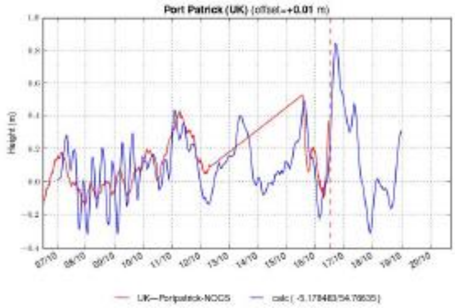
Sea Level Height at time 72 h

SEA LEVEL STORM SURGE MEASUREMENTS AND MODELLING ESTIMATES

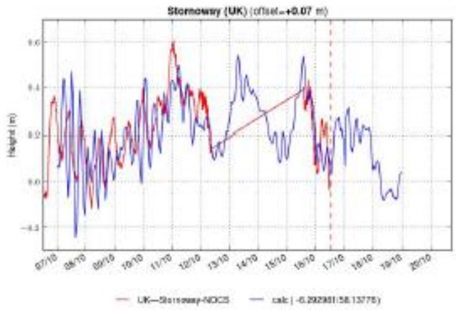
IRELAND and NORTHERN IRELAND (UK)

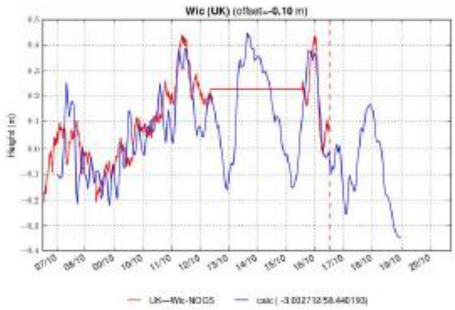


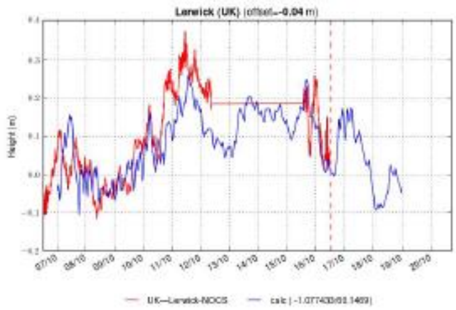
SCOTLAND (UK)

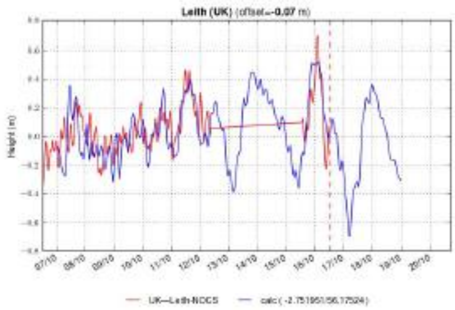

Port Patrick (UK) (offset=+0.01 m)
Height (m)
UK—Portpatrick-NOCS


Millport (UK) (offset=+0.04 m)
Height (m)
UK—Millport-NOCS

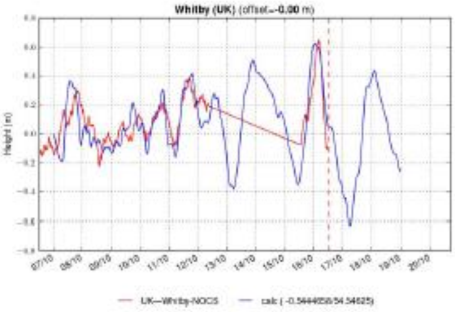

Stornoway (UK) (offset=+0.07 m)
Height (m)
UK—Stornoway-NOCS

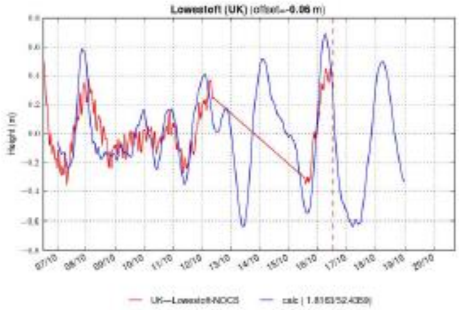

Wic (UK) (offset=-0.10 m)
Height (m)
UK—Wic-NOCS

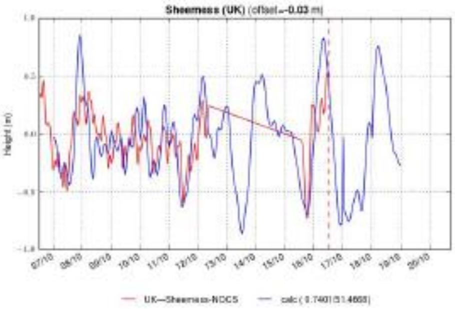

Lerwick (UK) (offset=-0.04 m)
Height (m)
UK—Lerwick-NOCS

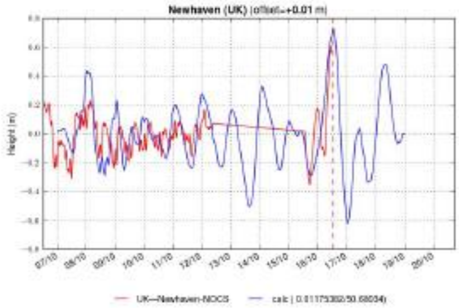

Leith (UK) (offset=-0.07 m)
Height (m)
UK—Leith-NOCS

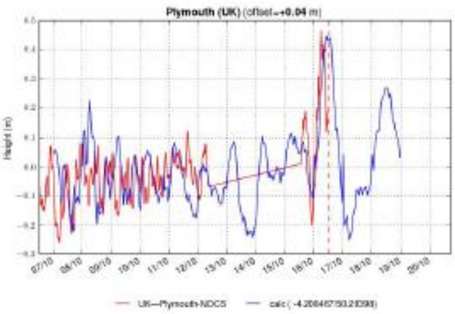
ENGLAND and WALES (UK)

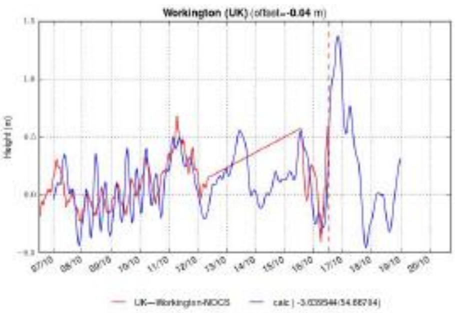


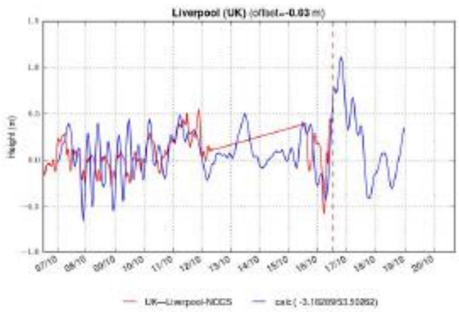


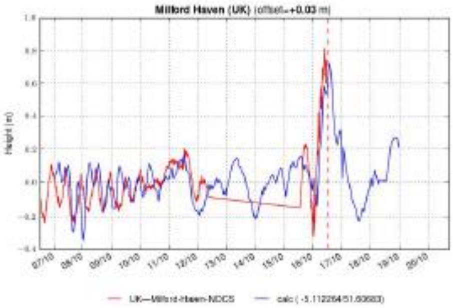


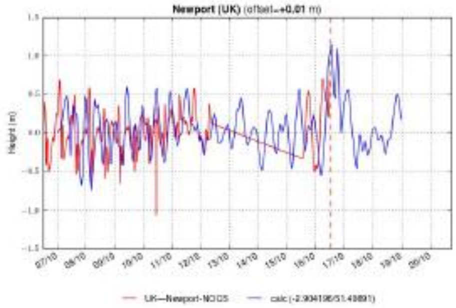


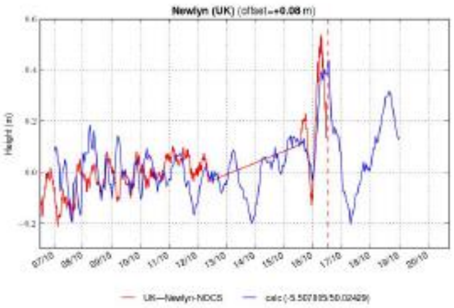


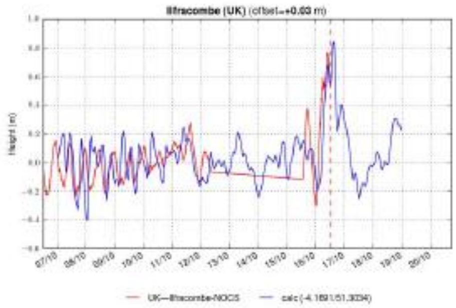












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Measured data from National Oceanographic Centre, Southampton (NOCS), Estimation from Joint Research Centre (JRC) based on Meteorological Forecasts from European Centre for Medium Weather Forecast (ECMWF) and using the DELTARES-DELFT3D Flow code.

- DELTARES: **https://www.deltares.nl/en/**
- DELFT3D: **https://oss.deltares.nl/web/delft3d**
- EUMETSAT: **http://www.eumetsat.int/website/home/index.html**
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