WP4
Forecast numerical modelling for coastal extreme weather and flooding risk management

Activity 4.3
Coupling of high-resolution meteorological and sea-waves models

D4.3.1 Description of the wave-model implemented and its performance into WRFAdria Model

PROJECT AND ACTIVITY DETAILS

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1. INTRODUCTION

Hydro-meteorological and other marine hazards triggered by meteorological events, affecting the Adriatic areas represent a dramatic threat which needs to be faced by enhancing monitoring and forecasting systems. In this respect, **AdriaMORE project** proposes increasing of the management capacity of the response to marine and coastal hazards in the Adriatic basin.

AdriaMORE goal is to improve an existing integrated hydro-meteorological risk management platform focusing on the Adriatic coastal areas of Italy and Croatia capitalizing the major achievements of ADRIARadNet and CapRadNet projects. The latter, successfully completed under the IPA Adriatic CBC Programme, were devoted to create a cross-border infrastructure of observing and forecasting systems for building real-time risk scenarios for civil protection purpose.

To this end, one of AdriaMORE's specific objective is to develop a wave model operative in the WRFAdria model over the Adriatic coastal. This objective has been performed within the action 4.3 of the WP4 of AdriaMORE project whose the main result is constituted by the **Output entitled "Forecast of the newly implemented numerical weather prediction model improved by assimilating coastal monitoring data, coupled with the wave model.".**

Two deliverables have contributed to the achievement of the above project Output:

- **deliverable 4.3.1** aimed at describing the meteorological model and wave model and how they are coupled;
- **deliverable 4.3.2** aimed at describing the operative coupled WRF-SWAN model.

The latter is described in another document while the **deliverable 4.3.1**, subject of this paper, has been organized as follows.

In the **chapter 2** some examples of wave models are described focusing on the purpose of each of them. In the **chapter 3** the attention is paid to SWAN model and its characteristics. In the **chapter 4** an overview of the meteorological WRF model is introduced and the **chapter 5** is dedicated to describe the WRFDA assimilation technique. In the **chapter 6** analysis and results on case studies are presented. References are in the **chapters 7.**

2. Purpose of wave models and examples

In fluid dynamics wind wave modeling describes the effort to depict the sea state and predict the evolution of the energy of wind waves using numerical techniques. These simulations consider atmospheric wind forcing, nonlinear wave interactions, and frictional dissipation, and they output statistics describing wave heights, periods, and propagation directions for regional seas or global oceans. Such wave hindcasts and wave forecasts are extremely important for commercial interests on the high seas. Other applications, in particular coastal engineering, have led to the developments of wind wave models specifically designed for coastal applications.

Early forecasts of the sea state were created manually based upon empirical relationships between the present state of the sea, the expected wind conditions, the fetch/duration, and the direction of the wave propagation. Alternatively, the swell part of the state has been forecasted as early as 1920 using remote observations.

During the 1950s and 1960s, much of the theoretical groundwork necessary for numerical descriptions of wave evolution was laid. For forecasting purposes, it was realized that the random nature of the sea state was best described by a spectral decomposition in which the energy of the waves was attributed to as many wave trains as necessary, each with a specific direction and period. This approach allowed to make combined forecasts of wind seas and swells. The first numerical model based on the spectral decomposition of the sea state was operated in 1956 by the French Weather Service, and focused on the North Atlantic. The 1970s saw the first operational, hemispheric wave model: the spectral wave ocean model (SWOM) at the Fleet Numerical Oceanography Center.

First generation wave models did not consider nonlinear wave interactions. Second generation models, available by the early 1980s, parameterized these interactions. They included the “coupled hybrid” and “coupled discrete” formulations. Third generation models explicitly represent all the physics relevant for the development of the sea state in two dimensions. The wave modeling project (WAM), an international effort, led to the refinement of modern wave modeling techniques during the decade 1984-1994. Improvements included two-way coupling between wind and waves, assimilation of satellite wave data, and medium-range operational forecasting.

Wind wave models are used in the context of a forecasting or hindcasting system. Differences in model results arise, with decreasing order of importance, from differences in wind and sea ice forcing, differences in parameterizations of physical processes, the use of data assimilation and associated methods, the numerical techniques used to solve the wave energy evolution equation.

A wave model requires as initial conditions information describing the state of the sea. An analysis of the sea or ocean can be created through data assimilation, where observations such as buoy or satellite altimeter measurements are combined with a background guess from a previous forecast or climatology to create the best estimate of the current conditions. In practice, many forecasting system rely only on the previous forecast, without any assimilation of observations.

A more critical input is the "forcing" by wind fields: a time-varying map of wind speed and directions. The most common sources of errors in wave model results are the errors in the wind field. Ocean currents can also be important, in particular in western boundary currents or in coastal areas where tidal currents are strong. Waves are also affected by sea ice and icebergs, and all operational global wave models take at least the sea ice into account.

The sea state is described as a spectrum; the sea surface can be decomposed into waves of varying frequencies using the principle of superposition. The waves are also separated by their direction of propagation. The model domain size can range from regional to the global ocean. Smaller domains can be nested within a global domain to provide higher resolution in a region of interest. The sea state evolves according to physical equations – based on a spectral representation of the conservation of wave action – which include: wave propagation/advection, refraction (by bathymetry and currents), shoaling, and a source function which allows for wave energy to be augmented or diminished. The source function has at least three terms: wind forcing, nonlinear transfer, and dissipation by whitecapping. Wind data are typically provided from a separate atmospheric model from an operational weather forecasting center.

For intermediate water depths the effect of bottom friction should also be added. At ocean scales, the dissipation of swells - without breaking - is a very important term.

The output of a wind wave model is a description of the wave spectra, with amplitudes associated with each frequency and propagation direction. Results are typically summarized by the significant wave height, which is the average height of the one-third largest waves, and the period and propagation direction of the dominant wave.

Wind waves also act to modify atmospheric properties through frictional drag of near-surface winds and heat fluxes. Two-way coupled models allow the wave activity to feed back upon the atmosphere. The European Centre for Medium-Range Weather Forecasts (ECMWF) coupled atmosphere-wave forecast system described below facilitates this through exchange of the Charnock parameter which controls the sea surface roughness. This allows the atmosphere to respond to changes in the surface roughness as the wind sea builds up or decays.

Coastal engineers often need high-quality, detailed wave information as represented by the significant wave height, period and mean direction or the two-dimensional wave spectrum, at a coastal location to:

- design engineering structures such as a breakwater, a storm surge barrier or dike,
- plan human activities such as construction works or a salvage operation or
- manage a sensitive, natural environment such as national marine parks or wetlands.

Such wave information is often available at open sea (from observations or from computer simulations) but not at a coastal location. The only short-term solution for solving the problem for a coastal location, is to acquire the open-sea database and to translate it to the coastal location. Occasionally this is not sufficient, particularly when extreme wave conditions must be estimated which have not (yet) occurred and are therefore missing in the database. In such cases, the database needs to be supplemented with additional numerical simulations.

2.1 WAM

The wave model WAM was the first so-called third generation prognostic wave model where the two-dimensional wave spectrum was allowed to evolve freely (up to a cut-off frequency) with no constraints on the spectral shape. The model underwent a series of software updates from its inception in the late 1980s. The last official release is Cycle 4.5, maintained by the German Helmholtz Zentrum, Geesthacht.

ECMWF has incorporated WAM into its deterministic and ensemble forecasting system, known as the Integrated Forecast System (IFS). The model currently comprises 36 frequency bins and 36 propagation directions at an average spatial resolution of 25 km. The model has been coupled to the atmospheric component of IFS since 1998.

The WAM wave model is a 3rd generation wave model, developed by the Wave Model Development and Implementation Group (WAMDI, 1988). It was developed to resolve known issues with first generation wave models (which erroneously used a non-existent universal high-frequency equilibrium wave spectrum) and second generation wave models (which could not properly simulate complex wave fields generated by rapidly changing winds, as for example occurs with hurricanes, small-scale cyclones or fronts).

The WAM model integrates the basic transport equation describing the evolution of a two-dimensional ocean wave spectrum without additional unplanned assumptions regarding the spectral shape. There are three explicit source functions which describe the wind input, non-linear transfer and whitecapping dissipation. There is an additional bottom dissipation source function and refraction terms are included in the finite-depth version of the model. The model runs on a spherical latitude-longitude grid and can be used in any ocean region.

WAM predicts directional spectra along with wave properties such as significant wave height, mean wave direction and frequency, swell wave height and mean direction, and wind stress fields corrected by including the wave induced stress and the drag coefficient at each grid point at chosen output times.

WAM can be coupled to a range of other models. Examples include the South East Asian Ocean Model (SEAOM), the Proudman Oceanographic Laboratory Coastal Ocean Modelling System (POLCOMS), the Nucleus for European Modelling of the Ocean model (NEMO), the High Resolution Limited Area Model (HIRLAM) model and the National Center for Atmospheric Research (NCAR) Regional Climate Model (RegCM).

2.2 WAVEWATCH

WAVEWATCH III® is a third generation wave model developed at NOAA/NCEP in the spirit of the WAM model (WAMDIG 1988). It is a further development of the model WAVEWATCH, as developed at Delft University of Technology and WAVEWATCH II, developed at NASA, Goddard

Space Flight Center. WAVEWATCH III®, however, differs from its predecessors in many important points such as the governing equations, the model structure, the numerical methods and the physical parameterizations. Furthermore, with model version 3.14, WAVEWATCH III® is evolving from a wave model into a wave modeling framework, which allows for easy development of additional physical and numerical approaches to wave modeling.

WAVEWATCH III® solves the random phase spectral action density balance equation for wavenumber-direction spectra. The implicit assumption of this equation is that properties of medium (water depth and current) as well as the wave field itself vary on time and space scales that are much larger than the variation scales of a single wave. With version 3.14 some source term options for extremely shallow water (surf zone) have been included, as well as wetting and drying of grid points. Whereas the surf-zone physics implemented so far are still fairly rudimentary, it does imply that the wave model can now be applied to arbitrary shallow water.

The latest version of WAVEWATCH III® is 4.18, released on 19 March 2014.

The operational wave forecasting systems at NOAA are based on the WAVEWATCH III® model. This system has a global domain of approximately 50 km resolution, with nested regional domains for the northern hemisphere oceanic basins at approximately 18 km and approximately 7 km resolution. Physics includes wave field refraction, nonlinear resonant interactions, sub-grid representations of unresolved islands, and dynamically updated ice coverage. Wind data is provided from the GDAS data assimilation system for the GFS weather model. Up to 2008, the model was limited to regions outside the surf zone where the waves are not strongly impacted by shallow depths.

The model can incorporate the effects of currents on waves from its early design by Hendrik Tolman in the 1990s, and is now extended for near shore applications.

2.3 SWAN

SWAN is a third-generation wave model, developed at Delft University of Technology, that computes random, short-crested wind-generated waves in coastal regions and inland waters. (See a short overview of the model features of SWAN, section 4.1).

It is used for obtaining realistic estimates of wave parameters in coastal areas, lakes and estuaries from given wind, bottom and current conditions. However, SWAN can be used on any scale relevant for wind-generated surface gravity waves. The model is based on the wave action balance equation with sources and sinks.

The technique of SWAN is to determine all physical processes that affect the waves as they travel from deep water to the coastal location. This involves the propagation across varying bottom topography, the growth by wind, the interaction between individual waves and the decay by wave breaking and bottom friction. The effects of currents, tides, reflection and diffraction are taken into account.

An important question addressed is how to choose various grids in SWAN (resolution, orientation,

etc.) including nesting. In general, two types of grids are considered: structured and unstructured. Structured grids may be rectilinear and uniform or curvilinear. They always consist of quadrilaterals in which the number of grid cells that meet each other in an internal grid point is 4. In unstructured grids, this number can be arbitrarily (usually between 4 and 10). For this reason, the level of flexibility with respect to the grid point distribution of unstructured grids is far more optimal compared to structured grids. Unstructured grids may contain triangles or a combination of triangles and quadrilaterals (so-called hybrid grids). In the current version of SWAN, however, only triangular meshes can be employed.
Often, the characteristic spatial scales of the wind waves propagating from deep to shallow waters are very diverse and would required to allow local refinement of the mesh near the coast without incurring overhead associated with grid adaptation at some distance offshore. Traditionally, this can be achieved by employing a nesting approach.
The idea of nesting is to first compute the waves on a coarse grid for a larger region and then on a finer grid for a smaller region. The computation on the fine grid uses boundary conditions that are generated by the computation on the coarse grid. Nesting can be repeated on ever decreasing scales using the same type of coordinates for the coarse computations and the nested computations (Cartesian or spherical). Note that curvilinear grids can be used for nested computations but the boundaries should always be rectangular.
The use of unstructured grids in SWAN offers a good alternative to nested models not only because of the ease of optimal adaption of mesh resolution but also the modest effort needed to generate grids about complicated geometries, e.g. islands and irregular shorelines. This type of flexible meshes is particularly useful in coastal regions where the water depth varies greatly. As a result, this variable spatial meshing gives the highest resolution where it is most needed. The use of unstructured grids facilitates to resolve the model area with a relative high accuracy but with a much fewer grid points than with regular grids.

2.4 RELATION OF SWAN TO WAM AND WAVEWATCH III

The basic scientific philosophy of SWAN is identical to that of WAM (Cycle 3 and 4). SWAN is a third-generation wave model and it uses the same formulations for the source terms. On the other hand, SWAN contains some additional formulations primarily for shallow water. Moreover, the numerical techniques are very different. WAVEWATCH III not only uses different numerical techniques but also different formulations for the wind input and the whitecapping.

This close similarity can be exploited in the sense that:

- scientific findings with one model can be shared with the others and
- SWAN can be readily nested in WAM and WAVEWATCH III (the formulations of WAVEWATCH III have not yet been implemented in SWAN).

When SWAN is nested in WAM or WAVEWATCH III, it must be noted that the boundary conditions for SWAN provided by WAM or WAVEWATCH III may not be model consistent even if the same physics are used. The potential reasons are manifold such as differences in numerical techniques employed and implementation for the geographic area (spatial and spectral resolutions, coefficients, etc.). Generally, the deep water boundary of the SWAN nest must be located in WAM or WAVEWATCH III where shallow water effects do not dominate (to avoid too large discontinuities between the two models). Also, the spatial and spectral resolutions should not differ more than a factor two or three. If a finer resolution is required, a second or third nesting may be needed.

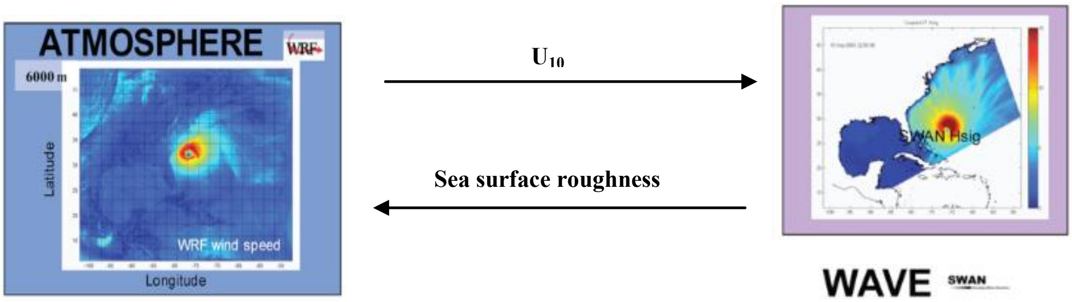
Moreover, it must be pointed out that the application of SWAN on ocean scales is not recommended from an efficiency point of view. The WAM model and the WAVEWATCH III model, which have been designed specifically for ocean applications, are probably one order of magnitude more efficient than SWAN. SWAN can be run on large scales (much larger than coastal scales) but this option is mainly intended for the transition from ocean scales to coastal scales (transitions where non-stationarity is an issue and spherical coordinates are convenient for nesting).

3. Simulating Waves Nearshore (SWAN) and its features

The SWAN (**S**imulating **WA**ves **N**earshore) model is a spectral wave model developed at the Delft University of Technology, The Netherlands. SWAN models the energy contained in waves as they travel over the ocean surface towards the shore. In the model, waves change height, shape and direction as a result of wind, white capping, wave breaking, energy transfer between waves, and variations in the ocean floor and currents. Initial wave conditions, including wave height, wave direction and wave period (time it takes for one wavelength to pass a fixed point), are entered into the model, and the model computes changes to the input parameters as the waves move toward shore. Model results are computed on a 500m by 500m grid for the area of research. Model output information (wave height, wave direction, and wave velocity) is produced for each cell in the model grid, and can be displayed in a map view to simplify visualization of changes in waves over the study area.

Waves play an important role in moving sediment, influencing the patterns of erosion and accretion along a coast, and ultimately shaping the shoreline. Wave models are important when studying a large coastal area. The expense of collecting in situ wave measurements, by installing multiple wave buoys, may be cost prohibitive. SWAN makes it possible to model waves over a large area, for any boundary input, in a cost-effective method, and results can be obtained in a relatively short period of time.

In the figure below the exchange fields between the atmospheric model WRF and wave model SWAN is showed.



SWAN---> WRF: Sea Surface Roughness (computed in WRF from Significant Wave Height, Length, Period)
WRF ---> SWAN: 10m Winds

Figure 1. Exchange fields between the atmospheric and wave model.

3.1 Features of SWAN

Physics

SWAN accounts for the following physics:

- Wave propagation in time and space, shoaling, refraction due to current and depth, frequency shifting due to currents and non-stationary depth.
- Wave generation by wind.
- Three- and four-wave interactions.
- White capping, bottom friction and depth-induced breaking.
- Dissipation due to aquatic vegetation, turbulent flow and viscous fluid mud.
- Wave-induced set-up.
- Propagation from laboratory up to global scales.
- Transmission through and reflection (specular and diffuse) against obstacles.
- Diffraction.

Computations

SWAN computations can be made on a regular, a curvilinear grid and a triangular mesh in a Cartesian or spherical coordinate system. Nested runs, using input from either SWAN, WAVEWATCH III or WAM can be made with SWAN.

SWAN runs can be done serial, i.e. one SWAN program on one processor, as well as parallel, i.e. one SWAN program on more than one processor.
For the latter, two parallelization strategies are available:

- distributed-memory paradigm using MPI and
- shared-memory paradigm using OpenMP.

Output quantities

SWAN provides the following output quantities (numerical files containing tables, maps and timeseries):

- one- and two-dimensional spectra,
- significant wave height and wave periods,
- average wave direction and directional spreading,
- one- and two-dimensional spectral source terms,
- root-mean-square of the orbital near-bottom motion,
- dissipation,
- wave-induced force (based on the radiation-stress gradients),
- set-up,
- diffraction parameter,
- and many more.

Limitations

SWAN does not account for Bragg-scattering and wave tunneling.
SWAN is the most widely used computer model to compute irregular waves in coastal environments, based on deep water wave conditions, wind, bottom topography, currents and tides (deep and shallow water).
SWAN explicitly accounts for all relevant processes of propagation, generation by wind, interactions between the waves and decay by breaking and bottom friction. Diffraction is included in an approximate manner in SWAN.
The computer code of SWAN is available in public domain through the website of Delft University of Technology (http://www.swan.tudelft.nl/ ---> http://swanmodel.sourceforge.net/download/download.htm).

4. The forecasting model WRF

The Advanced Research WRF (ARW) modeling system was developed at the National Center for Atmospheric Research (NCAR) laboratories. The ARW is designed to be a flexible, state-of-the-art atmospheric simulation system that is portable and efficient on available parallel computing platforms. The ARW is suitable for use in a broad range of applications across scales ranging from meters to thousands of kilometers. The WRF modeling system software is in the public domain and is freely available for community use. The following figure shows the flow chart for the WRF Modelling System Version 3.

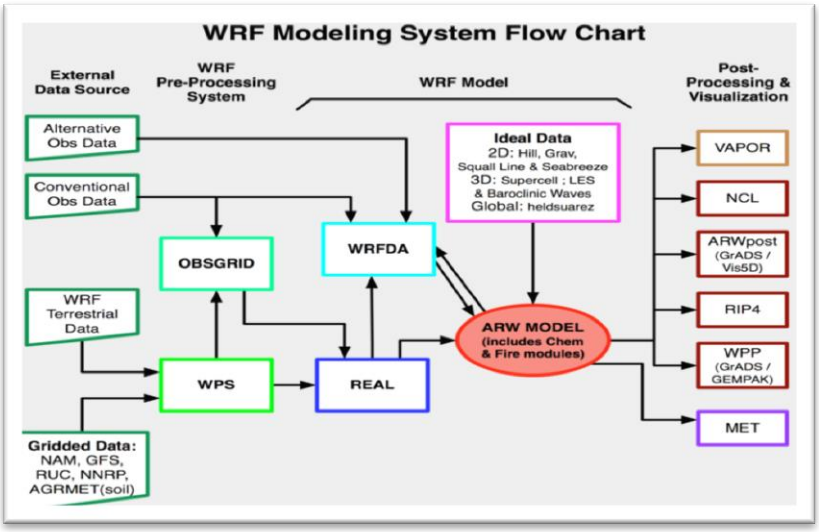


Figure 2. WRF modeling system flow chart.

As shown in the diagram, the WRF Modeling System consists of these major programs:

- the WRF Preprocessing System (WPS), which is used primarily for real-data simulations; its functions include 1) defining simulation domains; 2) interpolating terrestrial data to the simulation domain; and 3) degribbing and interpolating meteorological data from another model to this simulation domain;
- WRFDA can be used to ingest observations into the interpolated analyses created by WPS (cold-start); it can also be used to update WRF model's initial conditions when the WRF model is run in cycling mode (warm-start);
- ARW solver is the key component of the modeling system, which is composed of several initialization programs for idealized, and real-data simulations, and the numerical integration program;
- post-processing and visualization tools, such as RIP4 (based on NCAR Graphics), NCAR Graphics Command Language (NCL), and conversion programs for other readily available graphics packages like GrADS.

The WRF model is a fully compressible and non hydrostatic model (with a run-time hydrostatic option). Its vertical coordinate is a terrain-following hydrostatic pressure coordinate. The grid staggering is the Arakawa C-grid. The model uses the Runge-Kutta 2nd and 3rd order time integration schemes, and 2nd to 6th order advection schemes in both the horizontal and vertical. It uses a time-split small step for acoustic and gravity-wave modes. The dynamics conserves scalar variables.

The WRF domain was defined in the "*ndown*" configuration, where the parent domain (15km) driven by initial conditions (IC) and boundary (BC) provided by the NCEP center creates the IC and BC conditions for the inner domain (3km) covering all of Italy and Balkan area.

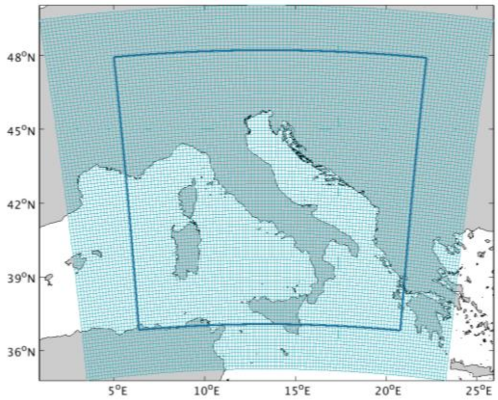


Figure 3. WRF configuration domains.

5. The WRFDA assimilation code

Data assimilation is the technique by which observations are combined with a Numerical Weather Prediction (NWP) product (the first guess or background forecast) and their respective error statistics to provide an improved estimate (the analysis) of the atmospheric state. Variational (Var) data assimilation achieves this through the iterative minimization of a prescribed cost (or penalty) function. Differences between the analysis and observations/first guess are penalized (damped) according to their perceived error. The difference between three-dimensional (3D-Var) and four-dimensional (4D-Var) data assimilation is the use of a numerical forecast model in the latter. Various components of the WRFDA system are shown in blue in the sketch below, together with their relationship with the rest of the WRF system.

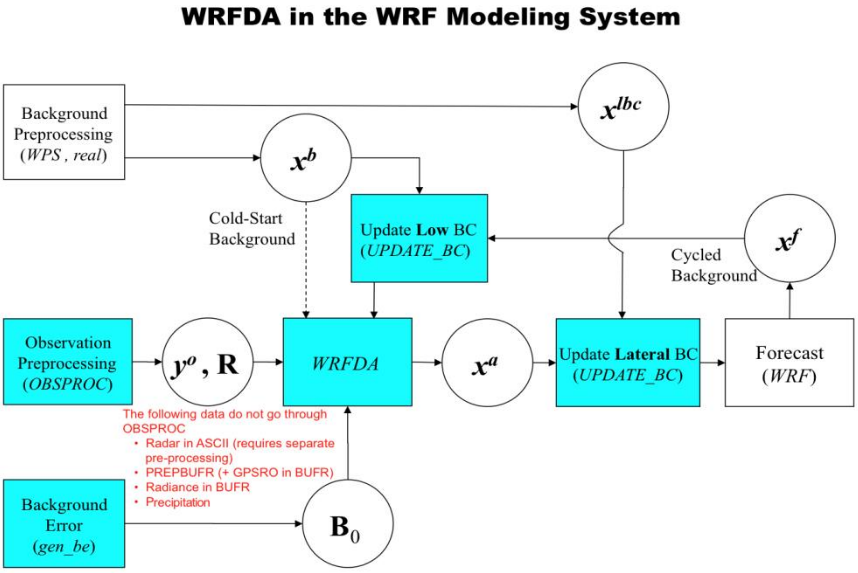


Figure 4. WRFDA in the WRF modelling system.

$\mathbf{x}^{b}$	first guess, either from a previous WRF forecast or from WPS/REAL output.
$\mathbf{x}^{lbc}$	lateral boundary from WPS/REAL output.
$\mathbf{x}^{a}$	analysis from the WRFDA data assimilation system.
$\mathbf{x}^{f}$	WRF forecast output.
$\mathbf{y}^{o}$	observations processed by OBSPROC (note: PREPBUFR input, radar, radiance, and rainfall data don't go through OBSPROC)
$\mathbf{B}_0$	background error statistics from generic BE data (CV3) or gen_be.
R	observational and representative error statistics.

The aim of the 3D-Variational approach is to produce the best compromise between an a priori estimation of the analysis field and observations, through the iterative solution that minimize a cost function *J*. This cost function *J* measures the distance of a field *x* from the observations y^o and from the background x^b: these distances are scaled through the matrices *R* and B_0, the observational error covariance matrix and the error covariance matrix of background, respectively. The cost function for 3DVAR is:

$$J(x) = J^b + J^0 = \frac{1}{2}\left\{[y^0 - H(x)]^T R^{-1}[y^0 - H(x)] + (x - x^b)^T {B_0}^{-1}(x - x^b)\right\}$$

where x^b is the generic variable of an a priori state (first guess), y^o is the observation, and *H* is the operator that converts the model state to the observations space. *R* also takes into account other sort of errors, such as representativeness and forward operator errors. A good estimation of these matrices is important for producing worthwhile initial conditions. *R* is usually a well known matrix and it has been assumed independent from weather conditions, while B_0 is weather-condition and flow-dependent, and it also depends from the background. Therefore, B_0 has to be estimated using a statistical method. The commonly used WRF-3DVAR Background Error Statistics is the NMC-method (Parrish and Derber, 1992) which uses a long time series of previous forecasts. A detailed description of the 3DVAR system can be found in Barker et al. (2003, 2004).

6. Performances analysis on case studies

Two case studies are analysed to test the performance of the coupled system WRF-SWAN: 3 May 2018 for Abruzzi Region and 24-25 September for Croatia.

On May 3, 2018 a deep intrusion of cold air from the Greenland turned in a cut-off low on the southern Tyrrhenian sea.

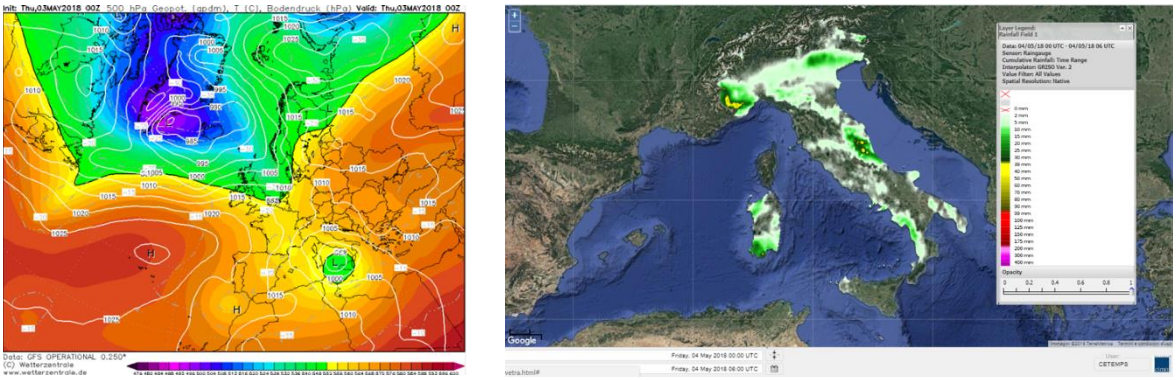


Figure 5. Geopotential at 500 hPa from NCEP GFS 0.25 operational forecast (left panel) and the observed precipitation over Italy (right panel) on May 3, 2018.

Figure 6 shows the reflectivity observed by each radar (excluding the AQ) at 14UTC and an image of the national composite at the same time with that of the MSG satellite overlapped half an hour earlier.

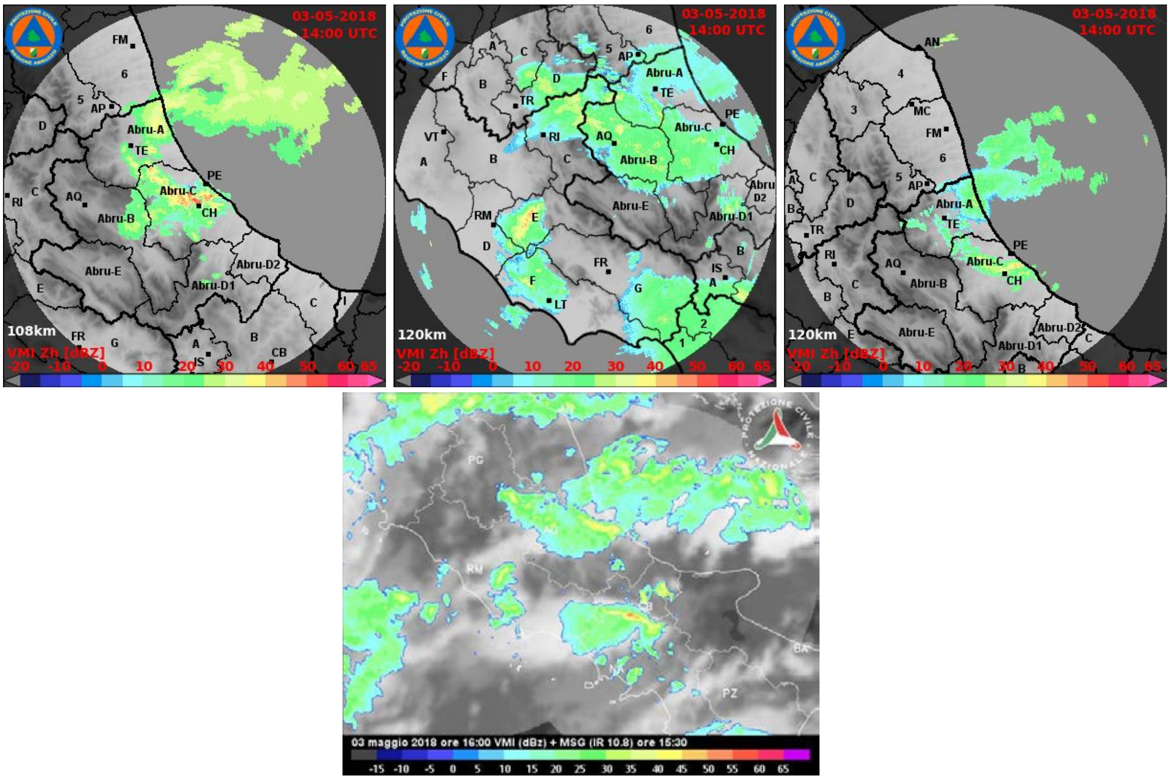


Figure 6. Reflectivity maps (VMI in dBZ) at 14:00 UTC on 3 May 2018 respectively of the Cepagatti radar (on the left), Monte Midia (in the center) and Tortoreto (on the right); in the lower left the VMI map of the national composite at the same time with the overlapped MSG satellite image (IR 10.8) at 17: 30UTC.

This structure persisted over the same region till May 10. During May 3 and 4 the low advected north-eastern flow over Marche region produced precipitation up to 50mm/6h.

The coupled model shows a better result in terms of cumulated precipitation over Marche, whereas the uncoupled simple WRF run tend to overestimate it.

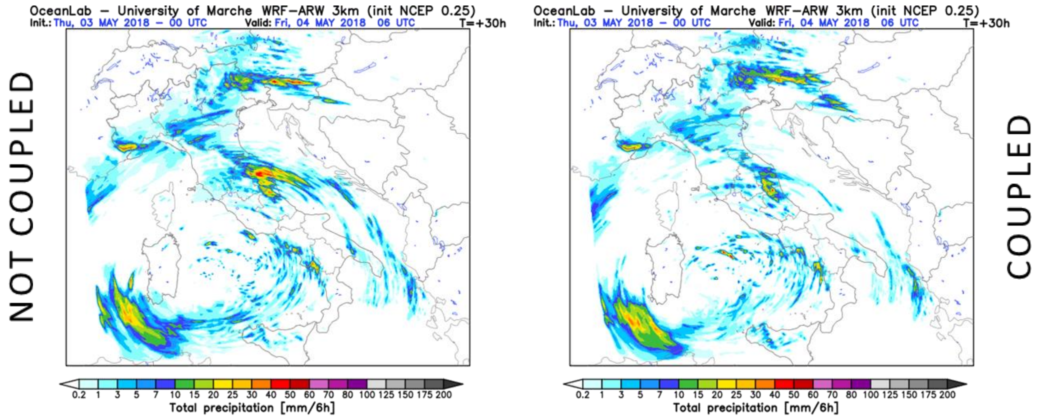


Figure 7. Cumulated precipitation from WRF not coupled (left panel) and WRF+ROMS+SWAN (right panel) on May 3, 2018.

Most likely this is due to a better estimate of the wind over the sea (lower speed in the coupled model) that brings to a more realistic lift of the moist air when encountering the Apennine reliefs.

This preliminar analysis of the results of the coupled model, in comparison with the uncoupled models, seems to improve the skillness of the forecasting system.

The other case study has been suggested from our Croatian colleagues and is 24-25 September 2018.

The ESTOFEX site (European Storm Forecast Experiment) provided for a probability level 1 occurrence from 06 UTC on the 24th and for the following 24 hours, especially for the possibility of tornadoes and hail for Slovenia and the Adriatic Sea, as shown in the image here below.

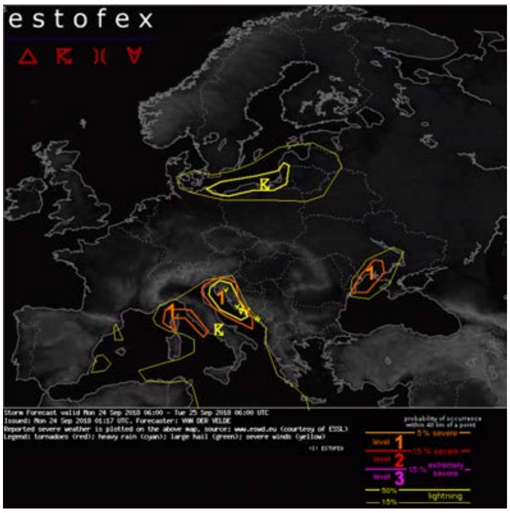


Figure 8. Map of probability of severe events issued by Estofex valid from 06UTC on 24 September to 06UTC on 25 September 2018.

Looking at the surface level temperature and wind stress, it seems that the event began on the morning of September 24th 2018 around 7:00 am e that lasted until September 26th.

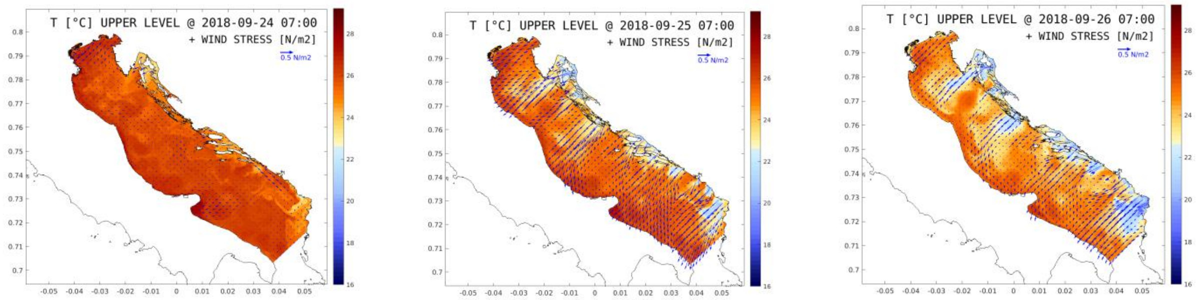
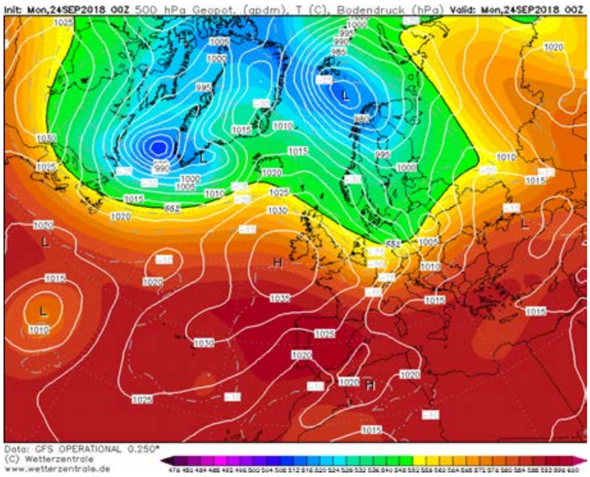


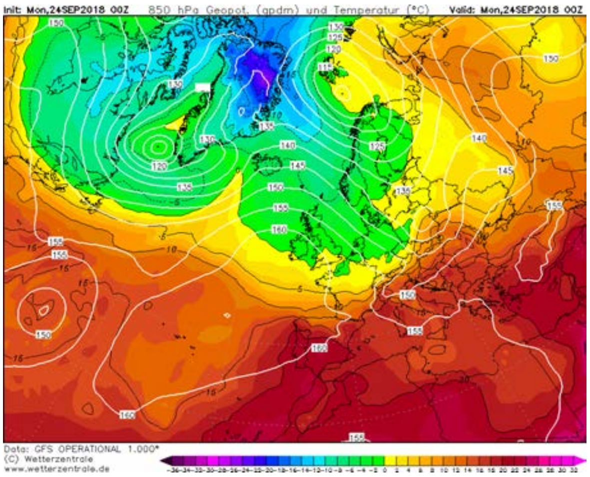
Figure 9. Temperature maps (°C) of surface level and wind stress (N/m2) at 07UTC on days 24, 25 and 26 September 2018.

The high pressure on the British Isles and the low pressure on Belarus have created a significant north-west flow over much of Europe. A very cold front for European standards made its way in the northern area of the Mediterranean Sea and in eastern and south-eastern Europe. The influence of the upper depression touched the Adriatic Sea after which it moved eastward over the Balkans.

Strong vertical wind shears in the upper levels of the atmosphere have increased the likelihood of hail, while the possibility of waterspouts has also increased due to the marked gradient between the temperature of the sea and that of the air.

The following are geopotential maps at 500 hPa and temperature at 850 hPa, respectively at 00UTC on 24 and 00UTC on 25 September 2018.





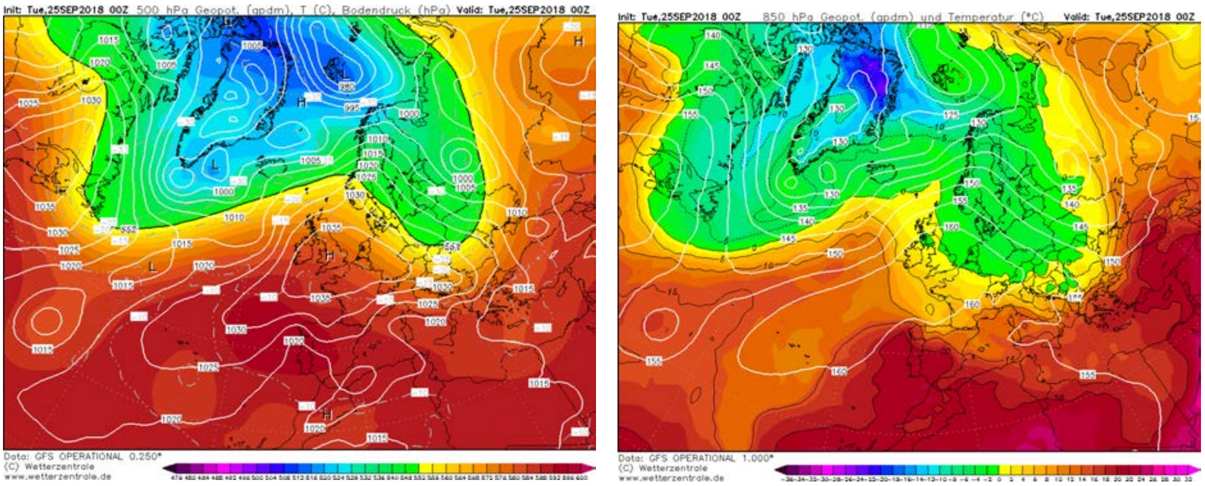


Figure 10. Geopotential maps (gpdm) at 500 hPa and temperature (°C) at 850 hPa, respectively at 00UTC on 24 and 00UTC on 25 September 2018.

What follows is the ground analysis map at 00UTC on 24 September which clearly shows the presence of a cold front downhill on Italy and the Balkans (red oval).

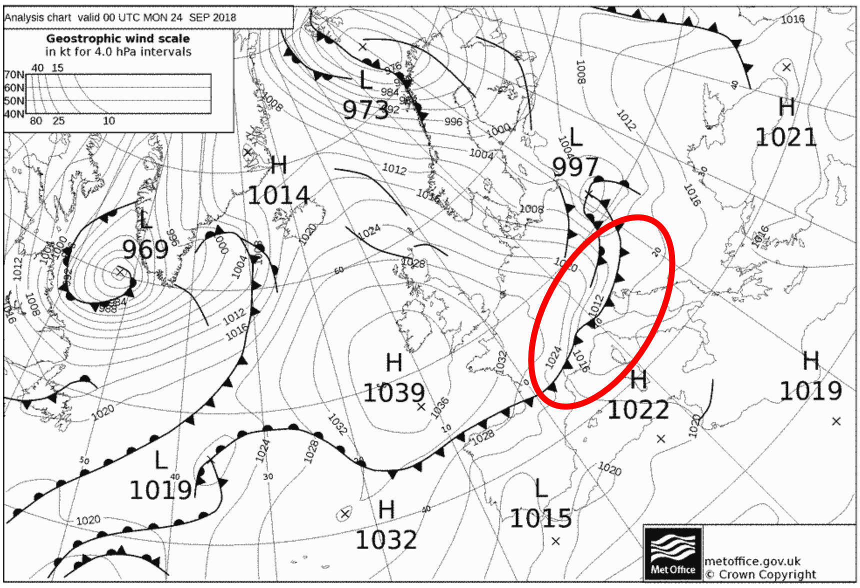


Figure 11. Ground analysis map at 00UTC on 24 September 2018.

Finally, two satellite images in the visible channel at 09 and 12UTC respectively on 24 September show the cloud band associated with the advanced part of the front (red line).

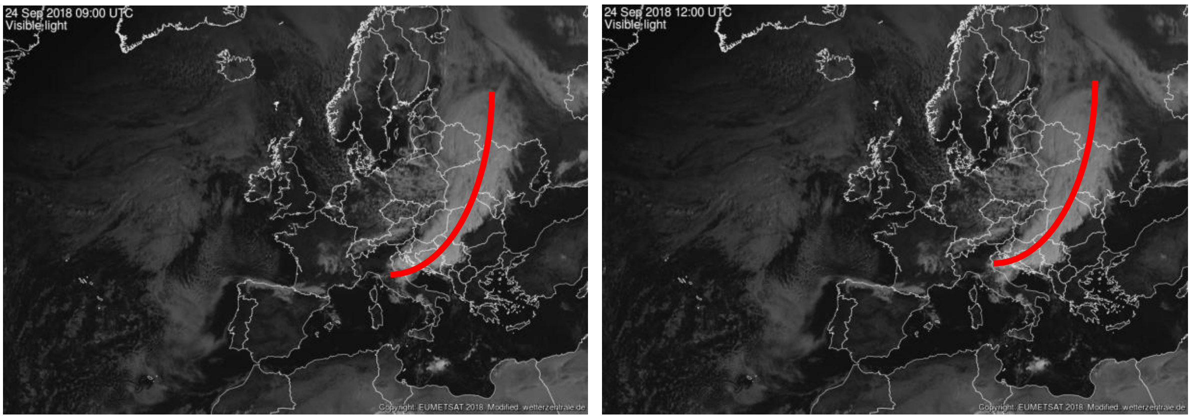


Figure 12. Satellite images in the visible channel at 09UTC (left) and at 12UTC (right) of 24 September 2018.

Following the hourly sea level data for the Ploce mareographic station during the day 24 September.

Date	Hour	Sea Level (m)
24.09.2018	00:00	1.259
24.09.2018	01:00	1.375
24.09.2018	02:00	1.424
24.09.2018	03:00	1.458
24.09.2018	04:00	1.480
24.09.2018	05:00	1.473
24.09.2018	06:00	1.425
24.09.2018	07:00	1.356
24.09.2018	08:00	1.261
24.09.2018	09:00	1.194
24.09.2018	10:00	1.238
24.09.2018	11:00	1.286
24.09.2018	12:00	1.312
24.09.2018	13:00	1.347
24.09.2018	14:00	1.254
24.09.2018	15:00	1.335
24.09.2018	16:00	1.467
24.09.2018	17:00	1.442
24.09.2018	18:00	1.305
24.09.2018	19:00	1.197
24.09.2018	20:00	1.228
24.09.2018	21:00	1.161
24.09.2018	22:00	1.021

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