Nat. Hazards Earth Syst. Sci. Discuss., 3, 3449–3485, 2015
www.nat-hazards-earth-syst-sci-discuss.net/3/3449/2015/
doi:10.5194/nhessd-3-3449-2015

Natural Hazards and Earth System Sciences Discussions
Open Access

Review Article: Explosive cyclogenesis over the south-east of Romania 2–3 December 2012

M. Bratu and C. Nichita

National Meteorological Administration, Timisoara, Romania

Received: 24 February 2015 – Accepted: 7 April 2015 – Published: 22 May 2015

Correspondence to: M. Bratu (marius.m.bratu@gmail.com)

Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

This paper is devoted to the study of the synoptic-dynamical conditions that contributed to the development of a rare explosive cyclogenesis event that occurred at the beginning of the winter from 2012 to 2013 in south-eastern Romania, more precisely between 2 and 3 December 2012. The minimum sea level pressure observed was 980.2 hPa, the lowest ever observed record for the surface of the Sulina weather station, and also over the western side of the Black Sea during the of period 1961–2000 and 1965–2004. It was found that the cyclone was not a regular one, but a real "meteorological bomb" one, where the central pressure at sea level recorded an extraordinary decrease at about 32.3 hPa in 24 h, equivalent with 1.7 B (Bergeron unit). Compared to the 20th century storms named Lothar and Martin (level 2 and 1 on the hurricane scale) which devastated western and central Europe in December 1999, this case of explosive cyclogenesis can be considered one of the most extreme for our area, from both a meteorological view as well as its effects.

1 Introduction

There are quite frequent situations in some areas as the Atlantic Ocean, the Pacific Ocean and the east coast of the USA (Roebber, 1984; Sanders, 1986; Gyakum et al., 1989), often also behind the seas with important surface thermic gradients of the water, where the transformation of a cyclone from the wave status to the maturity status happens so fast and with such intensity, that the surface atmospherical pressure reaches critical values in a short time, being characterized by abundant rains, strong winds (average wind $> 17\,\mathrm{m\,s^{-1}}$) and dangerous significant wave heights (swell) for human activities, such as sea and air navigations. By definition, the extra tropical cyclone settled to a precise latitude, whose pressure decreases in its centre with a ratio of $1\,\mathrm{hPa\,h^{-1}}$ during 24 h (Sanders and Gyakum, 1980) is called generally "meteorological bomb".

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An analysis of meteorological conditions, such as the heat flux, moisture budget and upper-air features was performed by Gyakum and Danielson (2000) and Strahl and Smith (2001). Studying a large number of weak and "bomb" events over the Pacific, they found out that large surface fluxes are crucial in the case of explosive cyclogenesis. Recently, Nielsen and Sass (2003) in their study of the North Sea severe storms have also identified the precursors, such as potential vorticity (PV) generated by latent heat release (LHR) that brings a major contribution to the deepening of the studied cyclone. Some important studies were done by Lagouvardos (2006) and Michele Conte (1986) closer to our geographical area, in the Mediterranean Sea, where the most frequent cyclogenesis processes that influence Romania's weather-climatic environment happen, especially during the cold season.

This work is dedicated to the investigation of a rare explosive cyclogenesis event that happened over the south-east of Romania and the western side of the Black Sea Basin, when an absolute record for the lowest sea level pressure (980.2 hPa) was recorded at Sulina meteorological station (15360) in December 2012. This value was 37 hPa lower than the previous one observed 23 h before. Sustained winds and gale winds in eastern Romania and the western part of the Black Sea exceeded 20–25 $\mathrm{m\,s^{-1}}$ on average, with gusts up to 38 $\mathrm{m\,s^{-1}}$, which resulted in all the harbours being closed, the trees blown down and the roofs dislocated and damaged. The power supply network was interrupted and the eolian power farm networks were out of order. The gradual filling of the cyclone slowly evolved in the next 15 h (with only 4 hPa pressure difference from the lowest one) until it reached the mature stage. On the back side of the low centre and near it, harsh weather conditions swept across the south-eastern Romania, the Pontic Coast and the western part of the Black Sea, also with important 12–24 h of total rain accumulations (torrential rain between 20 and 60 $\mathrm{L\,m^{-2}}$, with peaks at about 69. . . 70 $\mathrm{L\,m^{-2}}$) and blizzards in the mountainous area – Oriental Carpathian Mountains.

The "bomb" analysed in this work had a Mediterranean–Aegean origin and its evolution occurred on an unusual Trans-Balkan trajectory (Fig. 1) and deflected towards

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the North, in comparison with the classic one (type 2b'), as it was settled by Sorodoc (1962) and revised by Ecaterina Ion-Bordei (2009). It was concluded that the rapid deepening of the cyclone was associated with a short and rapid trough system (Stratospheric dry air intrusion, Fig. 4a) that, upon the influence of a very intense subtropical upper-level jet (STJ), merged into a steady baroclinic low-tropospheric environment still existent on the sea coast of Romania and Bulgaria. Prior to the rapid cyclogenesis, the growing trough acquired a negative tilt which intensified the process (Gaza and Bosard, 1990). Based on WRF-ARW non-hydrostatic mezzo-scale limited area model simulations (no coupled model developed in this study, CPLD), we could conclude that the upper-level dynamic factor (trigger) was not the main reason that led to the growth and decay of the explosive cyclogenesis under study. The significant level of the surface latent heat flux (diabatic heat) released within the cyclone, during its explosive phase, that generates an intense low-level vortex (in terms of potential vorticity values observed at about 3 to 5 PVU for at least 9 h), contributed as a crucial factor to its rapid deepening. The most recent studies show that a subsequent intensification could be the result of the occurrence and growth of a diabatic Rossby wave (DRW) and of the nonlinear interaction of its short wave (mezzo-scale 200 km) with an upper-level disturbance (Moore and Montgomery, 2004). Section 2 is devoted to the climatology description of the phenomenon through the investigations of ECMWF analyses, historical observations and different authors. An insight into the method and data used in this work is given in Sect. 3, which is based on the Bergeron unit calculus. Section 4 describes the synoptic environment under which the deepening of this cyclone occurred, and also helps to understand its damaging wind surface intensifications. The PV and DRW analyses based on WRF-ARW model output are shown in Sect. 5 followed by the storm weather impacts, while concluding remarks are provided in the final section.

This is the first approach to the synoptic-dynamic setting of this type of cyclogenesis event over the Romanian territory.

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2 Phenomenon climatology

Sanders and Gyakum (1980) presented the first climatological study of this subject when they introduced the notion of explosive cyclone development or "bomb" cyclogenesis. But their study was focused over the Pacific and North Atlantic regions. In time, many other authors have come with additional explanations and interpretations. In the past, few investigations were done in the Mediterranean Basin, but recently some Greek and Italian authors such as Lagouvardos (2006) and Brunetti (2005) have focused on this area. The Mediterranean Sea, due to its complex and particular geographical configuration as a closed and warm sea, is the reason why these phenomena are relatively frequent especially during the winter season. Because this phenomenon is very rare at the latitude of Romania and there are not sufficient studies regarding the Black Sea region, the majority of cyclogenesis having Mediterranean origins, we have considered it useful to have the studies made by Brunetti and Moretti (2005) in the entire Mediterranean Sea Basin as important reference.

From 1980 to 2004, 79 such events occured over the Mediterranean Sea, an average of 3 $year^{-1}$. The meteorological "bombs" started in October and ended in May. The maximum number of events happened in December (18 events) when the sea is generally still very warm, followed by January with 15 events while the minimum of events happened in May. Figure 2 indicates the frequency of the critical values expressed in Bergeron units (B), values observed between 1980 and 2004. The biggest drop of 1.59 B was reached only once (on 21 January 1981), when the pressure reached 27 hPa in 24 h at the latitude of 39° N. Similar events have never been recorded in June–September. Brunetti and Moretti (2005) also provided a very useful list of the meteorological bombs from the Mediterranean Sea, which contains: the date, the initial and final pressure values and also the differences between them, the recorded Bergeron value, the latitude and longitude of the maximum deepening, the geographical area and the type of cyclogenesis (e.g. frontal, continental, African).

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An important cyclogenesis is the Aegean source type (Fig. 1), with 6 events in a quarter of a century. In our case the cyclogenesis was initiated also in the Aegean Sea Basin, and in less than 24 h the central pressure of 32.3 hPa measured at 12:00 UTC on 2 December fell to 06:00 UTC on 3 December (Fig. 3, left) corresponding to 1.7 B and thus the low pressure system can be referred to as a strong "bomb".

According to the MEDEX (MEDiterranean EXperiment), the database constructed by ECMWF reanalyses the model, this case being the deepest cyclone observed in the entire Romanian area, including the western part of the Black Sea Basin between 1965–2004. At that time the Sulina weather station reported an extraordinary pressure fall of 37.5 hPa in 24 h (Fig. 3, right) and a minimum station pressure of 978.9 hPa; the minimum can be considered a record after the latest record value of 980.9 hPa (Table 1) according to 1961–2000 NMA database records.

There are a lot of studies starting with Sanders and Gyacum (1980) that describe the synoptic upper air aspects of explosive cyclogenesis. The main factors are: horizontal temperature gradient, surface heat fluxes, diabatic heating, air–sea instability, jet interactions and tropopause folds. Examining a number of cases, Bruce and Elmar (1988) made an analytical study of the continental bombs development over the Eastern USA, making comparisons between a regular cyclogenesis and an explosive one. They found significant signatures especially in divergence, vorticity advection and pressure tendency, latent heating and static stability which allow distinctions between bombs and regular cyclones. More recently, based on Parker and Thorpe (1995), Moore and Montgomery (2004), upon reexamining the dynamics of short-scale, also established that the diabatic Rossby waves growth mechanism may play an important role, considering it a precursor for an explosive cyclogenesis.

3 Methods and data

The method used in this work was discovered by Tor Bergeron (1891–1977), who studied the synoptic climatology and the motion of this process of the extra-tropical cyclones in the North Atlantic Ocean for the first time. He established the following principle to identify a meteorological bomb that has been used until today: the pressure in the centre of a cyclone must decrease by at least 1 hPa h^{-1} during a period of 24 h. The Bergeron definition used by Sanders and Gyakum (1980) to analyse the concept of explosive cyclogenesis ("bomb"), had as reference the 60° N latitude. In order to monitor the intensity and track of this type of cyclone step by step, the Bergeron formula was used:

$$\mathrm{NDR_c} = \frac{\Delta p_\mathrm{c}}{24} \cdot \frac{\sin 60^\circ}{|\sin \phi^\circ|}$$

where Δp_c represents the pressure variation in the center and ϕ represents the latitude. The Bergeron formula allows us to obtain a critical NDR$_\mathrm{c}$ ratio (normalized deepening rate of central pressure) according to the latitude we want to use. When the pressure variation is of 1 hPa h^{-1} and $\phi = 60^\circ$, the NDR$_\mathrm{c}$ = 1, namely the threshold value of 1 B where the explosive cyclogenesis can start to happen:

$$1\,\mathrm{hPa\,h^{-1}} \cdot \sin 60^\circ / \sin 70^\circ = 0.92\,\mathrm{hPa\,h^{-1}}$$

The measurement obtained by Bergeron indicates the decreasing speed of the atmosphere pressure in the depression center settled to a certain latitude. The critical ratio of 1 B is considered a reference value for a meteorological bomb. This indicator can vary from 28 hPa in 24 h (at the poles) to approx. 9 hPa in 24 h (at 20° N lat), this last value being calculated at the southern limit where the phenomenon has been observed until now. The Italian National Weather Service from the Mediterranean Sea Basin has adopted a critical value of 1 B that represents a lowering of the pressure in the center of at least 17 hPa in 24 h (which corresponds to an average latitude of 38° N). In the case of the Black Sea Basin, we have considered 19 hPa as the critical value for 1 B (19.6 = 24/1.22; 1 hPa h^{-1} $\cdot \sin 60^\circ / \sin 45^\circ = 1.22$ hPa h^{-1}), for the medium value of 45° N. In our case, the lowest value of the sea level pressure was 980.2 hPa (37.5 hPa in 24 h) recorded in Sulina (Dobruja), and the highest value of the slp was 1012.5 hPa

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registered in the initial stage of the cyclone over the Aegean Sea. Considering as reference the pressure variation of 32.3 hPa (1012.5 − 980.2 = 32.3) in 24 h in the center of the low-pressure, in the case of our country the critical ratio has reached the extreme value of 1.7 B (32.3 : 19 = 1.7), in comparison to our neighbour (the Mediterranean Sea basin), where the value of 1.59 was rarely reached (Brunetti and Moretti, 2005).

In this way the indicator NDR_c was monitored for 15 h (every 3 h) and the conclusion is that there is a gradual increase of its value from 1 to 1.7 B, from the explosive deepest status of the cyclone (Fig. 4a–d) up to the maturity status (Fig. 4e and f). The main meteorological data and sources used in this paper are presented below:

– Daily SYNOP and METAR messages mainly at 00:00, 03:00, 06:00, 09:00, 12:00, 15:00, 18:00, 21:00 UTC used for issuing 24 h weather diagnosis (T 2m, Td, mixing ratio, MSLP, pressure tendency, wind direction and speed, 24 h total precipitation, sea surface temperature, high sea wave) at all the met stations (RMS) and also radar observations belong to the Romanian Meteorological Administration NMA network; for the worldwide data we also used daily SYNOP and METAR messages provided via internet by Wyoming, Albany and Florida State Universities.

– Daily SOUNDINGS messages at 00:00 and 12:00 UTC 2/3 December provided via internet by Wyoming, Albany and Florida State Universities.

– Six hourly analysis ECMWF model at surface and upper levels (6 pressure levels at SLP, 1000, 850, 700, 500 and 300 hPa) different parameters (temp., temp. advection, geopotential, divergence, potential vorticity in pressure level hight, streamlines, max. wind), soundings and cross-section provided by EUMETNET.

– Daily analysis SKIRON model (horizontal resolution ∼ 5 km) about the Sea Surface Temperature and SST anomaly, sea surface height above the sea level provided by www.myocean.eu/.

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- Hourly analysis and forecast WRF-ARW 3.4.1 (4.5 km hor. resolution using 00:00 UTC GFS reanalysis on a Linux HPC Cluster Infragrid Cluster) non-hydrostatic limited area model surface mean-sea-level pressure, surface latent heat, potential vorticity (PVU unit) at 925, 850 and 887 hPa levels made by RoMetEx and West University of Timişoara, Romania.
- Hourly and six-hourly geo-stationary and polar satellite pictures (RGB, HRV, IR, WV) provided by Eumetsat and University of Dundee, UK.
- MEDEX (MEDiterranean Experiment) database (constructed by ECMWF analyses and ERA-40 reanalyses), available on http://medex.aemet.uib.es.
- Climatological database from NMA Atlas, Romania.

The hourly (for the surface) and 12 hourly (for the upper level) varied analyses have been computed using Digital Atmosphere Soft V2.07 (Weather Graphics) on the meso-α and meso-β scale. For this purpose we have used objective analysis methods such as the Nearest Neighbor and the Cressman type.

4 Synoptic overview

This event took place in quite abnormal climatic conditions, with a neutral NAO index and a slightly better negative AO index ($-1 \ldots -1.5$). A low pressure area dominating the central Mediterranean Basin area was linked to a large persistent upper Rossby wave (a geopotential negative anomaly), that remained in Western Europe for 3 days (Fig. 5). A maritime arctic airmass came from north-west Europe and reached Italy and the Balkan Peninsula. The main cold front separated the chilly unstable Italian air mass from the warm, also unstable eastern Mediterranean air mass. Also, both the Mediterranean and the Black Sea experienced positive SST anomalies in December. Regarding the Black Sea surface temperature, it was between 11 and 14 °C, 3–6 °C higher than the monthly normal values.

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4.1 Initiation phase I

At 00:00 UTC on 2 December, the cyclone being analyzed here had not been formed yet. At 12:00 UTC on 2 December, a low-pressure area in the incipient phase with 1008.3 hPa in its center was located in the maritime eastern area of Greece (Fig. 6a). There were two disturbances, a short-wave over the area of the Ionian Sea with its axis extending NW–SE (negatively tilted) and a cut-off low over the Sicilian Channel, observed at the 500 hPa constant pressure level (Fig. 7a and b). A strong upper-level subtropical jet (STJ) accompanied the cut-off wave, reaching a maximum value of ∼ 45 $m s^{-1}$ at 300 hPa (Fig. 7b).

4.2 Initiation phase II

During the following 12 h, at 21:00 UTC on 2 December, the low pressure was in its incipient phase II in the southern continental Bulgaria with a central pressure of 998.8 hPa (Fig. 6b). Regarding the 500 hPa two-trough system (∼ 5500 m a.s.l.), we can observe geopotential troughs in the western part (over the Sicilian Channel), almost quasi-stationary inoculated, moving on a SW–NE trajectory under the influence of the Subtropical Jet. At the 300 hPa level an intensification to 56–60 $m s^{-1}$ over the southern edge of the trough can be observed and also a detachment over the northern edge of the trough of an isolated upper level jet in diffluent flow (Drift), accompanying the cyclogenesis process (Figs. 7c and 9a). At the same 500 hPa level, as a band, we can see two positive vorticiy advection areas (Fig. 8b and c): one over the east of the Aegean Sea and the Marmara Sea towards the low centre, and another one, less intense, over the eastern Romania, Moldavian Republic and southern Ukraine. The trough axis is still negatively tilted, thus generating cyclonic vorticity (Gaza and Bosard, 1990). It can be noted that the cyclonic vorticity advection as a dynamical factor begins 12 h before the cyclone development (Fig. 8b) and it is more obvious over eastern Romania and the western part of the Black Sea Basin. Warm advection at the same level is also obvious over the Black Sea, Moldavian Republic and Ukraine

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(brown bold line, Fig. 8b and c). In the following 9 h on 3 December, the low pressure system moved northwards, rapidly deepening first to 991.2 hPa at 00:00 UTC and then to 985.0 hPa at 03:00 UTC (Fig. 6c). The explosive phase had just started. The intrusion of stratospheric dry stable air in the middle and lower troposphere levels, visible on the satellite infrared WV Channel as a black tongue shape (Santurette and Georgiev, 2005) indicates the presence of an active dynamic tropopause anomaly (DTA).

It was identified based on the analysis of the Ertel's potential vorticity (PV) field (magenta contour lines, taking 1 PVU from the dynamic tropopause as a reference value, Fig. 9a and b). The maximum potential vorticity area (PV max) became gradually narrower. The intrusion of stratospheric dry air created upward motions and local instability that led to the organization of a deep convection into a line on its eastern flank. At 06:00 UTC on 3 December, the mezzo-scale low-pressure reached its minimum central pressure (980.2 hPa) over the northern Dobruja (Fig. 7c). According to Sanders and Gyakum (1980), explosive cyclogenesis occurs when the deepening of the cyclone exceeds 1 B. In the area over the Black Sea (at $\sim 45^{\circ}$ N lat), 1 B equals 19 hPa in 24 h. Therefore the 24 h central pressure fall from 1012.5 hPa at 12:00 UTC on 2 December to 980.2 at 06:00 UTC on 3 December corresponds to 1.7 B and thus to a strong "bomb". Important modifications of the dynamic nature occured in the upper-level above the 500 hPa level, 6 h before the beginning of the explosive phase. The curvature trough amplified and the gradient of the geopotential height deepened. Meanwhile, in the low-levels, a critical potential vorticity anomaly at about 4.5–5 PVU appeared in a comma shape, being discussed in detail in Sect. 5. As inferred by the strong pressure gradient (~ 13 hPa pressure change in just 100 km range around the storm centre), the prevailing damaging winds, first in the eastern sector and then in the western sector, reached their maximum intensity in south-eastern Romania, over the Black Sea coast and off shore between 2 and 3 December. The local weather stations registered high intensity widespread winds exceeding 20–25 m s^{-1} and a gust of over 32 m s^{-1}. Maximum wind gusts at Gloria Oil Platform (15477), Medgidia (15462) and Sulina (15360) reached 35–38 m s^{-1}, which means 137 km h^{-1}, the first level on the

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Saffir–Simpson hurricane scale, the same as for the Lothar and Martin cyclones that devastated western and central Europe in December 1999. The strong gusts which were recorded appear to have been due mainly to the associated sting jet (SJ) in the low levels by formation of a bent-back front (BBF; Shapiro and Keyser, 1990; Neimann et al., 1993). According to the Browning study (2004), the SJ produces strong winds that reach the surface in the dry air just ahead of the tip of the hook-shaped cloud head that accompanies the BBF. However it is better not to lose sight of the fact that the strength of a cyclone is first determined by the interaction of the over-running potential vorticity anomaly with the baroclinic zone, and the SJ is only a secondary factor in creating a local intensification of the wind. Based on the Medgidia radar Doppler velocity field and the numerical model transverse cross section, we concluded that the SJ was responsible for stronger surface wind intensifications, but only for a short period. The Fig. 11b and c (right) indicates well the SJ location in its ascending (south-western) and in its descending (north-western) trajectory during the explosive cyclone phase. The satellite images provide a clear overview to describe the mezzo-scale evolution of our storm. Shortly after an explosive stage, a clearly defined "eye" along with spiral structured cloud bands were visible from the MSG-2 satellite RGB images on 3 December at 07:00 UTC (Fig. 12). Also, the polar NOAA-MODIS images show at a higher resolution the location of the low in the neighborhood of Odessa City (Ukraine) with a clearly defined "eye" (Figs. 12 and 13).

4.3 Mature phase

In the next 12 h the cyclone reached a mature stage moving towards north-east. The cyclonic perturbation is visible at all levels both at the surface and in the upper-air (Figs. 6d, 7d and 8d). On the 4 December, the cyclone dissipated over the northern part of the Russian Plain, after moving over ~2000 km at an average speed of 50–55 km h^{-1} in the explosive phase.

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5 Results

During the explosive phase, the largest deepening occurs from surface to 800–850 hPa and it is related to an intense moisture convergence field coming from the Black Sea (the eastern sector) towards the cyclone center (Figs. 14a, 15a and 16a) within a significant positive SST anomaly up to 5–6 °C (14b, 15b and 16b). This is connected to an intense low-level vortex associated with an ascending moist air movement that produced a rapid pressure drop, condensation, latent heat release and a thermal profile that is specific for warm cyclones beetwen 850 and 700 hPa (not shown). A closer analysis of the potential vorticity anomaly field provided us with the idea that the subsequent intensification could be the result of a growing diabatic Rossby wave (DRW) and of the nonlinear interaction of its short wave (small-scale less then 500 km) with the upper-level disturbance (Moore and Montgomery, 2004). The WRF-ARW 3.4.1 non-hydrostatic numerical model was used in a one nested grid configuration, with a finest horizontal resolution of 4.5 km, to simulate the genesis and the evolution of the low-level vortex (potential vorticity) and also the surface latent heat flux. The simulations were initialized with GFS model reanalyses input at 00:00 UTC on 3 December 2012. Figures 14c, d, 15c, d and 16c, d show a series of potential vorticity maps (between 925 and 850 hPa) at 01:00, 03:00 and 06:00 UTC on 3 December 2012. More specifically, the Ertel potential vorticity (defined as $q = \frac{1}{\rho}\eta\nabla\theta$, where ρ is the density, η is the absolute vorticity vector and θ is the potential temperature) is given in PVU (potential vorticity units: $10^{-6}\,\mathrm{km^2\,kg^{-1}\,s^{-1}}$). A few hours prior to the explosive phase, around 00:00 UTC on 3 December, near the border line between Romania and Bulgaria (Fig. 14c and d), the high PV values at about 3.5–4 PVU appeared first at the lower level of 925 hPa (600–700 m high), while at 850 hPa level (1300–1500 m high) the values were of only 2 PVU. In the next three hours, over the continental part of Dobruja district, the PV magnitude reached the phenomenal 5 PVU on both levels (Fig. 15c and d). Note that the maximum PV (red shaded contours) coincides very well with the maximum moisture convergence area and stream current confluence lines.

This means that the generation of diabatic wave (diabatic Rossby wave) appears to be tied with the moisture convergence field and with the maximum low-level jets intensity in the south-east sector (not shown). In the mature phase, the low-level vortex was dispersed in the upper troposphere by the presence of cyclonic vorticity advection. The model maps highlighted that the PV magnitude was maintained at high values as the same previous values (4–5 PVU) for another 5–6 h while the low-pressure system was away from the Black Sea area. In the next hours, the diabatic wave started to rotate into the seclusion front (Fig. 16a–d), reaching the minimum historical surface pressure of 978.9 hPa. The role of the surface heat flux has been investigated in many cases of explosive (as well as ordinary) cyclogenesis and it is considered to be a crucial feature during the cyclogenetical process (Gyakun and Danielson, 2000). Since 3 December, 03:00 UTC, the heating flux (just the surface latent heat shown) gradually increased during the explosive phase reaching a great evaporation rate at about 330 Watt m^{-2} from 07:00 to 10:00 UTC (Fig. 17). For comparison, a "hurricane-like" system could easily gain up to 600–800 Watt m^{-2}. The presence of a quasi-concentric surface heat distribution around the storm eyewall is noteworthy. In addition, it should be emphasized that the reasonable parametrization of the atmospheric-ocean-wave interaction in the numerical model is quite important and essential for a reliable extra-tropical cyclone intensity and accurate central pressure forecast.

6 Weather impacts

The phenomena associated with this "meteorological bomb" consisted not so much in the accumulation of precipitation, but especially in wind gusts that reached level 1 on the Saffir–Simpson hurricane scale (85 mph or 137 km h^{-1}). Also, off the Black Sea coast the waves reached 10 m in height and the water retracted 40 m towards the coast, also recording very strong rip tides. At that time, the local and national mass media related the damage of this explosive cyclogenesis. The disastrous effects in Constanta and Tulcea counties during the night of 2–3 December 2012 were: the winds reached

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over 100 km h^{-1} and tens of trees and electricity poles were blown down, national roads were blocked and electricity was interrupted for many hours. Only in Constanta county 28 cities remained without water, the gas network was damaged, 22 schools and 348 houses were damaged. In the case of the schools, the financial loss was around RON 1 888 000. In Medgidia, the roof of a house was blown away and a high school in Poarta Alba also remained without the roof, all the windows being broken and some walls dislocated. The 8 level storm (on the Douglas scale) which started on the sea forced the local authorities to close the ports at the Black Sea. In Galati the strong wind blew away the advertising panels, the trees and the road signs. In Braila, a tree blocked the tram lines and the storm was followed by a rainfall recording 40 L m^{-2}. In all Dobruja area, half of the eolian stations were out of order for at least 24 h and the nuclear reactor from Cernavoda was turned off for technical verifications only 3 days after this event finished. The most quantitative rains were recorded in Slobozia and Ialomita counties; in less than 12 h the water quantities recorded values between 30 and 69 L m^{-2}, resulting in a flood. In Slobozia a peak of 70 L m^{-2} was recorded in less than 12 h. Important floods were also recorded in Barlad county. Ukraine and the Republic of Moldavia were also affected. The strong winds and rainfalls interrupted the electricity in 80 villages, blew away the roofs, and in Chisinau many streets were flooded.

7 Conclusions

The analysed case fits well into the criteria established by Sanders and Gyakum regarding the explosive cyclogenesis, as a predominantly maritime type (inland during the explosive phase), specific to the cold season, in the maximum deepening phase having the features of a tropical cyclone (hurricane), both in the wind field (powerful wind, devastating swell) and in terms of cloud appearance (spiral shaped cloud system at sub-synoptic scale, eye formed above the cyclone recorded on satellite images). The superficial surface temperature of the water in the western and southern basin

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of the Black Sea showed a significant discontinuity and a positive anomaly of 3–6 °C, which, on an eastern circulation, increased considerably by the convergence of warm and humid air contribution to the centre of the cyclone. Given the rarity of this phenomenon in our geographical region, unprecedented in recent history from the strength magnitude point of view, it is necessary to reconsider this type of rapid cyclogenesis. In this research, which is not an analytical one, we have tried to investigate which factors (diabatic or dynamic) have the largest contribution in its evolution. Although the cyclogenesis was initiated over the Aegean Sea by classical processes such as the positive advection of vorticity and the divergence in the upper troposphere, we have found that the deepening of the "bomb" in south-eastern Romania took place under the diabatic mechanisms rapidly associated to these processes, that generated for a short time (6–9 h), in low-levels, an intense mezzo-scalar vortex over the baroclinic zone (positive PV anomaly) that depleted it later in the upper levels during the mature stage. The major development occurs when the presence of the cyclonic vorticity in the upper levels continues in spite of the diabatic mechanism tending to weaken it. The surface latent heat fluxes and the Pontic marine features (SST anomaly) seem to play a key role in the deepening of the storm and a less important one during its mature phase. The aim of this paper is to understand the synoptic and dynamic mechanisms relevant to this development inside the Romanian geographical environment and to use it further in similar cases. For meteorologists and operational weather forecasters, it is therefore very important to recognise on the satellite maps and different numerical model prognosis output this phenomena features usually accompanied by high-impact and meteorological risk.

Acknowledgements. The authors are indebted to Liviu Oana (West Univ. Timisoara, RoMetEx organization) who contributed to the numerical simulations performed with the WRF-ARW model in the frame of this study about the potential vorticity and the surface heat flux. The Romanian National Meteorological Administration is kindly acknowledged for providing radar and surface stations data used in this paper. We are especially grateful to Ion Draghici for thought-provoking discussions and professional advice. Gratitude is expressed to the

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www.myocean.eu/ and the National Observatory of Athens for providing us with SST and Sea Wave High analyses and also to all who supported and encouraged us in this research.

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Table 1. The monthly and annual lowest station pressure (hPa) at Sulina (1961–2000).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
hPa	983.0	981.6	983.5	987.3	993.2	989.7	993.5	996.6	988.3	993.7	985.8	980.9	980.9
New Record												978.9	978.9

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Figure 1. The 25-year geographic distribution of the meteorological bomb events (the number of cases) from 1980 to 2004 in the entire Mediterranean Sea Basin (Brunetti and Moretti, 2005).

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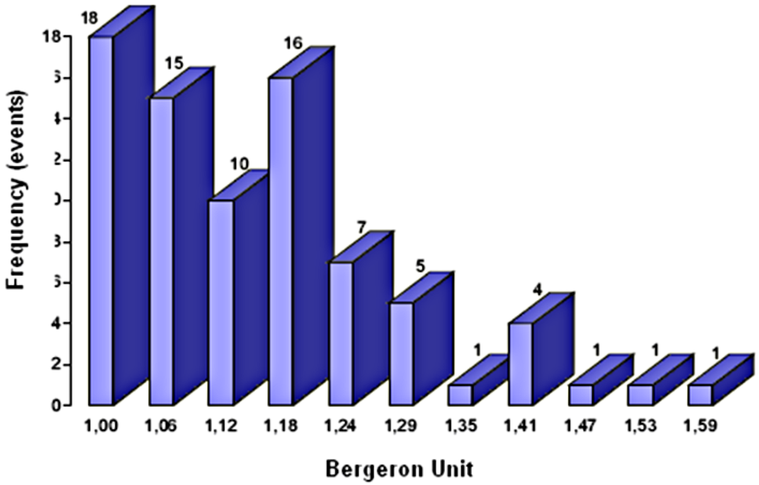

Figure 2. The "bomb" frequency events related to their intensity on the Bergeron scale over the Mediterranean Basin from 1980 to 2004 (Brunetti and Moretti, 2005).

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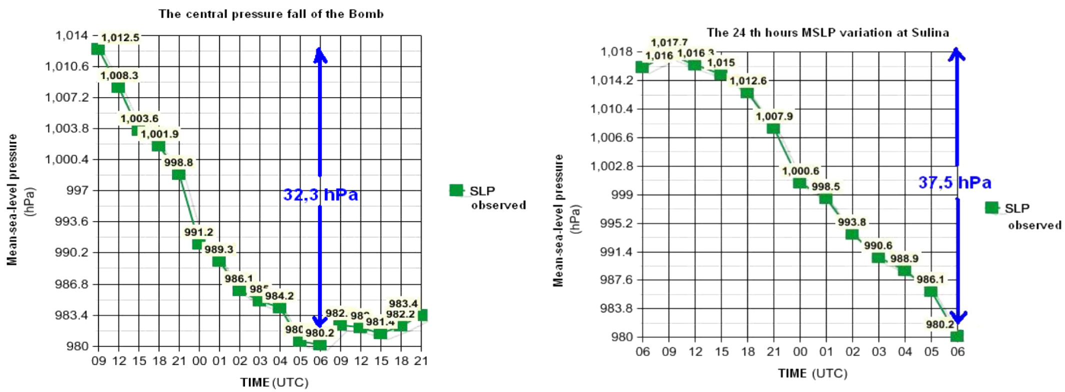

Figure 3. Observed 36 h central pressure fall inside the cyclone (left) and at Sulina weather station (right) from 09:00 UTC on 2 December to 21:00 UTC on 3 December 2012.

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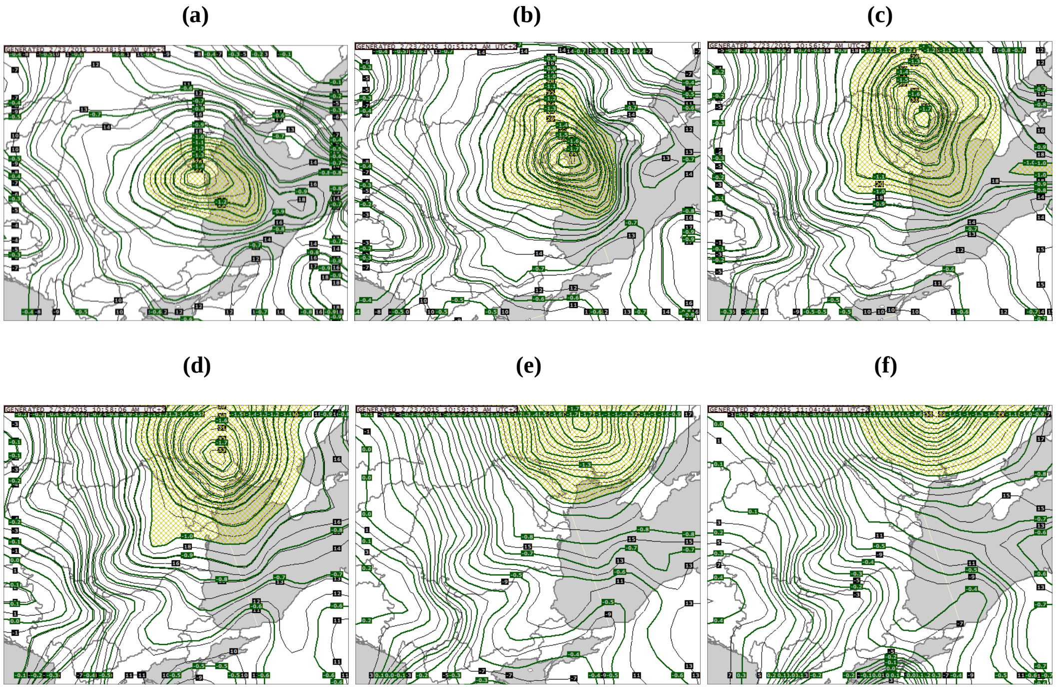

Figure 4. Analysis of Δp in 24 h (black line, contours are labeled in 1 hPa) and NDR ≥ 1 (green shade areas) at: **(a)** 03:00 UTC 3 December 2012, **(b)** 06:00 UTC 3 December 2012, **(c)** 09:00 UTC 3 December 2012, **(d)** 12:00 UTC 3 December 2012, **(e)** 15:00 UTC 3 December 2012, **(f)** 18:00 UTC 3 December 2012.

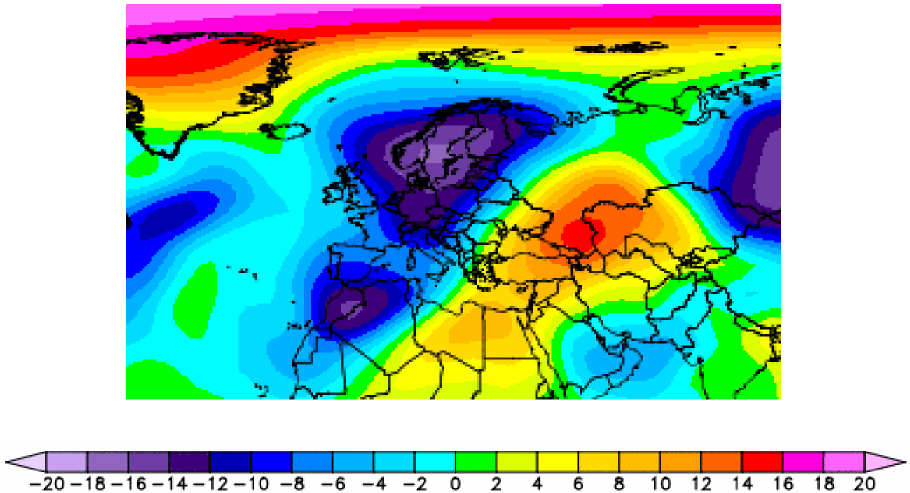

Figure 5. Analysis of 1000–500 thickness anomaly (shaded contours in dam) 3 day average ending on 3 December 2012.

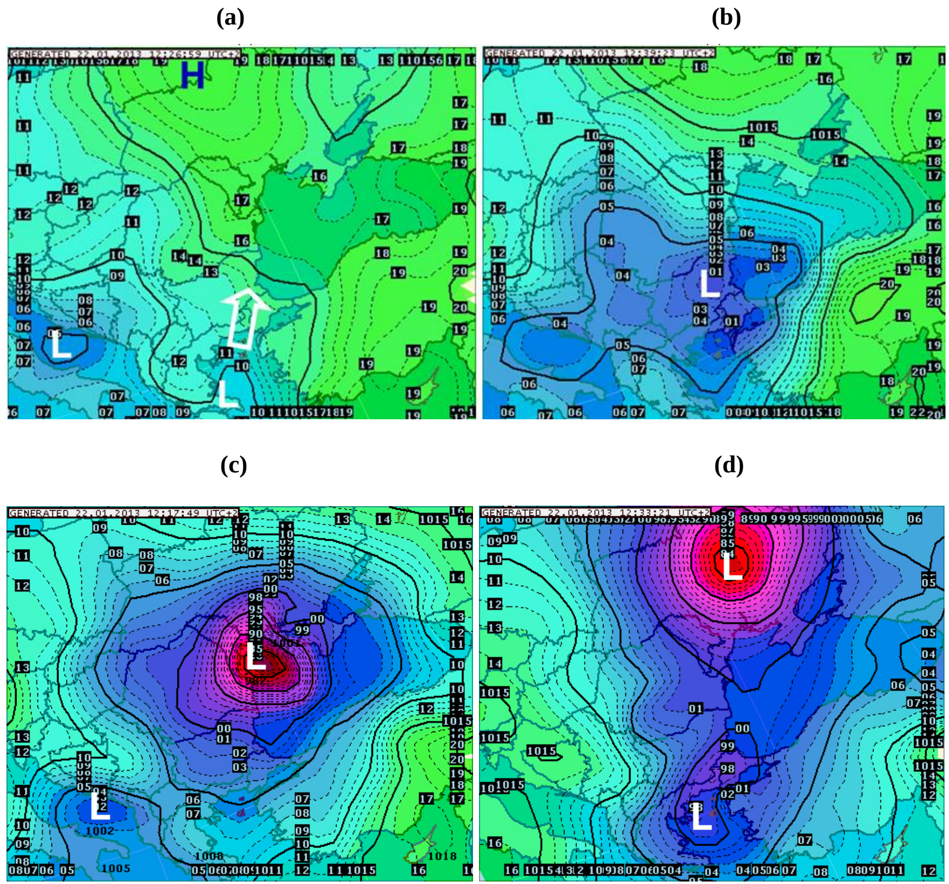

Figure 6. Analysis of mean-sea-level pressure (contours are labeled in 1 hPa) at: **(a)** 12:00 UTC 2 December 2012 in the incipient phase I, **(b)** 21:00 UTC 2 December 2012 in the phase II, **(c)** 06:00 UTC 3 December 2012 in the explosive phase, **(d)** 18:00 UTC 3 December 2012 in the mature phase.

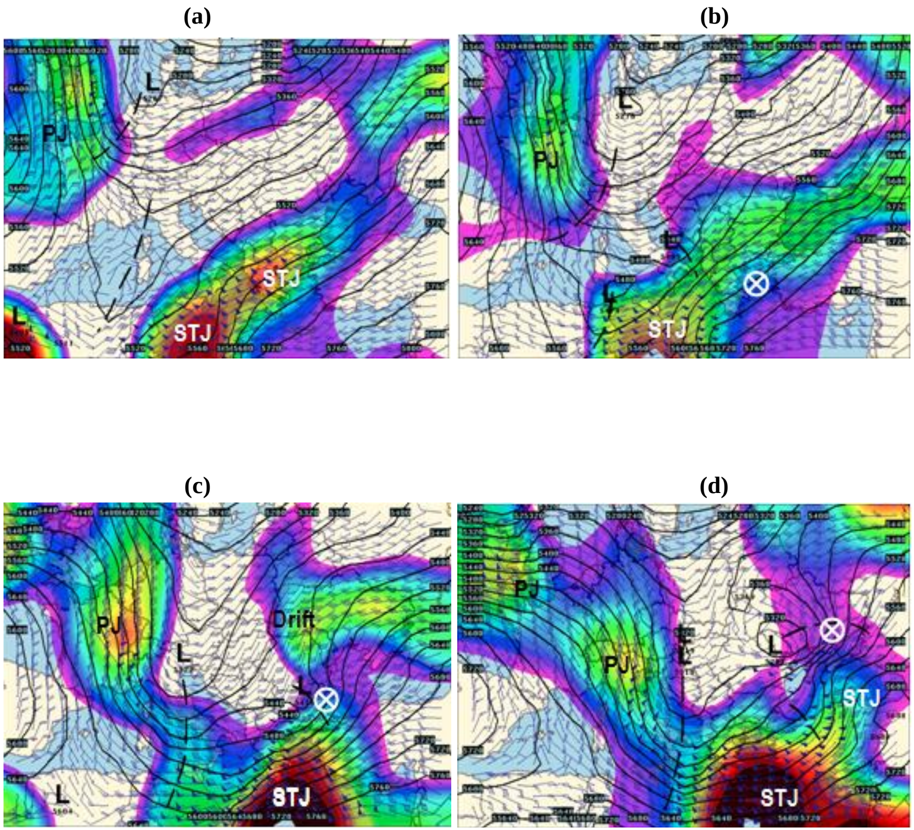

Figure 7. Analysis of 500 hPa geopotential height (solid line at 40 m intervals and of 300 hPa wind speed – shaded contours at 1 m s^{-1} values, greater than 25 m s^{-1} are shown) and surface locations (indicated by white circles) of the meteorological bomb at: **(a)** 00:00 UTC 2 December 2012, **(b)** 12:00 UTC 2 December 2012, **(c)** 00:00 UTC 3 December 2012, **(d)** 12:00 UTC 3 December 2012.

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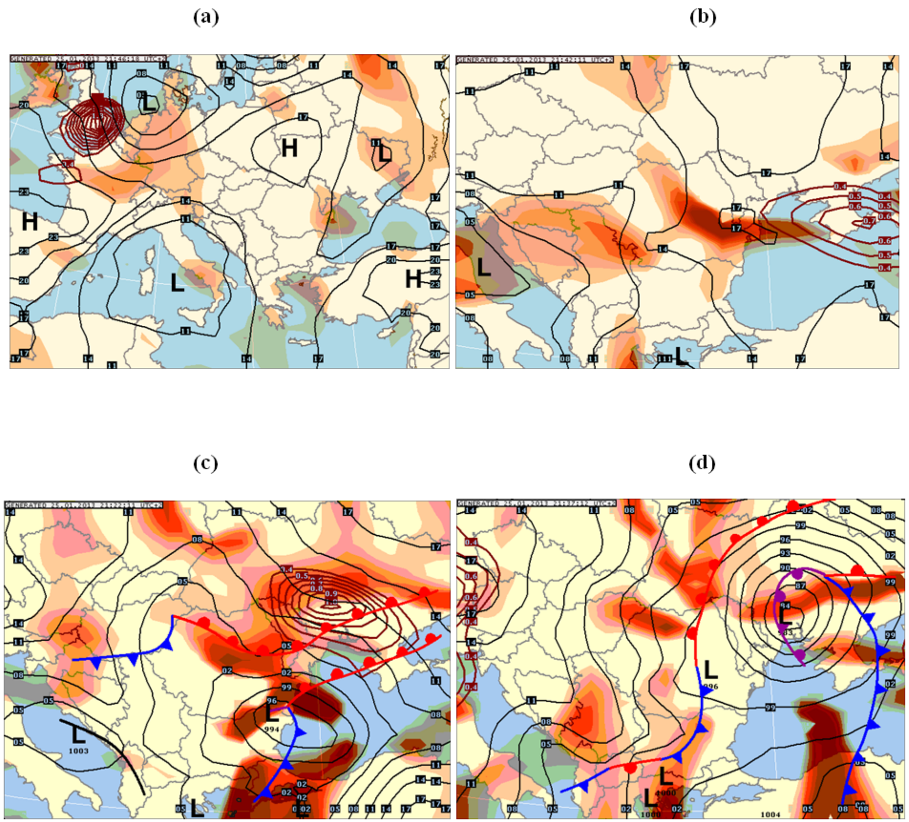

Figure 8. Analysis of the sea-level pressure (black solid lines at 3 hPa intervals) and of 500 hPa positive vorticity advection (shaded contours in $10^{-8}\,\mathrm{K\,s^{-2}}$) and of 500 hPa temperature positive advection (brown contour lines in $10^{-4}\,\mathrm{K\,s^{-1}}$) at: **(a)** 00:00 UTC 2 December 2012, **(b)** 12:00 UTC 2 December 2012, **(c)** 00:00 UTC 3 December 2012, **(d)** 12:00 UTC 3 December 2012.

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(a) (b) (c)

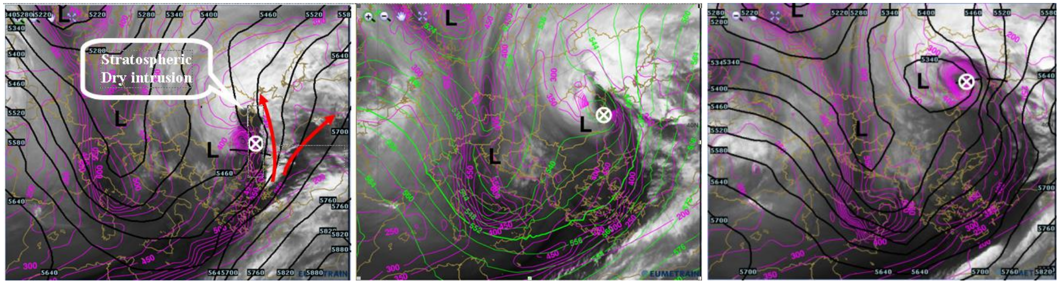

Figure 9. ECMWF analysis of 500 hPa geopotential height (lines at 40 m intervals) and of PV (magenta solid line in pressure height referred to 1 PVU) superimposed over Eumetsat IR images (ch.WV 6.3 micro) and surface locations (indicated by white circles) of the cyclone from 00:00 UTC 3 December in the explosive phase to 12:00 UTC 3 December 2012 in the mature phase.

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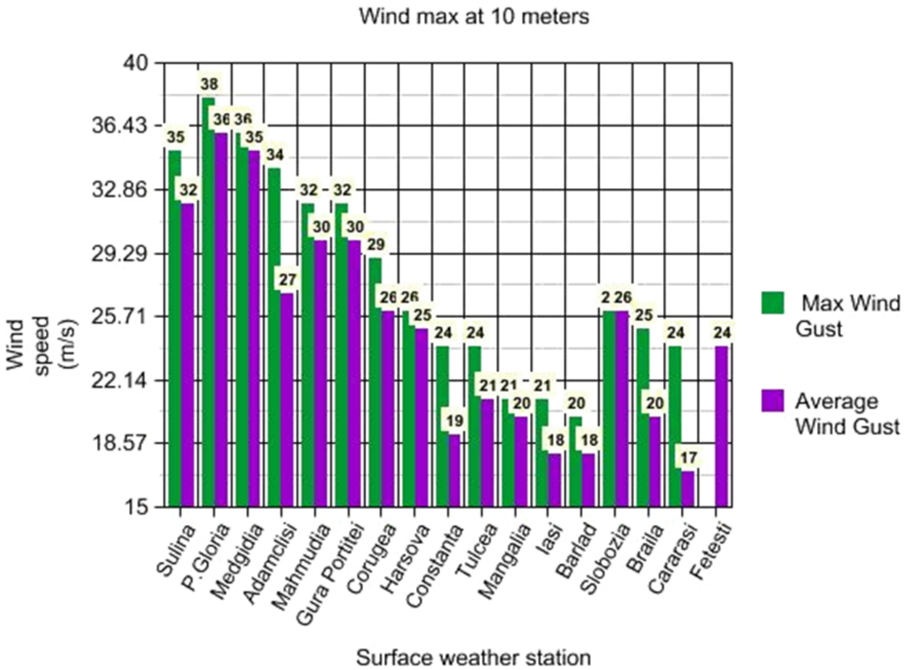

Figure 10. Wind observations from the surface weather network stations during the storm.

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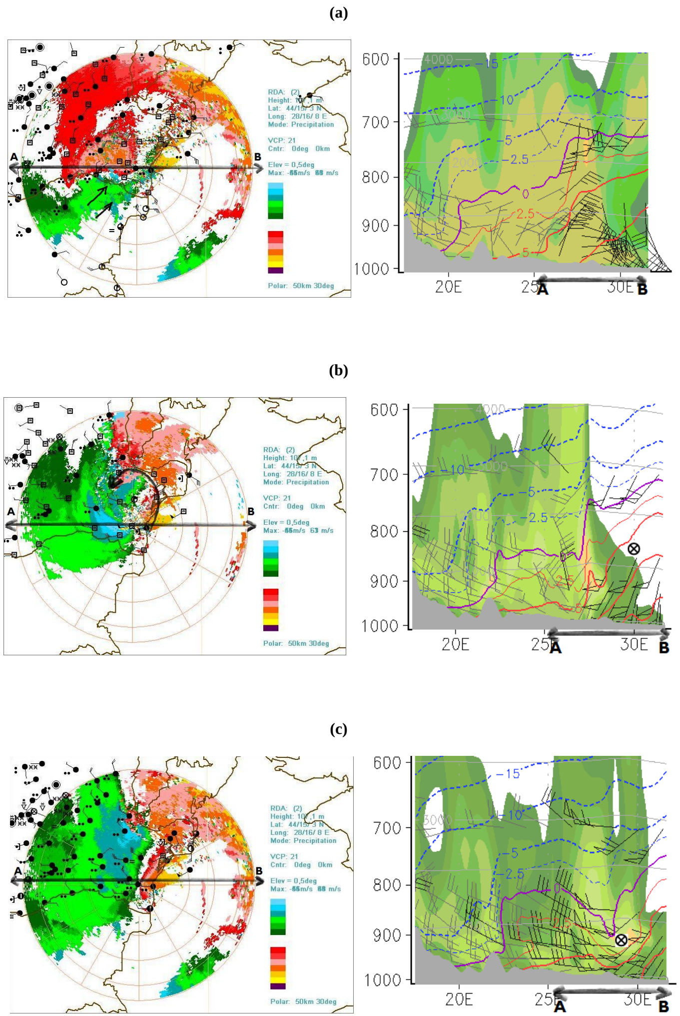

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Figure 11. Sequence of base velocity from the WSR-98 D Medgidia radar at 0.5 grades tilt at: **(a)** 00:24 UTC, **(b)** 02:48 UTC and **(c)** 05:23 UTC (left). The mask clouds, negative and positive wind flow speed and station plotting observations are identified. The radar distance coverage is about 500 km. Vertical cross-section from numerical model 00:00 UTC runs along the line AB at: **(a)** 00:00 UTC, **(b)** 03:00 UTC and **(c)** 06:00 UTC (right). The green-yellow shaped area is RH (70–120 %), the thin color lines represent the temperature (at 2.5 °C intervals), and the plotting barbs represent the wind direction and velocity; altitude is given in hPa. The relative location of the SJ is shown with a black circle.

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Figure 12. The 60 h surface track (indicated by red squares) of the meteorological bomb from the incipient phase to the mature and dissipating phase (12:00 UTC 2 December–00:00 UTC 5 December 2012). Source: EUMETSAT RGB Channel at 09:00 UTC 3 December 2012.

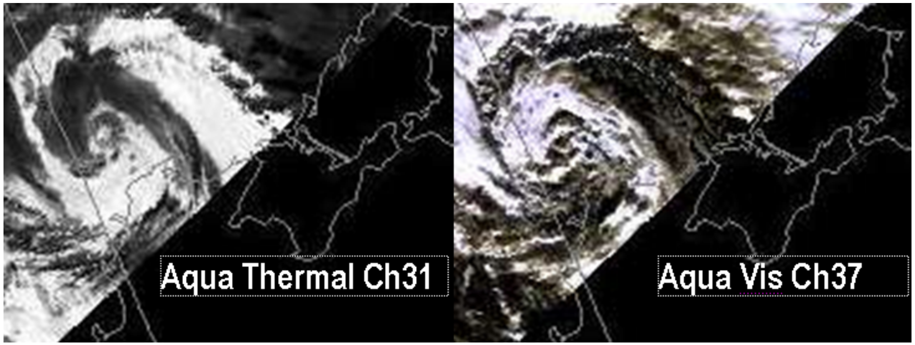

Figure 13. Polar satellite images during the explosive phase of the cyclone. Source: NOAA-MODIS Channel 31/37 at 10:40 UTC 3 December 2012.

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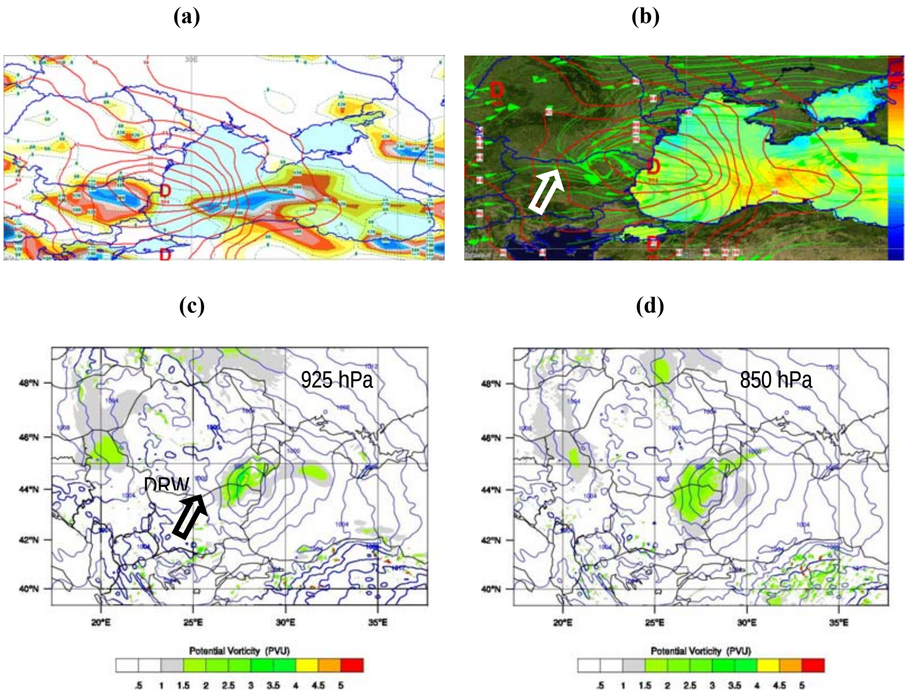

Figure 14. Observation analysis of the sea-level-pressure (red solid lines at 2 hPa intervals), of the surface moisture convergence (shaded colour contours, in $g\,kg^{-1}\,s^{-1}$), of the surface streamlines wind (green lines), and of the SST anomaly (shaded contours in Centigrades) at 03:00 UTC 3 December 2012. Model analysis of the potential vorticity anomaly (shaded colour contours) at 00:00 UTC 3 December 2012. “D” is similar to “L” from low pressure.

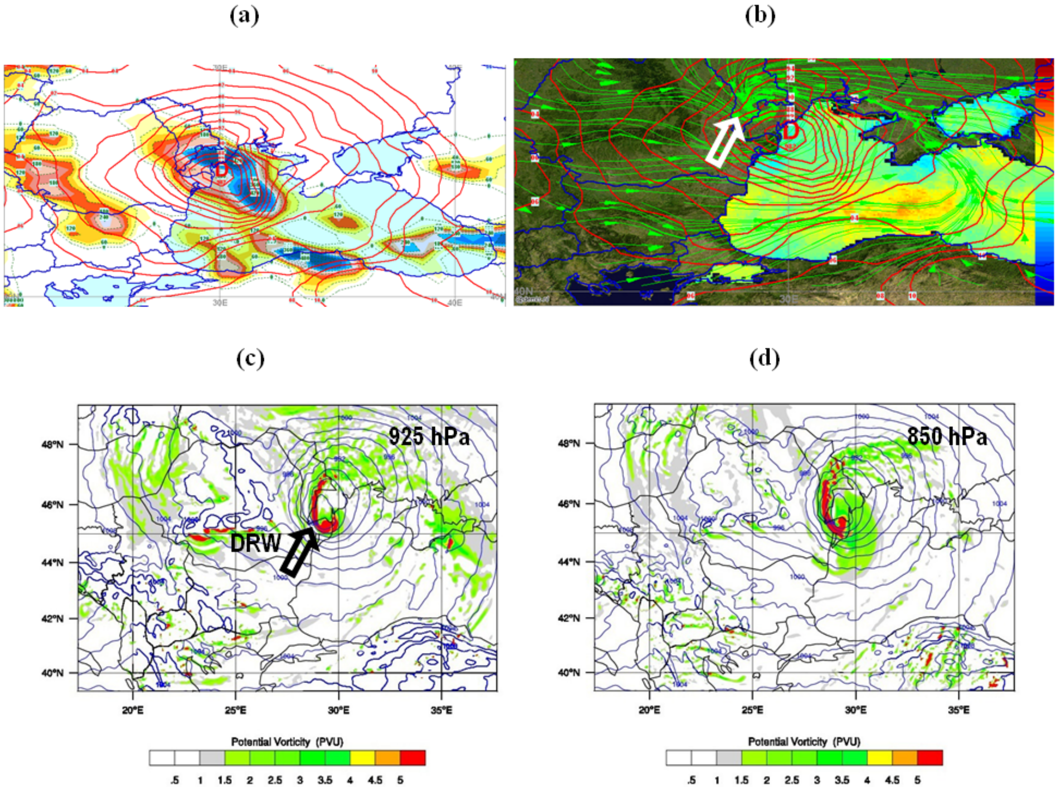

Figure 15. Observation analysis of mean-sea-level-pressure (red solid lines at 2 hPa intervals), of the surface moisture convergence (shaded colour contours, in $g\,kg^{-1}\,s^{-1}$), of the surface streamlines wind (green lines), and of the SST anomaly (shaded contours in °C) at 03:00 UTC 3 December 2012. Model analysis of the potential vorticity anomaly (shaded colour contours) at 03:00 UTC 3 December 2012. "D" is similar with "L" from low pressure.

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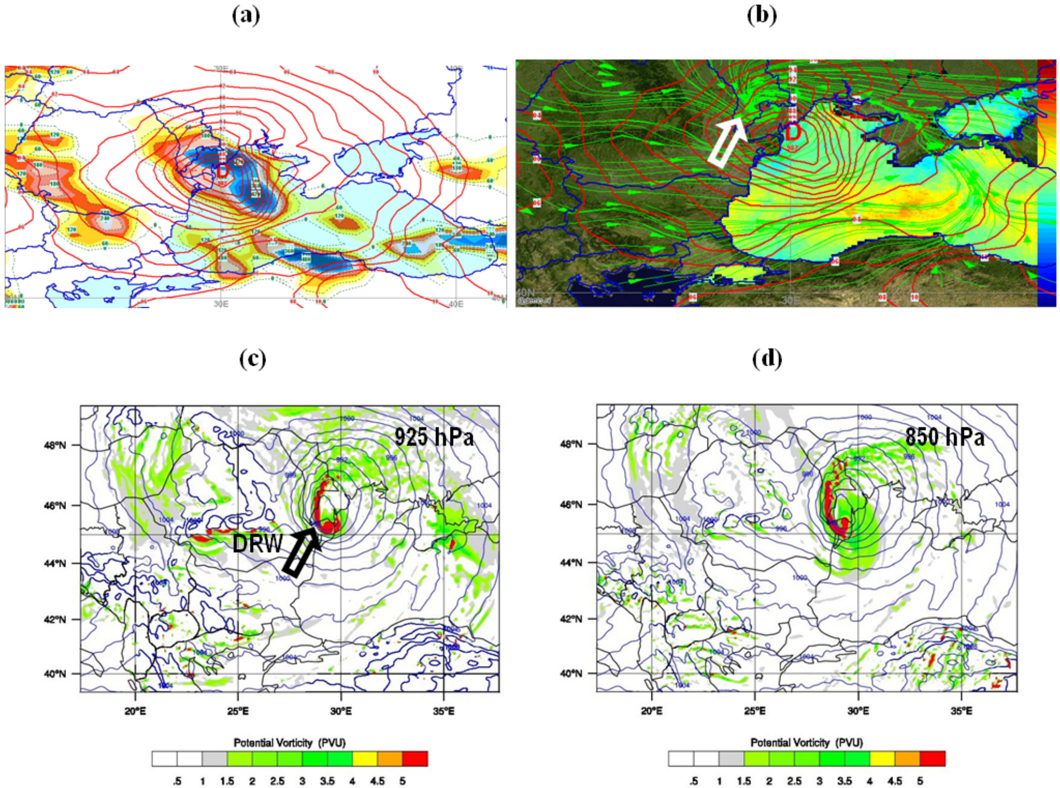

Figure 16. Observation analysis of the mean-sea-level-pressure (red solid lines at 2 hPa intervals), of the surface moisture convergence (shaded colour contours, in $\mathrm{g\,kg^{-1}\,s^{-1}}$), of the surface streamlines wind (green lines), and of the SST anomaly (shaded contours in °C) at 03:00 UTC 3 December 2012. Model analysis of the potential vorticity anomaly (shaded colour contours) at 06:00 UTC 3 December 2012.

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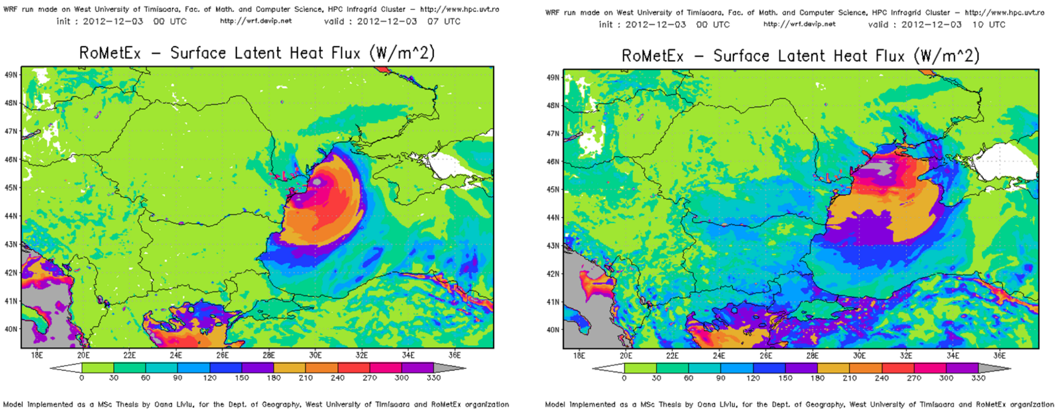

Figure 17. Surface latent heat flux on 3 December at 07:00 UTC (left) and 10:00 UTC (right).

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