The DOI for this manuscript is doi: 10.1175/JHM-D-12-083.1

The final published version of this manuscript will replace the preliminary version at the above DOI once it is available.

If you would like to cite this EOR in a separate work, please use the following full citation:

Rebora, N., L. Molini, E. Casella, A. Comellas, E. Fiori, F. Pignone, F. Siccardi, F. Silvestro, S. Tanelli, and A. Parodi, 2013: Extreme rainfall in the Mediterranean: what can we learn from observations?. J. Hydrometeor. doi:10.1175/JHM-D-12-083.1, in press.

Extreme rainfall in the Mediterranean: what can we learn from observations?

Rebora, N.[(1)], Molini, L.[(1)], Casella, E.[(1),(3)], Comellas, A.[(1),(3)], Fiori, E.[(1),(3)], Pignone, F.[(1),(3)], Siccardi, F. [(1),(3)], Silvestro, F. [(1)], Tanelli., S. [(2)], and Parodi, A. [(1)]

(1) CIMA Research Foundation, Savona, Italy
(2) Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California, US
(3) University of Genoa, Italy

Corresponding author address: Nicola Rebora , CIMA Research Foundation, via Magliotto 2, 17100., Savona, Italy.
E-mail: nicola.rebora@cimafoundation.org

Abstract

Flash-floods induced by extreme rainfall events represent one of the most life-threatening phenomena in the Mediterranean. While their catastrophic ground effects are well documented by post-event surveys, the extreme rainfall events that generate them are still difficult to observe properly.

Being able to collect observations on such events will help scientists in better understand and model these phenomena. The recent flash-floods that hit Liguria Region (Italy) between the end of October and the beginning of November 2011 give us the opportunity to use the measurements available from a large number of sensors, both ground based and spaceborne, to characterize these events.

In this paper we analyze the role of the key ingredients (e.g. unstable air masses, moist low-level jets, steep orography and a slow evolving synoptic pattern) for severe rainfall processes on complex orography. For the two Ligurian events, this role has been analized through the available observations (e.g. Meteosat Second Generation - MSG, Moderate Resolution Imaging Spectroradiometer, the Italian Radar Network mosaic and the Italian Raingauge Network observations).

We then address the possible role of the sea-atmosphere interactions and propose a characterization of these events in terms of their predictability.

1 Introduction

The Mediterranean coastal cities, both on southern and northern sides, are used to flood and flash-floods. The Mediterranean Sea acts as a large heat and moisture reservoir and source from which convective and baroclinic atmospheric systems get part of their energy. The interaction between convective processes originating on the warm sea and sudden orographic lifting very close to the coast produces heavy rainfalls. It often happens that the rain accumulated in one hour accounts for the entire monthly average for that location, and the rain accumulated in one day can account for the entire yearly average (Altinbilek et al. 1997). The morphology of the Mediterranean basin with numerous small and steep river catchments can turn the intense precipitation into severe devastating flash-floods and floods. Large scale environment propitious to heavy precipitation is relatively well known. However progress has to be made on the understanding of the mechanisms that govern the precise location of the precipitation system as well as of those that can occasionally produce uncommon amounts of precipitation (Ricard et al. 2012).

To mention a few of these disastrous events we should recall, for example, the flooding of Genoa city - northern Italy- in 1970 (Roth 1996, Siccardi 1996), the Vaison-la-Romaine – southern France – in 1992 (Massacand et al. 1998 and Ducrocq et al. 2008), the Izmir case - west Turkey- in 1995 (Komoscu et al. 1998), and the most catastrophic flash flood of Algiers in 2001. Each event hit very small-size catchments (10-50 km^2), leaving unaffected nearby basins, thus exhibiting a very fine-grained structure of the rainfall precipitation field. They produced many casualties: in particular the last one produced a very large number of victims, on the order of seven hundred, in the Bab el Oued borough of Algiers. The spatio-temporal evolution of the Algiers event was discussed by a number of papers (Argence et al. 2008, Brancovic et al. 2008 and Tripoli et al. 2005): the apparent predictability of the Algiers event suggested a controlling role by large-scale forcing. In fact the European Centre for Medium-Range Weather Forecast model (IFS model version 23r4, with a horizontal spacing of 1.8° - about 200 km resolution – and 40 sigma levels in the vertical) detected the structure of the cyclogenesis of the event. Furthermore the Office National de la Meteorologie of Algeria issued a flood forecast as early as 5 November 2001. The flooding took place between 9 and 10 November: it was a flash flood phenomenon on a very small creek (about 15 km^2) flowing trough the Kasbah city center. In the same period the total rain depth observed at a raingauge 18 km away was negligible. The closer examination introduced numerically by Tripoli et al. (2005) revealed that significant mesoscale development led to the actual weather pattern over the city. Wind Induced Surface Heat Exchange (WISHE, Emanuel 1994) over the warm waters north of Tunisia and Libya raised the Planetary Boundary Layer (PBL) humidity and temperature until matched potential temperature values and therefore the resulting reduction of the Level of Free Convection (LFC) triggered deep moist convective processes. The rainfall amount was estimated up to 250mm in 48 h.

The characteristics of the events that hit the small catchments of Liguria in October and November 2011 seem very similar to the historical ones mentioned above, in terms of dynamics and thermodynamics forcings, as well as from a hydrological impacts standpoint. The difference is that for the recent Liguria events the rainfall measurements at the surface were very dense, and meteorological radar and satellite observations were available as well, whilst little more than numerical modeling results could be used to explain the fine-grained structure of the rainfall field of the previously mentioned historical events. This is the reason why we devoted this paper to the description of the available observations of the recent Liguria events: in these cases the physical hypotheses about the development of the events can be validated, at least partially, based on the available observations.

The first flash-flood took place on 25 October, hereinafter we will refer to OCT25 to indicate this event. An anomalous intense rainstorm ripped through the region and inflicted serious damage on the Cinque Terre coastal towns of Monterosso and Vernazza, on eastern Liguria complex orography area (Figure 1, lower right). The Brugnato raingauge station, in the center of the event (10 km from the coast over a 500 m hill) registered up to 470 mm of rain in 6 hours – a third of the average annual rainfall, with a peak of 150 mm in one hour. Thirteen people lost their life.

Nine days later, on 4 November, the city of Genoa, the capital of the Liguria region, located at the meridional edge of the local Appennines range (Figure 1, lower left) was gutted by a torrential rainfall event with up to 450 millimetres (7 km from the coast over a 300 m hill) of rain in 5 hours. Six people were killed. Hereinafter we will refer to NOV4 to indicate this event.

The large-scale features of theses events were well predicted by the Liguria region meteo-hydrological Center (Silvestro et al. 2012).

The goal of this paper is to gain a deeper understanding of these events according to the works of Doswell et al. (1996), Miglietta and Rotunno (2010), Romero et al. (2000), Rotunno and Ferretti (2001), and Yu et al. (2007) all together converging on the these key ingredients for severe flood events on complex orography: i) conditional or potential unstable air masses; ii) moist low-level jets that impinge the first foothills; iii) steep orography which helps to release the conditional instability associated with the low-level jet; and iv) a slow evolving synoptic pattern that slows down the advance of the heavy precipitation system, hence increasing their persistency, or maintains the same favourable environment for heavy precipitation.

Section 2 is devoted to characterize both events at the synoptic scale; to understand the mesoscale forcings through the use of remote sensing observational datasets (Meteosat Second Generation - MSG, Moderate Resolution Imaging Spectroradiometer and Italian Radar Networkmosaic); to analyze the rainfall patterns, and to address the possible role of the sea-atmosphere interactions.

Section 3 focuses on the characterization of the predictability of the two events, based on the approach of Molini et al. (2011). Section 4 presents final discussion and conclusions.

2 October 25th event

2.1 Synoptic scale

The severe weather event that struck eastern Liguria on October 25th was associated to a large depression positioned off Ireland's western shore since the day before. A deep trough extending almost from the arctic circle to northern Africa entered the Mediterranean late on October 24th, whilst a high pressure system (1035 mbar) was between north-eastern Europe and the southern Balkans, with a maximum near the Baltic countries, not allowing the cyclonic structure to move eastwards (Figure 2a, ingredient iv).

Early on October 25th a cold front was evident on the western Mediterranean, as depicted by the airmass RGB (Figure 2b), which is a combination of data from SEVIRI WV6.2, WV7.3, IR9.7 and IR10.8 channels and thus usable day and night (Lensky et al., 2008).

This synoptic configuration stimulated the second ingredient of mid-latitude meteorological extremes, i.e., intensive advection of warm and moist air of sub-tropical origin on the Ligurian sea area (Figure 2c, ingredient ii), inducing two different weather regimes over western and eastern Liguria. Western Liguria was mainly affected by a widespread and stratiform precipitation, while deep moist convection played the main role in eastern Liguria . Thus, the atmospheric scenario saw a southwesterly flow on the storm’s right wing (warm front) channeled between Italy and the Sardinia/Corsica east coasts and moistened by the warm Mediterranean water that began to bring a significant amount of water vapor on eastern Liguria (Figure 2c).

Radiosoundings data shown in Figure 2 (Barcelona, Palma de Mallorca, Nimes, Pratica di Mare, Ajaccio and Milan) provide a quantification of the thermodynamical atmospheric structure on November 4th at 00UTC. All the stations are located in the western Mediterranean, appreciably near to the places where the severe event occurred. Relative humidity values in the lower troposphere were around 70% and temperature gradient around 6K/1000 m, hence confirming the presence of potentially instable air masses (ingredient i) during OCT25.

In the meantime, a vigorous north wind blowing across the central ligurian Apennines prompted by the high pressure on the Adriatic sea (ingredient iv), stuck the moist flow over eastern Liguria for almost the whole day and promoted a local uplift supportive for flash-flood storms: the resulting prominent convergence line (Wang et al. 2000) on the eastern portion of the Genoa sea is depicted by the ASCAT image (Figure 4) by a solid red curve. Coastal wind stations (Table 1) on the line left side showed wind blowing from

N-NW (15-20 km/h), while stations on its right measure wind from S-SE and speed around 15-20 km/h.

2.2 Mesoscale

At the mesoscale, local steep topography (ingredient iii) was the trigger to the onset of an organized and self-regenerating mesoscale convective system (MCS) that poured severe rainfall on Cinque Terre, Brugnato (Vara river) and later on Magra river. Sudden rainfall amounts reached 160mm/h, 350/3h and 450/6h. Several landslides, mudslides and debris flows together with flash floods affected the small catchments in this area.

The C-band, dual polarization radar of Mt. Settepani (located on the Appennine ridge approximately 100 km south-west from the area of interest) allows to gain a deeper understanding of the MCS morphology (Figure 5): the vertical cross-sections clearly show the slantwise organization of the system with its upwind coastal portion mainly associated to warm rain processes (zero isotherm around 4000 m), while the horizontal view depicts the observed V-shaped precipitation system with well-defined boundaries and highly persistent localization, as suggested by the map in Figure 6, which highlights the period of time (between 8:00 UTC and 15:00 UTC) where reflectivity was above a 40 dB threshold.

The V-shaped structure is also evident in the enhanced IR10.8 MSG image on October 25th at 12 UTC (Figure 7a). This product is used in combination with the severe storm RGB (Figure 7b) to refine the overshooting top characteristics by cloud top microphysics: in this case the continental top cloud appears to be thick and composed of small ice particles. This inference is confirmed by another MSG product, Cloud Top Temperature and Height (CTTH, Figure 7c). The CTTH product confirms the slantwise structure of the

V-shaped convective cell, with cloud top heights ranging from 4000-5000 m in the Liguria sea portion of the structure up to 15000 m over the continental part.

2.3 Precipitation analysis

OCT25, mainly affecting Brugnato-Borghetto and Cinque Terre (Figure 8), was observed by the remotely automated weather stations network operated by the National Civil Protection Department. Between 8 UTC and 15 UTC, rainfall accumulation reached 500 mm in the areas that were hit most severely. The radar derived rainfall map shows very pronounced spatial variability of the rainfall processes (Figure 10). As Figure 8 shows, Serò di Zignago and Santa Margherita Vara are two villages located about 4 and 6 km respectiveley from the small town of Brugnato in the Vara Valley: Vara is a left-bank tributary to the Magra river and drains an area slightly bigger than 1700km^2 with a hydrological concentration time (T_c) around 6 hour.

The comparison of the raingauges at these three adjacent locations shows large differences in the hyetographs, confirming the very localized features of the auto-regenerating thunderstorm responsible for this event (Figure 9). There is a factor 3 between Brugnato's raingauge and Serò di Zignago (S.ta Margherita Vara) for d=1hour and d=3 hours. Differences smoothen as longer durations are analyzed, yet the ratio stays over 1.7 (Table 2) even for d=24 hours.

Conversely, rainfall hit with approximately the same strength Monterosso and Vernazza, two coastal villages separated by more than 10 km from Brugnato. The reason has to be found in their position, since they are both aligned along the main direction of the south-westerly moist air jet that fed the thunderstorm triggered by coastal topography, and they experienced a very similar total amount of rainfall as well as Brugnato, as the radar derived rainfall map also suggests (Figure 10).

3 November 4th event

3.1 Synoptic scale

The heavy rainfall episode that provoked the deadly flooding in Genoa was the most powerful outburst within the larger system that affected southern Europe November 3rd to 8th. The extra tropical macro-storm originated from the extension of the 2011 Halloween Nor'easter (Ryan, 2011) that brought early heavy snowfall on central and eastern US in the last October day. This system, coming across the Atlantic Ocean, regained strength by combining with the remnants of tropical storm Rina (October 23rd-28th, Yucatan and Cuba), which enhanced significantly its precipitable water content.

The developing of severe rainfall was the result of the complex combination the aforementioned meteorological ingredients for flash floods. Figure 11a presents the 500-hPa height analysis at 00 UTC on NOV4, just a few hours in advance of the beginning of the precipitation period over Liguria. An upper-level cold low centered north-west of Ireland and extended southbound to the Iberian Peninsula (Figure 11b), resulted in diffluent southwesterly flow over the Ligurian Appenines ridge at 500 hPa, while the main flux at lower altitude was southeasterly. At the same time, a strong pressure ridge centred on Ukraine and the eastern Balkans acted as a block to the eastward motion of the cyclonic structure (ingredient iv).

This synoptic pattern result in the onset of an intense south-south-eastern and very moist flow (Figure 11c, ingredient ii) which triggered, together with the local topography (ingredient iii), a series of severe rainfall episodes beginning on November 3rd late in the afternoon (south-eastern France). In the early morning of November 4th, Genoa's western boroughs were hit by a series of organized self-regenerating thundercells caused by the convergence of the moist flow on a pretty small area (less than 10 km^2). The hypothesized presence of Doswell's ingredient i) is supported by skew-T diagrams of six radiosonde sounding stations (Barcelona, Palma de Mallorca, Nimes, Pratica di Mare, Ajaccio and Milan; Figure 11) located under or near the frontal system at 00 UTC 4 November 2011: relative humidity values are around 70-75% in the lower troposphere, and temperature gradient around 6 K/1000 m.

3.2 Mesoscale

As in the case of the OCT25, also NOV4 was associated at the mesoscale with a V-shaped, isolated and self-regenerating convective cell triggered in the Gulf of Genoa during the night of November 4th (1-2UTC). The cell was again produced by the interaction of cold air coming from north-northwest in the central-western part of the Gulf of Genoa, with warm and moist air coming from southeast into the same region, resulting again into a mechanism of cold pool-shear interaction (Moncrieff and Changai, 1999), driven by local convergence at low-level-flow separation lines (Wang et al., 2000), well depicted by the ASCAT image (Figure 13). As in OCT25, coastal wind stations on the left side of the convergence line showed wind blowing from N-NW (15-20 km/h), while stations on its right measure wind from S-SE and speed around 15-20 km/h. The Italian Radar Network observed the structure but unfortunately the closest radar located at Mt. Settepani, in Liguria, was not running due to technical problems. The radar that actually observed the structure is located near Turin (Bric della Croce - ARPA Regione Piemonte), more than 100 km from the center of the storm. The low quality of the observation is mainly due to the long distance combined with attenuation and orographic beam blocking. The reflectivity pattern over the city of Genoa suffered strong attenuation, but it is nevertheless possible to quantify its persistence: Figure 14 shows a structure persistence over Genoa city basins (Bisagno and Rio Fereggiano) weaker than that exhibited by the October 25th cell. This cell started wandering along the eastern coast (from 3:00 to 9:00 UTC) of Liguria and finally was stuck over the western portion of Genoa hills (Figure 15a) generating the dramatic flash flood of the Rio Fereggiano. Once again, the very high rainfall depth is associated with a slantwise structure with the cloud top continental portion appearing to be thick, composed of small ice particles (Figure 15b), while the upwind one is dominated by warm rain processes, as for the October 25th event. When compared with the convective structure responsible for the October 25th event, this self-regenerating convective cell appears to be less developed vertically (11000-12000 m) and less coherent (Figure 15c).

3.3 Precipitation analysis

The precipitation analysis of this event relies on Liguria's National Civil Protection Department raingauge network, named OMIRL (Liguria Region Hydro-Meteorological Observatory), and on real-time semi-professional stations, belonging to the LIMET (Liguria Meteorological) association: the total number of sensors is about 200, with an average regional density of about 1/40km^2. The most severe rainfall hit Genoa's mid-eastern part and in particular the borough of Quezzi, which is a densely populated borough built on the left bank of the Bisagno creek, a small catchment that drains a total area of 90 km^2 (Figure 16). One of its inlets, Rio Fereggiano (5 km^2 area), crosses Quezzi and its flood was responsible for 6 casualties. Two raingauges are here considered

(Figure 17): one belonging to LIMET network and located on the Rio Fereggiano, and the other belonging to OMIRL official network, located 2 km away on the Bisagno.

The sensors provide further proof of the localization of the severe rainfall (Figure 17), already discussed in Figure 14: despite their proximity, these two sensors observed quite dissimilar rainfall amounts. Differences are displayed in Table 3. LIMET exceeds OMIRL by almost 30%. The return period of the event evaluated with the OMIRL observations is in the order of 50 years whilst the return period of the event with LIMET observations exceeds 200 years, as computed by means of the TCEV (Two Components Extreme Value Distribution) and for a level of confidence $\alpha = 0.05$ (Boni et al. 2006). Raingauges 5-10 km away observed nearly no rain.

4 October 25th event and November 4th event: sea surface temperature role

While the role of tropical north Atlantic Sea Surface Temperature (SST) in driving tropical storm activity has been discussed and assessed extensively in the literature (Landsea 1996, Trenberth 2005), a similar potential role has not been explored in detail in the case of mid-latitude storms over the Mediterranean area. It is however well understood that a warmer SST increases air-sea surface heat fluxes which in turn moisten and destabilize the marine atmospheric boundary layer, resulting in an increase of the available energy and moisture for atmospheric convection and thus precipitation.

In this context, an SST analysis is undertaken to gain a deeper understanding of the spatio-temporal properties of these events and the possible role of sea-atmosphere interactions in triggering and driving torrential events.

The OCT25 SST Anomaly scenario is shown in Figure 18. The left panel shows the G1SST (Global 1-km Sea Surface Temperature) product (Chao et al., 2009) produced daily by the Jet Propulsion Laboratory Regional Ocean Modeling System (JPL-ROMS) group[1] while the right panel displays the Italian Research Council - Mediterranean Sea Surface Temperature L4 (CNR-MED SST L4) produced and distributed in near-real time, in the framework of the GMES MyOcean[2] project, by the Institute of Atmospheric Sciences and Climate - Satellite Oceanography Group (ISAC-GOS).

Both anomaly products are computed using the CNR daily pentad mean climatology sea surface temperature, which is based on the AVHRR PATHFINDER v5 data set over the 1985-2004 time period (Marullo et al. 2007).

Although the use of these products is limited by the lack of input SST data from microwave sensors when the cloud cover is significant, they are a useful tool for a qualitative description of a very likely SST Anomaly (SSTA) scenario.

Both panels show a positive anomaly of temperature in the central part of the Ligurian sea: certainly the two datasets give different SSTA patterns, that can be attributed to different data fusion techniques adopted (Chao et al. 2009 and Buongiorno Nardelli et al. 2012), and to the fact that for G1SST over the Mediterranean sea the IMAGER/GOES observational data are not available. However for both of them a major anticyclonic eddy structure and several minor structures distributed in the central part of the basin are evident.

Figure 18 also shows a map of SST anomaly overlayed with he footprint of the radar-derived rainfall accumulation map.

The main positive SST anomaly located in the northeastern part of the basin, from which the flash-flood producing storm seems to have originated, broadened both in north-

[1]http://ourocean.jpl.nasa.gov/SST/#
[2]http://www.myocean.eu.org/

southand east-west directions as it approached the coast (Figure 18), and possibly fed the storm according to the WISHE mechanism (see section 3).

Along the same lines, the maps of SST anomaly for NOV4 are shown in Figure 19: a positive temperature anomaly in the central part of the Ligurian basin is evident in both figures with several structures characterized by positive values distributed in the central part of the basin, from which the finger-convection responsible for NOV4 seems to originate. The link between anomaly and rainfall origin is still present, but it appears somewhat weaker than for OCT25. We must recall that the radar of the Italian Radar Network closest to the precipitation field was only partly operational during the first part of this event. For this reason, the rainfall pattern was very likely underestimated and the localization of its starting point is more uncertain than in the previous case.

5 October 25th event and November 4th event: predictability analysis

Mid-latitude severe events affecting Mediterranean regions can be classified into two categories (Molini et al. , 2009): events mainly long-lived (lifetime >12hours) and widespread (area>50x50km^2, hereinafter referred to as T1), and events characterized by smaller space-time extent (hereinafter T2). A quasi-equilibrium environment is a common feature for T1 events, while in general localized and intense storms belong to the T2 group (Molini et al., 2010).

Differences between the two groups are found not only in their spatio-temporal length scales but also on the role that large- or local-scale forcing play on their outbreak, which can be determined by considering theconvective heating time scale τ_{CH}. This timescale provides a measure of the rate at which Convective Available Potential Energy (CAPE) is consumed by convective heating. Usually mid-latitude severe events are triggered in a quasi-equilibrium environment (Emanuel 1994 and 2000). This means that the CAPE growth rate due to large scale forcing almost balances its consumption by local convection: in this case, convective timescales τ_{CH} are typically small compared to timescales of forcing changes, thus large scale forcing determines the statistical properties of convection and the spatio-temporal behavior of the corresponding severe rainfall events, making them more predictable (Done et al. 2006 and Molini et al. 2010). On the contrary a non-equilibrium environment requires heavy rainfall to originate from a weaker synoptic forcing. Therefore in a non-equilibrium case, convection is controlled by local modalities of triggering, e.g. the existence of a strong convective inhibition condition, thus with a low degree of predictability.

Done et al. (2006) describes how to calculate τ_{CH} from raindepths and CAPE, according to the following formula:

$$\tau_c = \frac{CAPE}{\frac{dCAPE}{dt}}$$

with

$$\frac{dCAPE}{dt} = \frac{1}{3600}\frac{i_R L_V g}{c_p T_0 \rho_0}$$

where i_R is the rainfall intensity (mm h^{-1}), L_v the latent heat of vaporization, g the acceleration due to gravity, c_p the specific heat of air at constant pressure and T_0 and ρ_0 reference values of temperature and density, respectively.

Molini et al. (2010) found that quasi-equilibrium environments typically show τ_{CH} smaller than 6 hours, whilst values larger than that characterize non-equilibrium configurations. Done et al. (2006) argue that a typical synoptic time-scale would be a day or more. Overland, changes in forcing associated with the diurnal cycle are likely to be relevant, so a shorter threshold time-scale of around 6 h is adopted (Done et al. 2006, Molini et al. 2010).

Hourly τ_{CH} calculations were carried out using the hourly raindepth provided by the Italian National Civil Protection real-time raingauges network, and 3-hourly CAPE estimates at 0.7° horizontal resolution retrievedfrom the ERA Interim database, the latest ECMWF global atmospheric reanalyses available for the period 1989-present (Simmons et al. 2007). The 3-hourly CAPE field was linearly interpolated in space and time to match the geographical coordinates of the raingauges that actually observed the event and their hourly sampling.

The τ_{CH} values for NOV4 stay small during its most intense phase (from 9 am to 1 pm; Figure 20, lower panel); they indicate this event to be a T1. The increase in the last part is due to the rainfall on the leeside of the Apennines ridge, loosely related to the event that hit the city in the morning. OCT25 is as well a T1 event (Figure 20, upper panel). Heavy rainfall started around 9UTC morning whilst the observed maxima were observed between 13 and 14UTC (at the Cinque Terre and Brugnato stations).

The T1 classification of OCT25 and NOV4 is also supportive of the importance of the SSTA for these events and thus of their feeding according to a WISHE mechanism: since WISHE involves a positive feedback between the circulation and heat fluxes from the sea surface, with stronger circulation giving rise to larger surface fluxes of heat, which are then quickly redistributed aloft by convection, in turn strengthening the circulation. Then this emphasises the role of the surface fluxes as the principal rate-limiting process, while convection serves only to redistribute heat, this corresponding to the quasi-equilibrium vision for OCT25 and NOV4.

6 Discussion and conclusions

OCT25 and NOV4 show similarities from several points of view.

Both are characterized by a pretty short duration (approximately 6 hours in their most intense part) and in both cases the total rainfall amount significantly exceeds the value of multi-centennial return period (Boni et al. 2006).

The large-scale features of the two can be assumed to be analogous: a depressionary system originated on the western Atlantic and broke into the Mediterranean to find a robust block exerted by a stationary high pressure structure located over eastern Europe.

In both events the creation of positive vertical vorticity in the low and mid troposphere by the wind-shear is clear from the synoptic maps (reanalyses from NOAA/NCEP Model corresponding to 12UTC of corresponding days) at different levels shown in Figure 21. The surface wind direction over Liguria on October 25th (November 4th) was from the SSW (S), while at mid-levels it was from the WSW (SW); in either situation and in a similar fashion, therefore, we note the very moist air flux towards land, and how it rotates clock-wise and notably intensifies with height in the low to middle layers of atmosphere.

The effect of such a configuration contributed to the long persistence of auto-regenerating V-shaped heavy rainfall structures over small areas, smaller than 50x50km^2 which in turn were responsible for flash floods that affected small and medium-sized catchments.

Following these considerations, large-scale forcing played a leading role in provoking heavy rains. The consequent quasi-equilibrium configuration is confirmed by the analysis of the convective timescale: in both cases the value of τ_{CH} stays below the threshold of 6 hours for most of the event as the production of CAPE by large-scale processes is nearly balanced by its consumption by convective phenomena, and thus CAPE values stay small. Moreover low values of CAPE were measured by numerous radiosoundings of the nearby stations.

The local factor which, together with the strong south-westerly (south-easterly) circulation, triggered precipitation was represented for the October 25th (November 4th) study case by the steep coastal topography which compelled moist air to rise suddenly and then condensate into rain, i.e. the well-known orographic lifting mechanism that usually causes flash-floods in Italian shoreline towns and in the nearby inland boroughs. Miglietta and Rotunno (2009) developed a conceptual model for large convective orographic rainfall based on three non-dimensional numbers: the ratio of mountain height to the level of free convection h_m/LFC, the slope parameter h_m/a (with a ridge half-width), and the third is the ratio of an advective timescale τ_a =a/U to a convective growth timescale $\tau_c=h_t/(CAPE)^{1/2}$ (the time that convective elements take to grow, covering the tropopause height h_t and producing rain at the surface). For the two Liguria events, the following scales can be estimated: $h_m \approx$ 500 m, LFC ≈ 1000 m (estimated using Lawrence 2005), a ≈ 10000 m, U ≈ 8 m/s (from Advanced Scatterometer, ASCAT, data products), $h_t \approx$ 10000 m (average value for OCT25 and NOV4 from CTTH product), and CAPE ≈ 500 J/kg (from ERA-Interim reanalysis). Consequently, both events respect the pre-requisites for large convective orographic rainfall:

- $\tau_a/ \tau_c \approx 3.0$
- $h_m/LFC \approx 0.5$
- $h_m/a \approx 0.05$

corresponding to a regime where the orographic trigger is significant and the peak is located near the top of the ridge (see figure 2 in Miglietta and Rotunno 2010), as indeed observed for both events.

Another very interesting aspect deals with the measure of sea surface temperature and especially its anomaly with respect to climatological values. In particular, the sea surface positive anomaly is a concomitant factor which possibly contributes to the exceptional severity of the rainfall processes, according to the WISHE mechanism. Furthermore, in both cases, if SSTA patterns and the radar-derived rainfall accumulation map are overlaid, there are considerable similarities: V-shaped precipitation patterns seem to spread out from the higher anomalies sectors. This feature is more evident for the October 25th study case since radar products did not suffer any gap in the timeseries as unfortunately happened during November 4th.

Some studies discuss the effect of SST on torrential Mediterranean rain events (Pastor et al 2001, Lebeaupin et al. 2006). These studies state that SST plays a key role in the recharge of moisture and heat and contributes to increased conditional convective instability. However this fact remains to be verified and further research is needed for fully defining the role of SST in controlling Ligurian intense events. For the two Ligurian events here presented, it is planned to run high resolution numerical models to clarify whether the presence of a positive anomaly of sea surface temperature can be a factor which is significant in the process of triggering and driving Ligurian torrential events.

Future work will be devoted to undertaking a modelling study of the November 4th event to gain a deeper understanding of the physical processes associated with these prototypal Mediterranean storm events.

Acknowledgments.

This work is supported by Italian Civil Protection Department and by Regione Liguria. We acknowledge Regione Liguria and Regione Piemonte for providing us with the data of the regional meteorological observation networks. We acknowledge the Italian Civil Protection Department for providing us with the Italian Radar Network data. We acknowledge the LIMET association for providing us with the data from their meteorological observation network. We acknowledge the Institute of Atmospheric Sciences and Climate - Satellite Oceanography Group (ISAC-GOS) for providing us with the CNR-MED Sea Surface Temperature data. We are very grateful to the meteorologists and the hydrologists of the Meteo-Hydrologic Centre of Liguria Region, for many useful discussions. The portion of work carried out by Simone Tanelli was performed at Jet Propulsion Laboratory, California Institute of Technology, under contract with National Aeronautics and Space Administration, support from the Precipitation Measurement Missions program is gratefully acknowledged. Nicola Rebora and Antonio Parodi would like to acknowledge the support by the FP7 DRIHM (Distributed Research Infrastructure for Hydro-Meteorology, 2011-2015) project (contract number 283568). The authors thanks also Garvin Cummings for the help in revising this paper.

References

Altinbilek D., E. C. Barret, T. Oweis, E. Salameh, and Siccardi F,1997: Rainfall Climatology on the Mediterranean, EU-AVI 080 Project ACROSS – Analyzed Climatology Rainfall Obtained from Satellite and Surface data in the Mediterranean basin. *EC reports*..

Chao, Y., Z. Li, J. D. Farrara, and P. Huang,2009: Blended sea surface temperatures from multiple satellites and in-situ observations for coastal oceans. *J. Atmos. Oceanic Technol.*, **26** (7), 1435-1446, 10.1175/2009JTECHO592.1.

Argence, S., D. Lambert, E. Richard, J.P. Chaboureau, and N. Söhne, 2008: Impact of initial condition uncertainties on the predictability of heavy rainfall in the Mediterranean: a case study. *Quart. J. Roy. Meteor. Soc*.,**134** (636), 1775-1788.

Boni, G., A. Parodi, and R. Rudari, 2006: Extreme rainfall events: learning from rain gauge time series, *Journal of Hydrology*, **327**, 304–314, doi:10.1016/j.jhydrol.2005.11.050.

Branković, Č., B. Matjačić, S.Ivatek-Šahdan, and R. Buizza, 2008: Downscaling of ECMWF Ensemble Forecasts for Cases of Severe Weather: Ensemble Statistics and Cluster Analysis. *Monthly Weather Review*,**136**(9), 3323-3342.

Buongiorno Nardelli B., C. Tronconi, R. Santoleri, 2013: High and Ultra-High resolution processing of satellite Sea Surface Temperature data over the Southern European Seas in the framework of MyOcean project, *Rem. Sens. Env*, **129**, 1-16, doi: 10.1016/j.rse.2012.10.012.

Delrieu, G., V. Ducrocq, E. Gaume, J. Nicol, O. Payrastre, E. Yates, P.-E. Kirstetter, H. Andrieu, P. A. Ayral, C. Bouvier, J. D. Creutin, M. Livet, A. Anquetin, M. Lang, L. Neppel, C. Obled, J. Parent-du-Chatelet, G. M. Saulnier, A. Walpersdorf, and W. Wobrock, 2005: The catastrophic flash-flood event of 8-9 September 2002 in the Gard region, France: a first case study for the Cévennes-Vivarais Mediterranean Hydro-meteorological Observatory. *J. Hydrometeorology*, **6**, 34-52.

Done J.M., G.C. Craig, S.L. Gray, P.A. Clark, and M.E.B. Gray, 2006: Mesoscale simulations of organized convection: importance of convective equilibrium. *Quart. J. Roy. Meteor. Soc*.. **132**, 737–756.

Doswell, C.A., H.E. Brooks, and R.A. Maddox, 1996: Flash Flood Forecasting: An Ingredients-Based Methodology. *Wea. Forecasting*, **11**, 560–581. doi: http://dx.doi.org/10.1175/1520-0434(1996)011<0560:FFFAIB>2.0.CO;2.

Ducrocq, V., O. Nuissier, D. Ricard, C. Lebeaupin, and T. Thouvenin, 2008: A numerical study of three catastrophic precipitating events over western mediterranean region (Southern France): Part II: Mesoscale triggering ans stationarity factors. *Quart. J. Roy. Meteor. Soc*., **134** (630), 131–145

Emanuel K.A, 1994.:Atmospheric Convection. Oxford University Press,580 pp.

EmanuelK.A., 2000:. Quasi-equilibrium thinking. General Circulation Model Development. D. A. Randall, Ed. Academic Press, 225–255.

Komuscu, A.U., A. Erkan, and S. Celik, 1998: Analysis of the Meteorological and Terrain Features Leading to the Izmir Flash Flood, *Natural Hazards*,**18**,1-25.

Landsea, C. W., R. A. Pielke Jr., A. M. Mestas-Nunez, and J. A. Knaff, 1999: Atlantic basin hurricanes: Indices of climatic changes. *Climatic Change*,**42**, 89–129.

Lawrence, M. G., 2005: The Relationship between Relative Humidity and the Dewpoint Temperature in Moist Air: A Simple Conversion and Applications. *Bull. Amer. Meteor. Soc.,* **86**, 225–233.

Lebeaupin, C., V. Ducrocq, and H. Giordani,2006: Sensitivity of torrential rain events to the sea surface temperature based on high-resolution numerical forecasts, *J. Geophys. Res.*, **111**, D12110, doi:10.1029/2005JD006541.

Lensky, I. M., and D. Rosenfeld: Clouds-Aerosols-Precipitation Satellite Analysis Tool (CAPSAT). *Atmos. Chem. Phys.,* **8**, 6739–6753, 2008.

Marullo, S., BB. Nardelli, M. Guarracino, and R. Santoleri, 2007: Observing the Mediterranean Sea from space: 21 yearsof Pathfinder-AVHRR sea surface temperatures (1985 to2005): re-analysis and validation. *Ocean Sci*, **3**, 299–310.

Massacand, A. C., H. Wernli, and H. C. Davies,1998: Heavy precipitation on the alpine southside: An upper- level precursor, *Geophys. Res. Lett.*, **25(9)**, 1435–1438, doi:10.1029/98GL50869.

Miglietta, M. M., and R. Rotunno, 2009: Numerical simulations of conditionally unstable flows over a ridge. *J. Atmos. Sci.*, **66**, 1865-1885.

Miglietta, M. M., and R. Rotunno, 2010: Numerical Simulations of Low-CAPE Flows over a Mountain Ridge. *J. Atmos. Sci.*, **67**, 2391–2401 doi: http://dx.doi.org/10.1175/2010JAS3378.1.

Molini, L., A. Parodi, N. Rebora, and G. C. Craig, 2011: Classifying severe rainfall events over Italy by hydrometeorological and dynamical criteria, *Quart. J. Roy. Meteor. Soc.*, **137**, 148–154.

Moncrieff, M. W., and Changhai L., 1999: Convection Initiation by Density Currents: Role of Convergence, Shear, and Dynamical Organization. *Mon. Wea. Rev.*, **127**, 2455–2464. doi: http://dx.doi.org/10.1175/1520-0493(1999)127<2455:CIBDCR>2.0.CO;2.

Pastor, F., M. J. Estrela, D. Peñarrocha, M. M. Millán, 2001: Torrential Rains on the Spanish Mediterranean Coast: Modeling the Effects of the Sea Surface Temperature. *J. Appl. Meteor*., **40**, 1180–1195.

Ricard, D.,V. Ducrocq, and V. Auger, 2012: A Climatology of the Mesoscale Environment Associated with Heavily Precipitating Events over a Northwestern Mediterranean Area. J. Appl. Meteor. Climatol., 51, 468–488.

Ryan, S., 2011:Storm Summary Number 01 for Potential Autumn Mid-Atlantic to Northeast U.S. Major Winter Storm", *NCEP Hydrometeorological Prediction Center*.

Romero, R., C. A. Doswell III, and C. Ramis, 2000: Mesoscale Numerical Study of Two Cases of Long-Lived Quasi-Stationary Convective Systems over Eastern Spain. *Mon. Wea. Rev.*, **128**, 3731-3751.

Roth, G., Barrett, E., Giuli, D., Goddard, J., Llasat, M.C., Minciardi, R., Mugnai, A., Scarchilli, G. and Siccardi, F., 1996: The STORM Project: aims, objectives and organisation. *Remote Sensing Reviews*, **14**, 23-50.

Rotunno, R., and R. Ferretti, 2001:Mechanisms of intense Alpine rainfall. *J. Atmos. Sci.*, **58**, 1732–1749.

Siccardi, F., 1996: Rainstorm hazards and related disasters in the western Mediterranean region. *Remote Sens. Rev*, **14**, 5–21.

Simmons A, Uppala C, Dee D, Kobayashi S., 2007: ERA-Interim: New ECMWF reanalysis products from 1989 onwards, *ECMWF Newsl.*, **110**,25–35.

Trenberth, K., 2005:Uncertainty in hurricanes and global warming, *Science*, **308**, 1753–1754.

Tripoli, G. J., C. M. Medaglia, S. Dietrich, A. Mugnai, G. Panegrossi, S. Pinori, E. A. Smith, 2005: The 9–10 November 2001 Algerian Flood: A Numerical Study. *Bull. Amer. Meteor. Soc.*, **86**, 1229–1235.

Yu, C.-K., D. P. Jorgensen, and F. Roux, 2005: Multiple Precipitation Mechanisms over Mountains Observed by Airborne Doppler Radar during MAP IOP5. *Mon. Wea. Rev.*, **135**, 955–984.

Wang, J.-J., R. M. Rauber, H. T. Ochs III, and R. E. Carbone, 2000: The Effects of the Island of Hawaii on Offshore Rainband Evolution. *Mon. Wea. Rev.*, **128**, 1052-1069.

List of Figures

Figure 15. November 4th2011. From left to right: a) enhanced IR10.8 channel from EUMETRAIN at 12UTC, b), severe storm RGB channel (EUMETRAIN) at 12UTC, c) cloud top temperature and height (CTTH) product (EUMETRAIN) at 12UTC (courtesy of EUMETRAIN, which is an international training project sponsored by EUMETSAT, to support and increase the use of meteorological satellite data).

Figure 16. November 4th2011.Position of two rain gauges located inside the area hit by the storm: OMIRL, on the Bisagno creek, and LIMET on the Rio Fereggiano whose main drainage channel is represented by a thick line (in grey the portion flowing in the culvert). The thin black line shows the Bisagno creek

Figure 17. November 4th 2011. Comparison of two rain gauges located inside the area hit by the event (see Figure 16). The hyetograph represents the hourly accumulations. LIMET is a private weather station located in the district, courtesy of the Ligurian Association of Meteorology - LIMET. OMIRL is an official Weather Station located about 2 km far apart the first one, courtesy of the Liguria Civil Protection Agency (data courtesy of Liguria Civil Protection Agency and LIMET.)

Figure 18. October 25th 2011: Sea Surface Temperature Anomaly by JPL-ROMS (left) and CNR-MED (right) displayed together with 24 hourly rainfall depth halo-regions (above 50 mm).

Figure 19. November 4th 2011: Sea Surface Temperature Anomaly by JPL-ROMS(left) and CNR-MED (right) displayed together with 24 hourly rainfall depth halo-regions (above 50 mm).

Figure 20. Temporal evolution of the convective adjustment time-scale (τ_{CH}) for the event of October 25th (upper panel, local time is UTC+1h) and November 4th (lower panel, local time is UTC+2h).

Figure 21. Reanalyses from NOAA/NCEP Model corresponding to 12UTC of October 25th (left column) and November 4th (right column). The marked low-mid troposphere positive vorticity is clear by comparing the geopotential height at 500hPa, 700hPa, 850hPa and mean sea level (courtesy of NOAA/NCEP).

Tables

Station	Longitude [°E]	Latitude [°]
Cenesi	8.14	44.08
Castellari	8.27	44.15
Genova Centro	8.95	44.41
Cavi	9.38	44.31

Table 1. Geographical coordinates of a sample of the OMIRL coastal wind stations.

Stations/Raindepths	1h	3h	6h	12h	24
Brugnato/Borghetto	143	303	469	493	538
Serò di Zignego	58	133	227	269	303
S.ta Margherita Vara	40	107	168	243	274

Table 2. Rainfall depths accumulated on standard durations observed by the three stations in Vara Valley.

Stations/Raindepths	1h	3h	6h	12h	24
OMIRL	96	209	281	302	N.A.
LIMET	159	307	388	423	556

Table 3. Rainfall depths accumulated on standard durations observed by the two stations nearby the storm center.

Figures

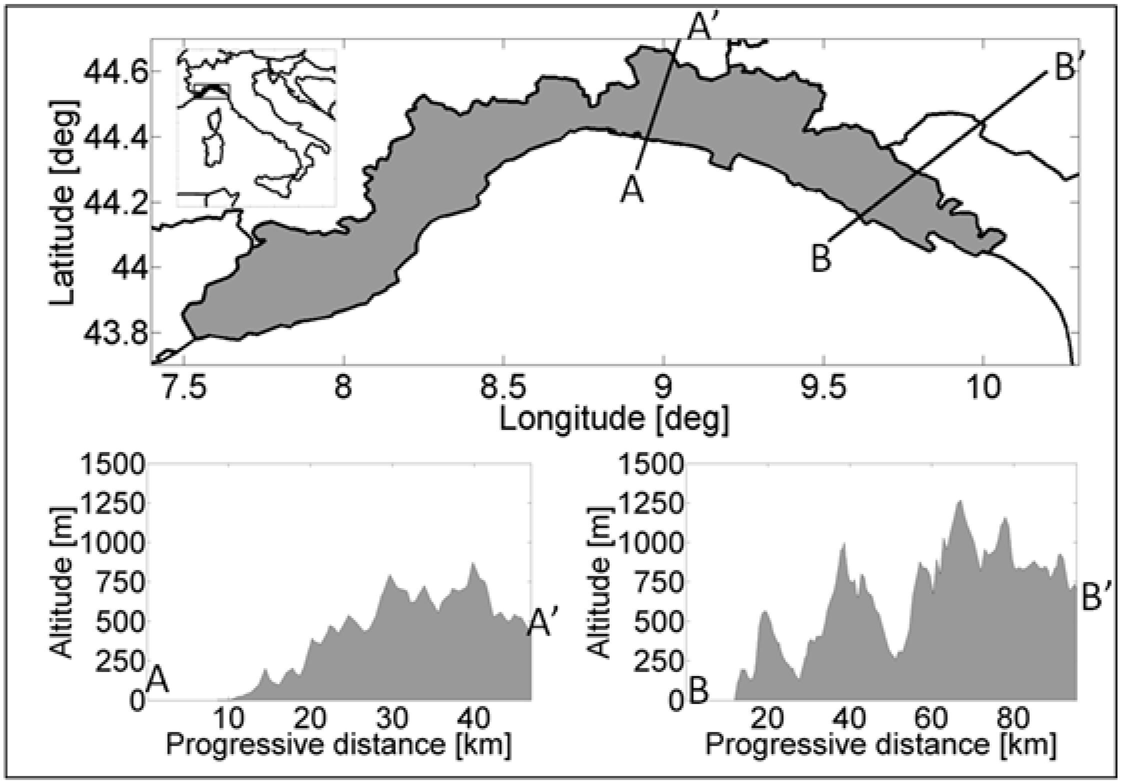

Figure 1. Topography and vertical sections of the affected areas.

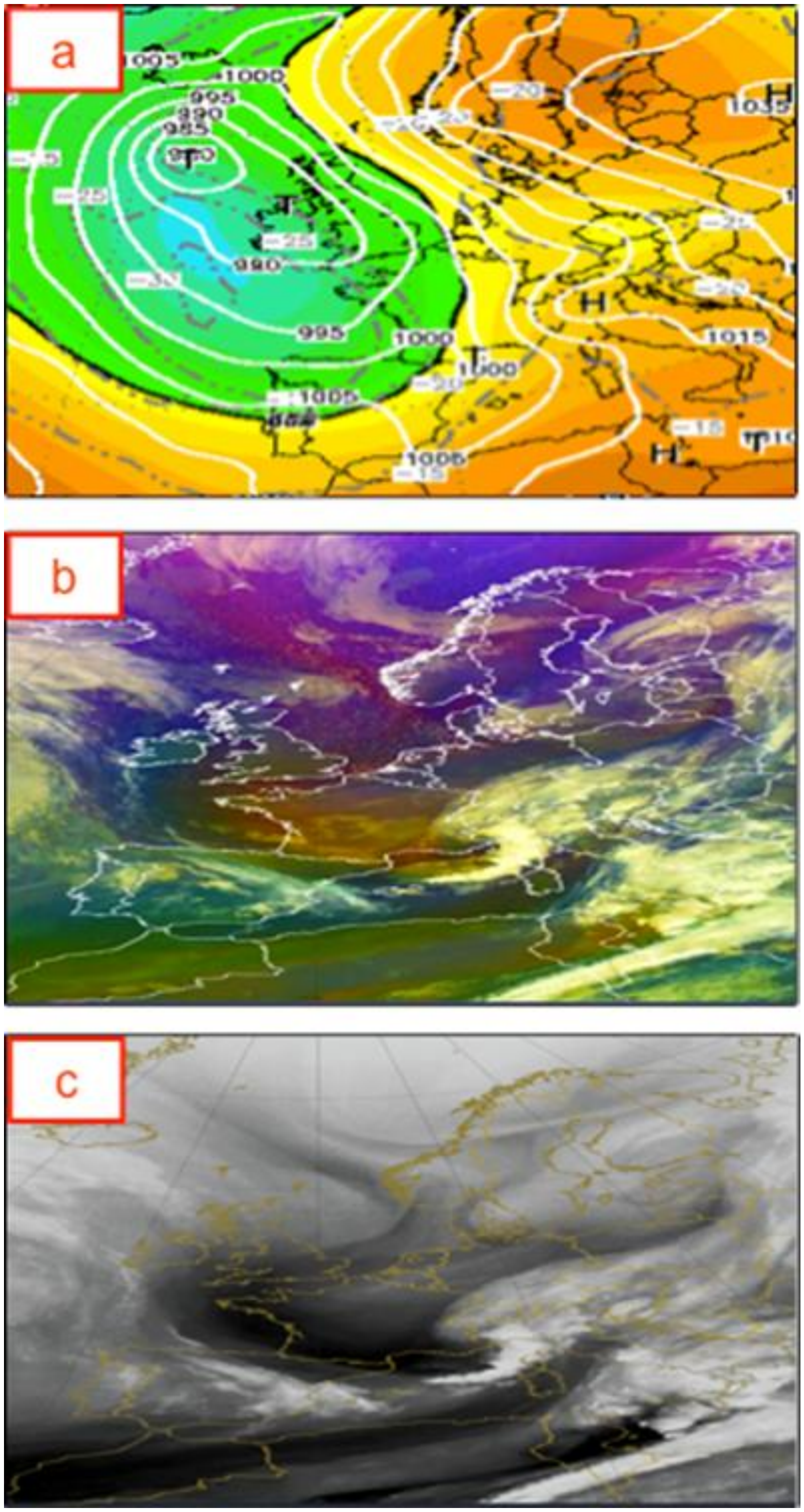

Figure 2. Synoptic situation on October 25th 2011. From top to bottom: a) GFS reanalyses map for the 00UTC geopotential field at 500 hPa , b) airmass RGB (EUMETRAIN) at 00UTC and c) water vapor 6.2 channel (EUMETRAIN) at 00UTC (courtesy of EUMETRAIN, which is an international training project sponsored by EUMETSAT, to support and increase the use of meteorological satellite data).

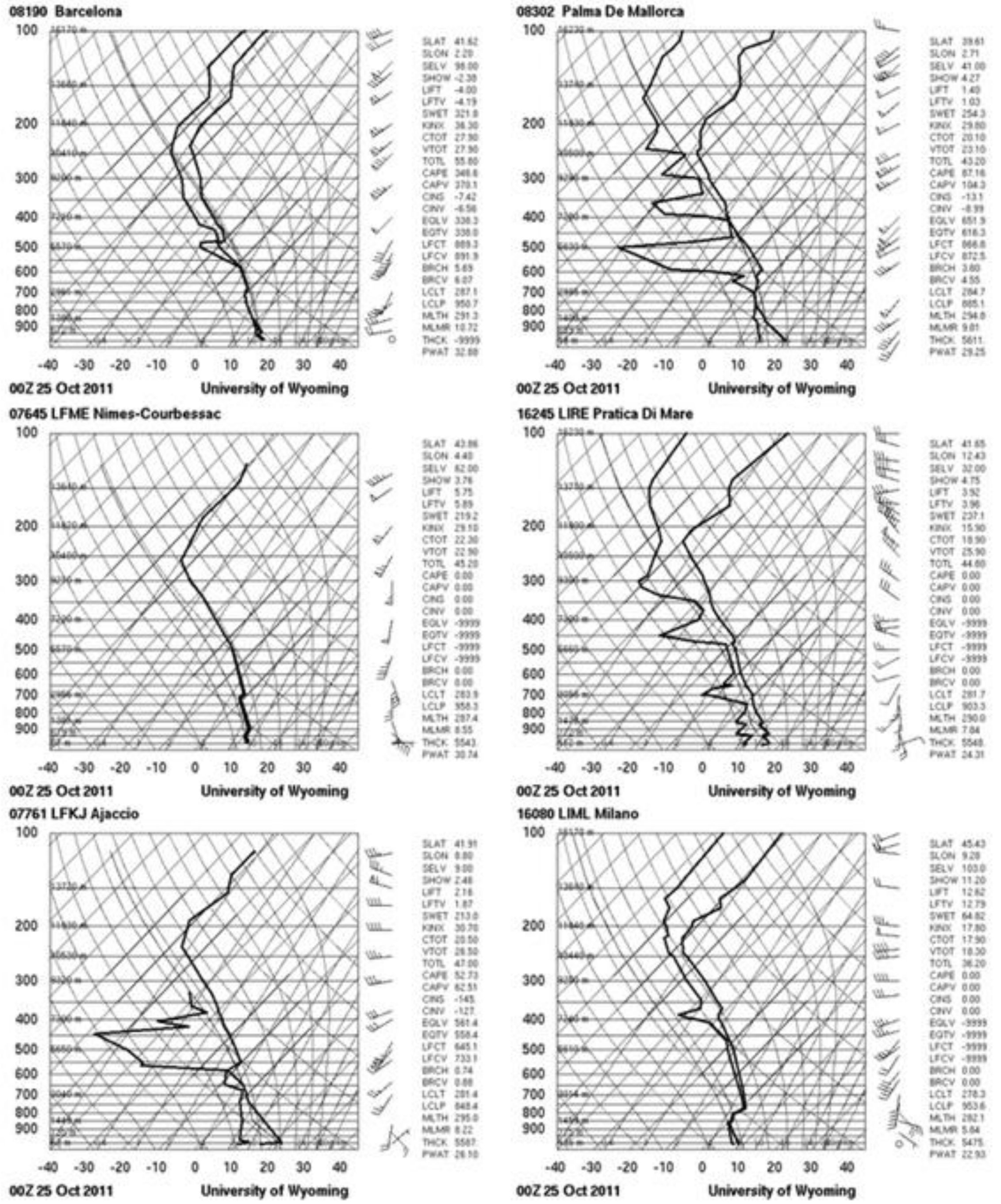

Figure 3. **Skew-T diagrams at 00UTC, 25 October 2011, for Barcelona, Palma de Maiorca, Nimes, Pratica di Mare, Ajaccio, and Milano Linate (**courtesy of University of Wyoming - Department of Atmospheric Science)**.**

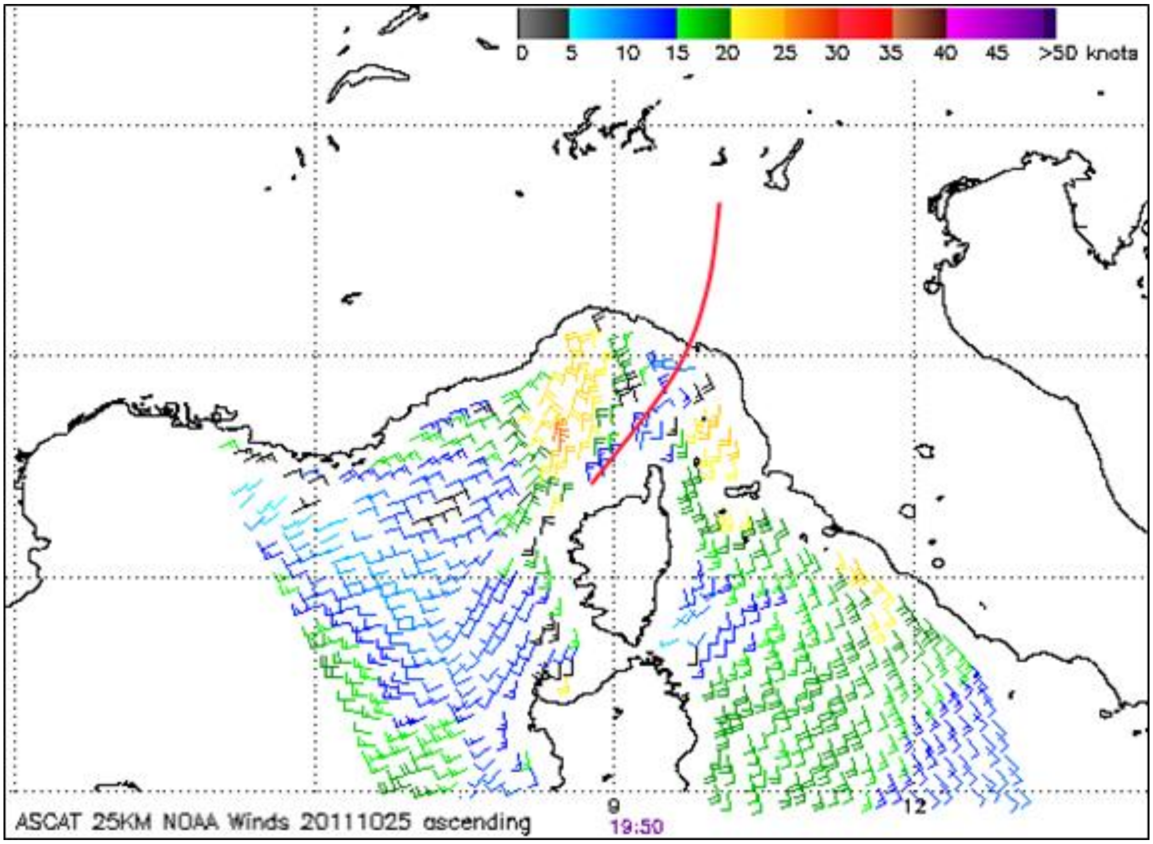

Figure 4:Advanced Scatterometer (ASCAT) ocean surface wind vectors data of 25km resolution, on october 25 th 2011, ascending pass (20 UTC). The red line identifies the low-level convergence zone of the windfield over the ocean.

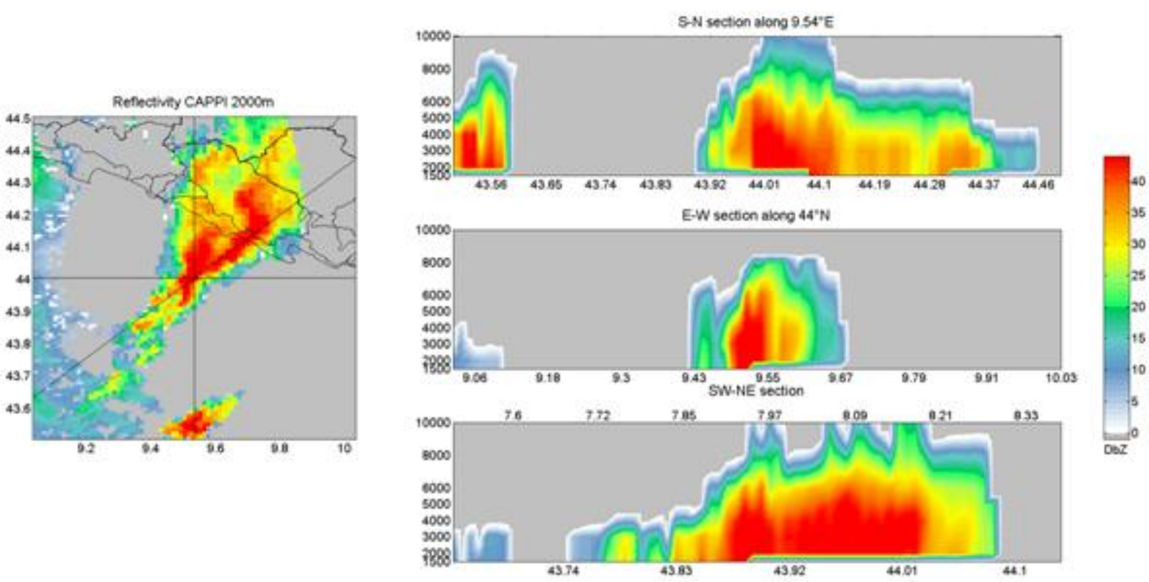

Figure 5. Radar reflectivity patterns of the October 25th 2011 (10:00 UTC) precipitation structure . a) 2000m CAPPI ; b) S-N transect ; c) E-W transect; d) SW-NE transect.

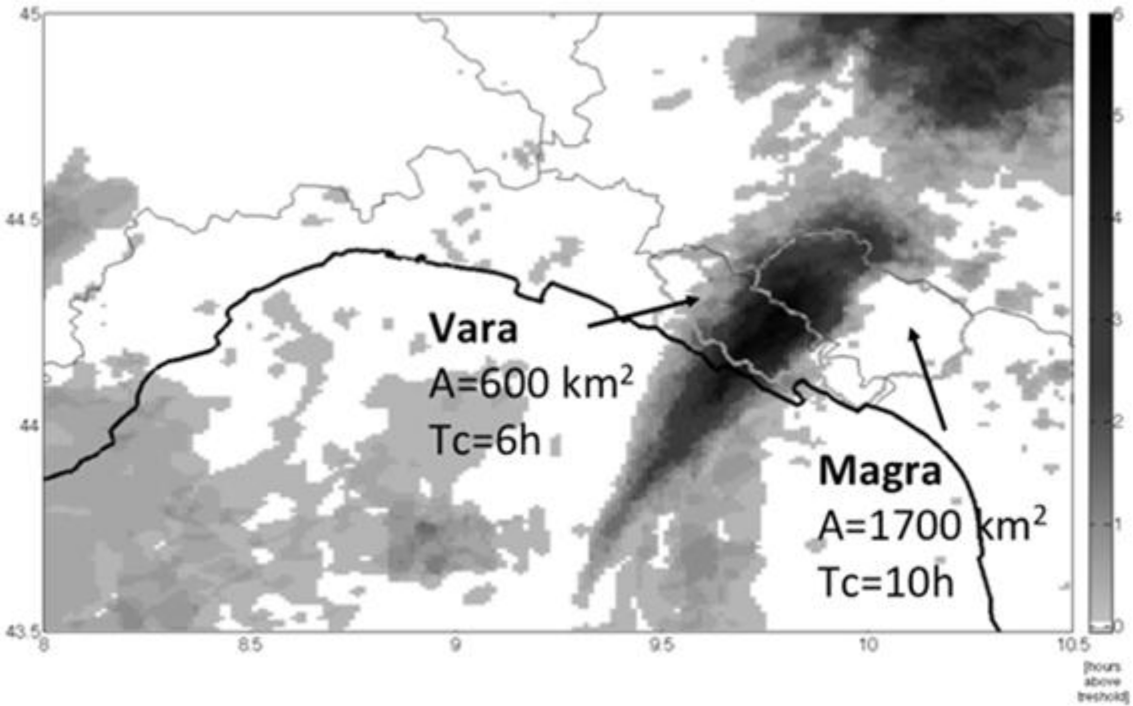

Figure 6. Persistence of the October 25th 2011 structure referenced to 8:00 UTC to indicate the period of time (between 8:00 UTC and 15:00 UTC) where reflectivity was above a 40 dB threshold. The Vara and Magra catchments mainly affected by the severe rainfall phenomena are depicted in the picture, together with the corresponding area and hydrological concentration time Tc.

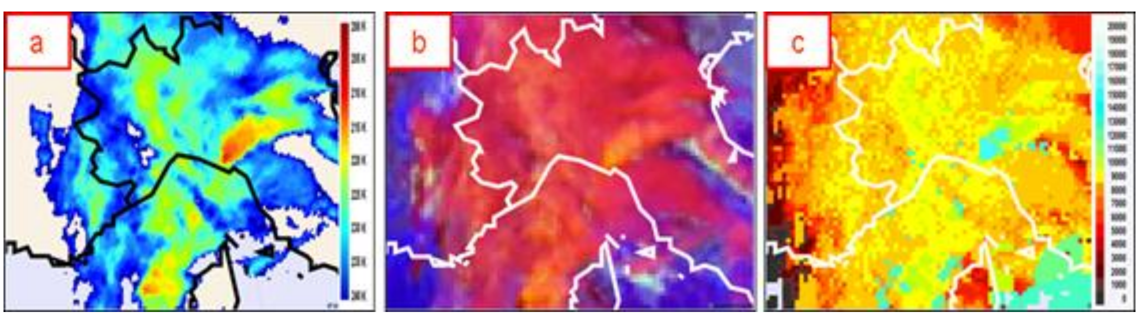

Figure 7. October 25th 2011. From left to right: a) enhanced IR10.8 channel from EUMETRAIN at 12UTC, b) severe storm RGB channel (EUMETRAIN) at 12UTC, c) cloud top temperature and height (CTTH) product (EUMETRAIN) at 12UTC (Courtesy of EUMETRAIN).

Figure 8. October 25th 2011. Geo-location of the three analyzed rain gauges: Brugnato/BorghettoVara, Santa Margherita Vara and Serò di Zignago. In the lower right corner, the port of La Spezia on eastern Liguria.

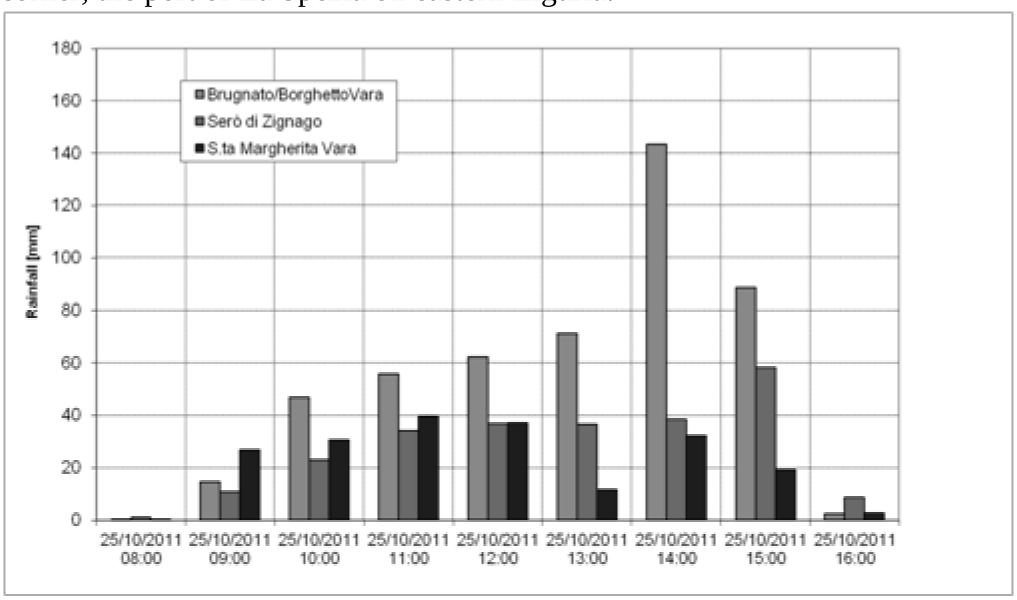

Figure 9. October 25th 2011. Comparison of the three rain gauges located inside the area hit by the storm (see Figure 8). The hyetograph represents the hourly accumulations of the three rain gauges of Brugnato (orange), S.ta Margherita Vara (blue) and Serò di Zignago (purple) in the time windows between 8 and 16UTC. Courtesy of Liguria Civil Protection Agency.

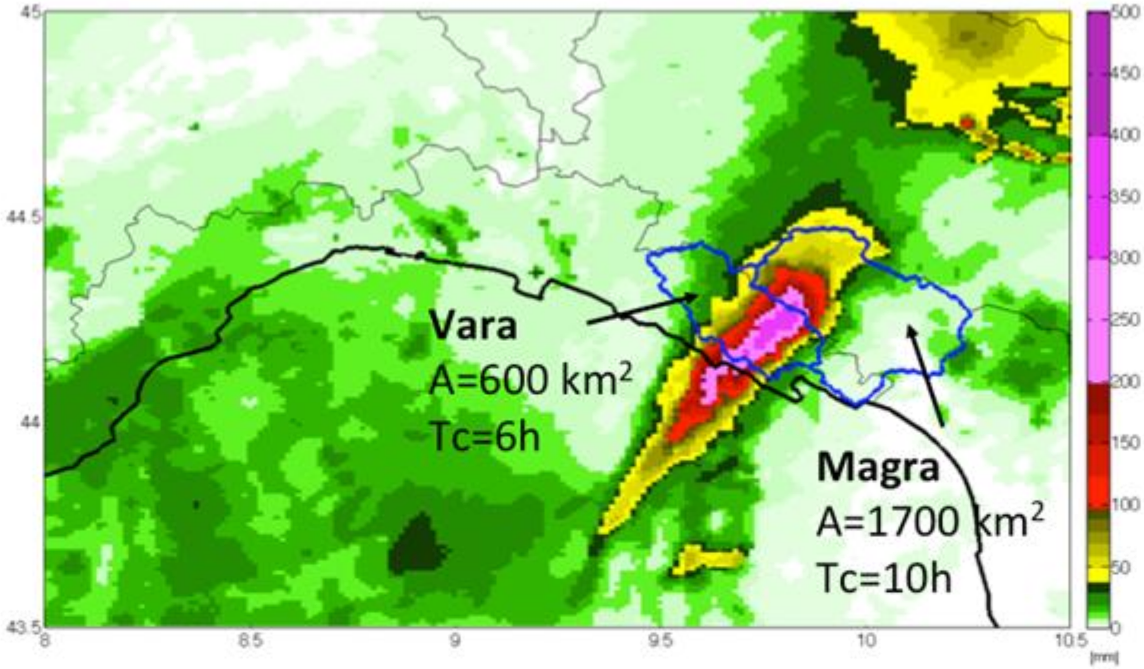

Figure 10. October 25th 2011. Radar-derived rainfall depth from 9:00 UTC to 15:00 UTC (Italian Radar Network mosaic). The Vara and Magra catchments mainly affected by the severe rainfall phenomena are depicted in the picture, together with the corresponding area and hydrological concentration time T_c.

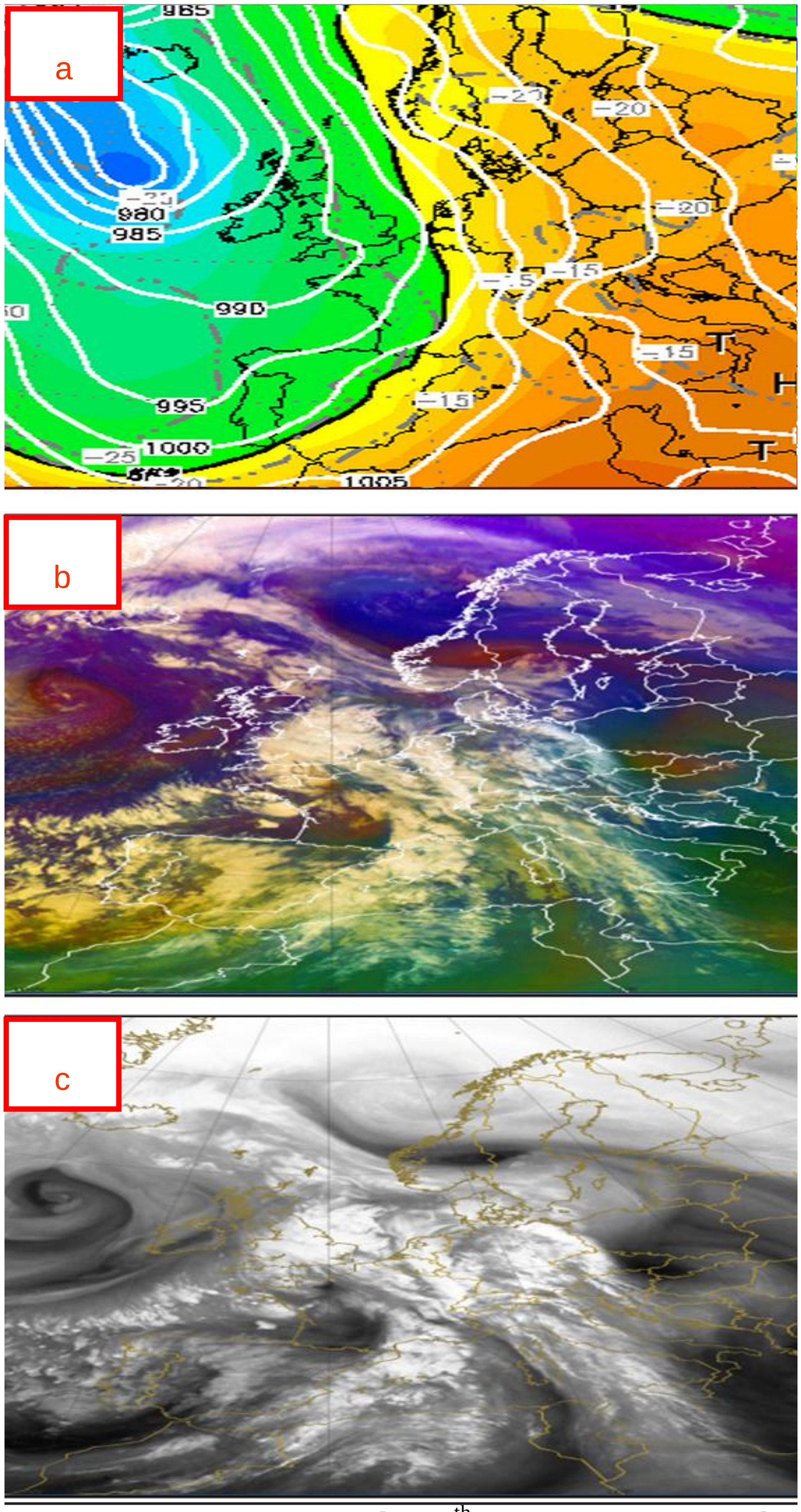

Figure 11. Synoptic situation on November 4th 2011. From top to bottom: a) GFS reanalyses map for the 00UTC geopotential field at 500 hPa , b) airmass RGB (EUMETRAIN) at 00UTC and c) water vapor 6.2 channel (EUMETRAIN) at 00UTC (courtesy of EUMETRAIN).

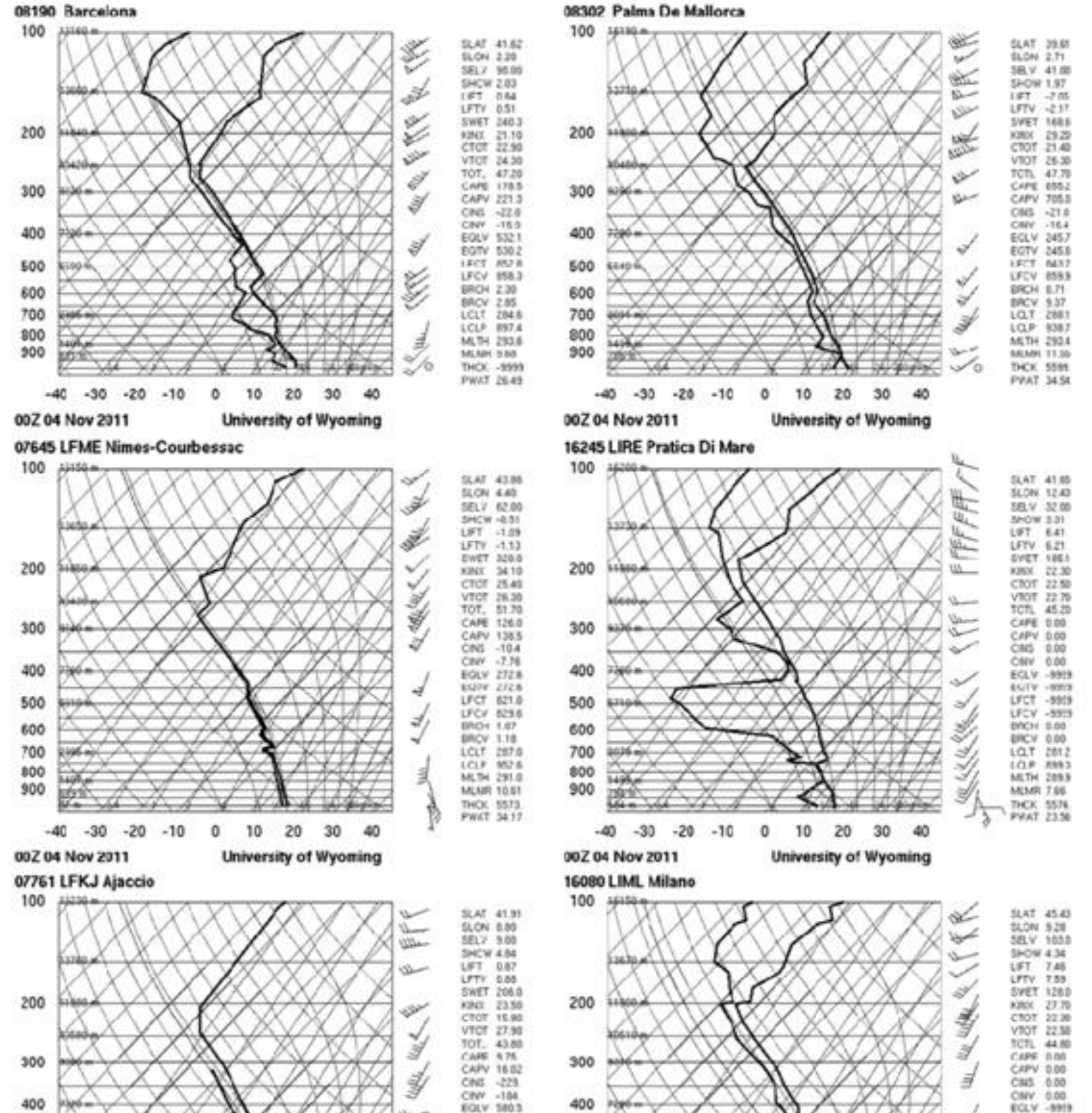

Figure 12. **Skew-T diagrams at 00UTC, 4 November 2011, for Barcelona, Palma de Maiorca, Nimes, Pratica di Mare, Ajaccio, and Milano Linate (c**ourtesy of University of Wyoming Department of Atmospheric Science)**.**

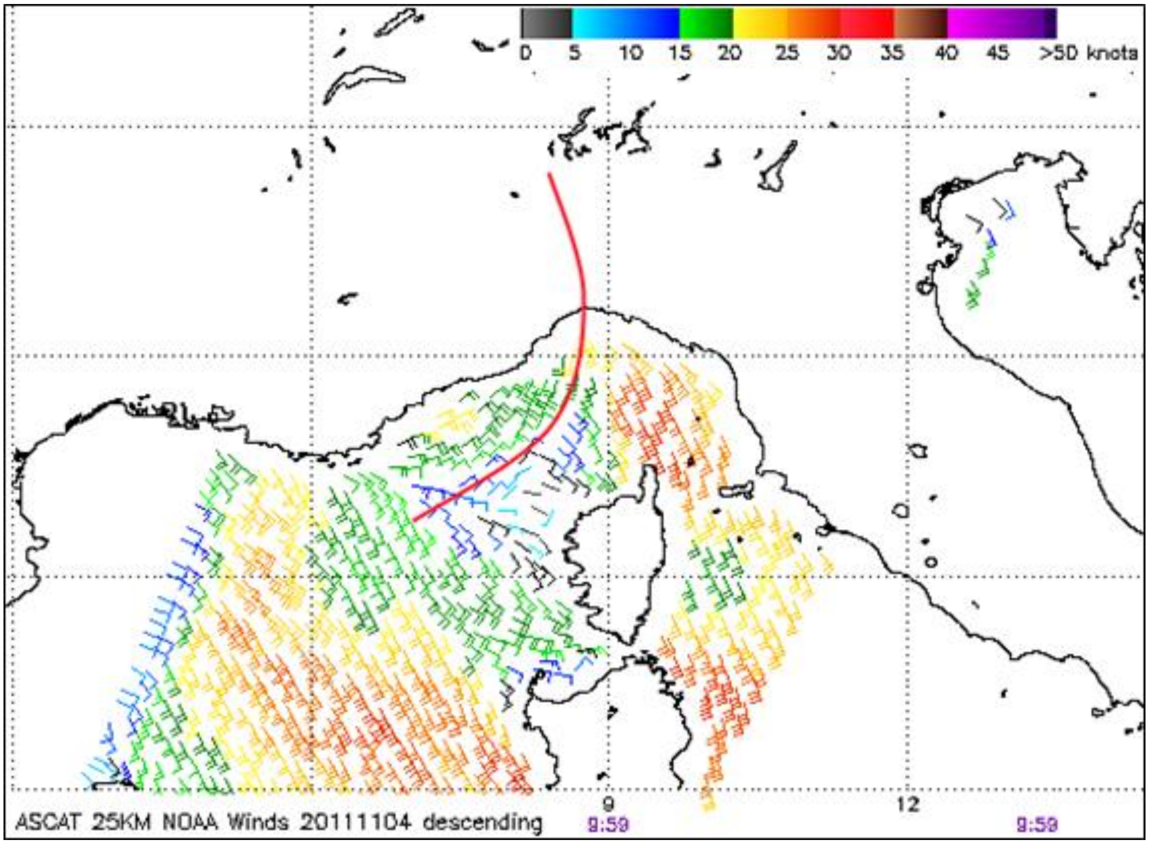

Figure 13:Advanced Scatterometer (ASCAT) ocean surface wind vectors data of 25km resolution, on october 4th 2011, descending pass (10 UTC). The red line identifies the low-level convergence zone of the windfield over the ocean (courtesy of NOAA)

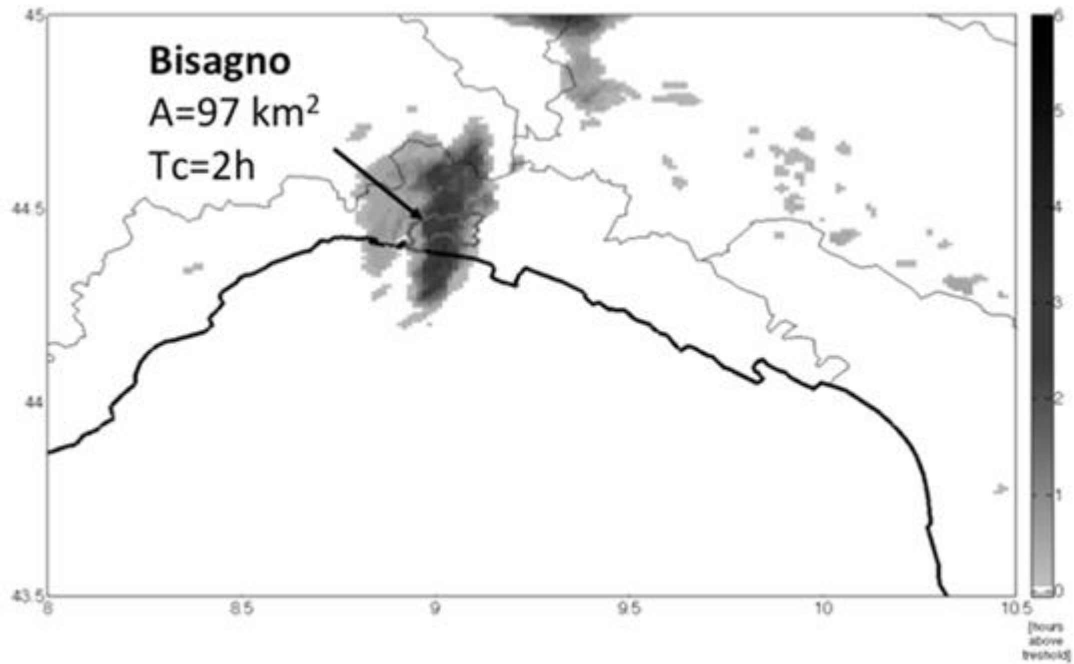

Figure 14. Persistence of the November 4[th]2011 structure referenced to 9:00 UTC to indicate the period of time (between 9:00 UTC and 15:00 UTC) where reflectivity was above a 40 dB threshold. The Bisagno catchment mainly affected by the severe rainfall phenomena is depicted in the picture, together with the corresponding area and hydrological concentration time Tc.

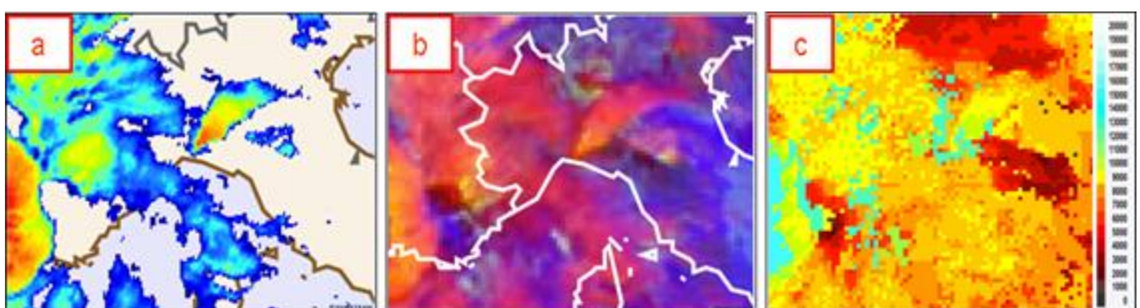

Figure 15. November 4[th]2011. From left to right: a) enhanced IR10.8 channel from EUMETRAIN at 12UTC, b), severe storm RGB channel (EUMETRAIN) at 12UTC, c) cloud top temperature and height (CTTH) product (EUMETRAIN) at 12UTC (courtesy of EUMETRAIN, which is an international training project sponsored by EUMETSAT, to support and increase the use of meteorological satellite data).

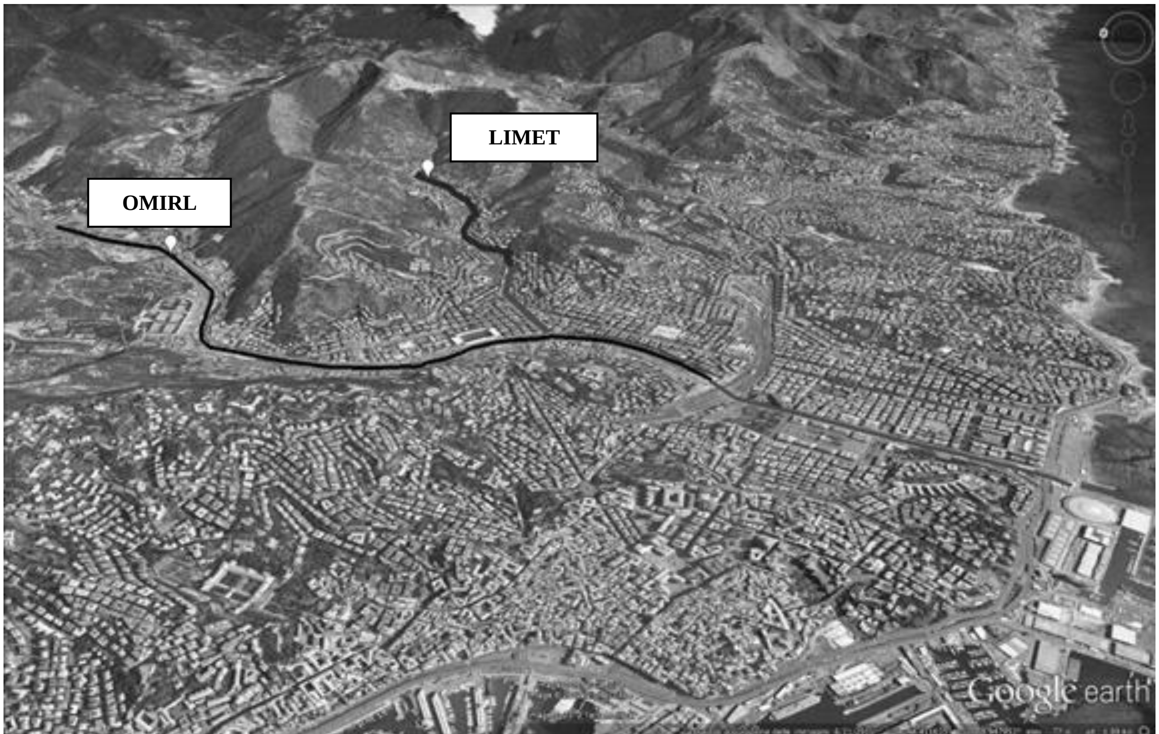

Figure 16. November 4th 2011.Position of two rain gauges located inside the area hit by the storm: OMIRL, on the Bisagno creek, and LIMET on the Rio Fereggiano whose main drainage channel is represented by a thick line (in grey the portion flowing in the culvert). The thin black line shows the Bisagno creek (in grey the portion flowing in the culvert).

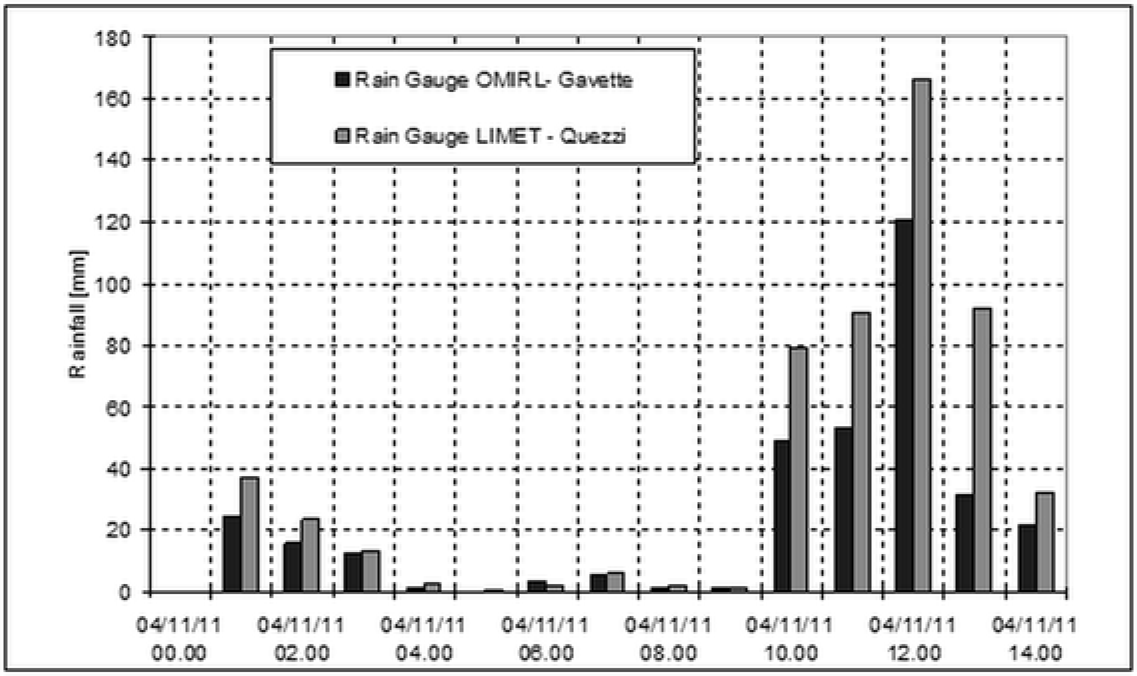

Figure 17. November 4th 2011. Comparison of two rain gauges located inside the area hit by the event (see Figure 16). The hyetograph represents the hourly accumulations. LIMET is a private weather station located in the district, courtesy of the Ligurian Association of Meteorology - LIMET. OMIRL is an official Weather Station located about 2 km far apart the first one, courtesy of the Liguria Civil Protection Agency (data courtesy of Liguria Civil Protection Agency and LIMET.)

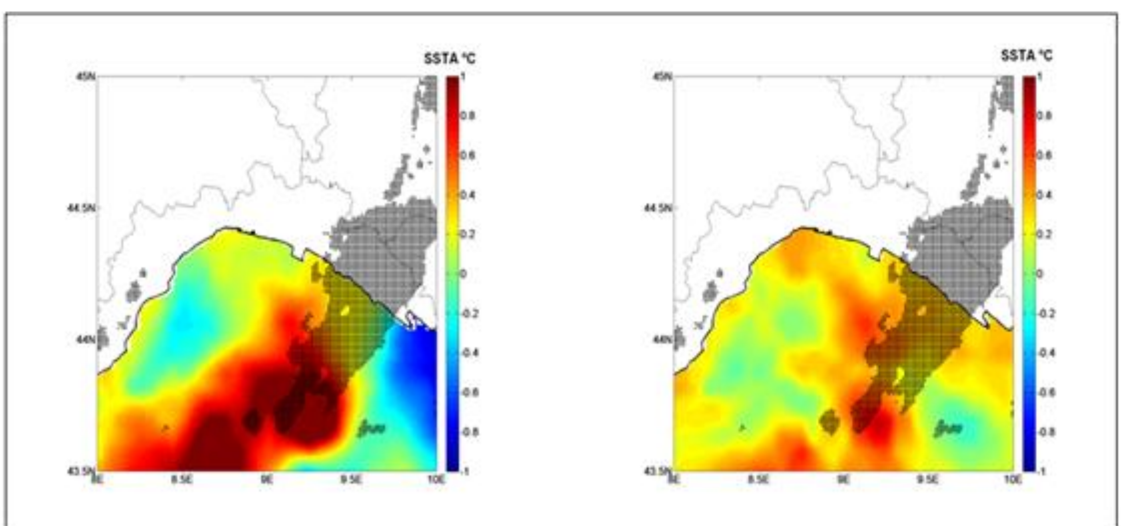

Figure 18. October 25th 2011: Sea Surface Temperature Anomaly by JPL-ROMS (left) and CNR-MED (right) displayed together with 24 hourly rainfall depth halo-regions (above 50 mm).

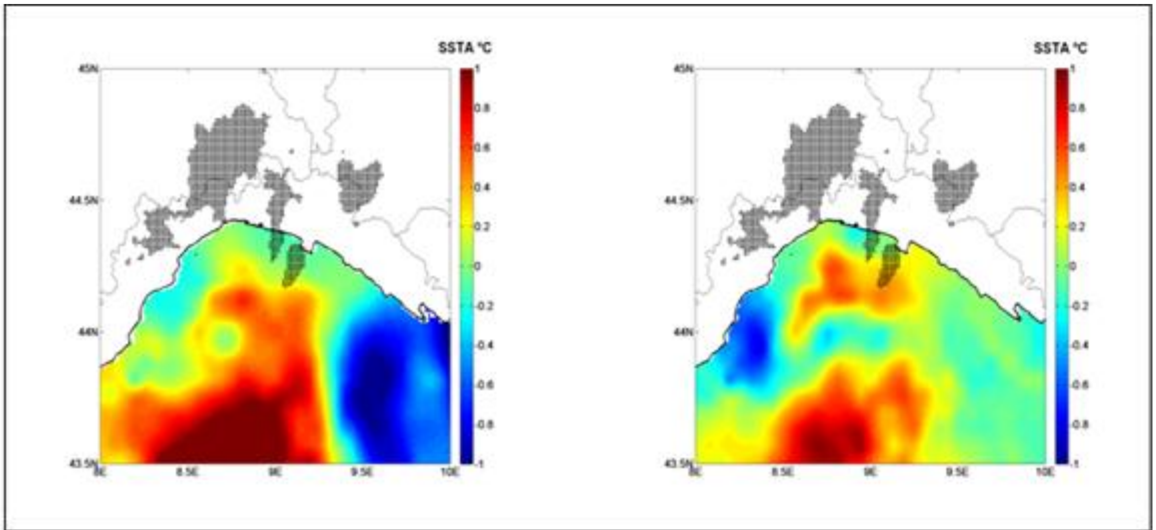

Figure 19. November 4th 2011: Sea Surface Temperature Anomaly by JPL-ROMS(left) and CNR-MED (right) displayed together with 24 hourly rainfall depth halo-regions (above 50 mm).

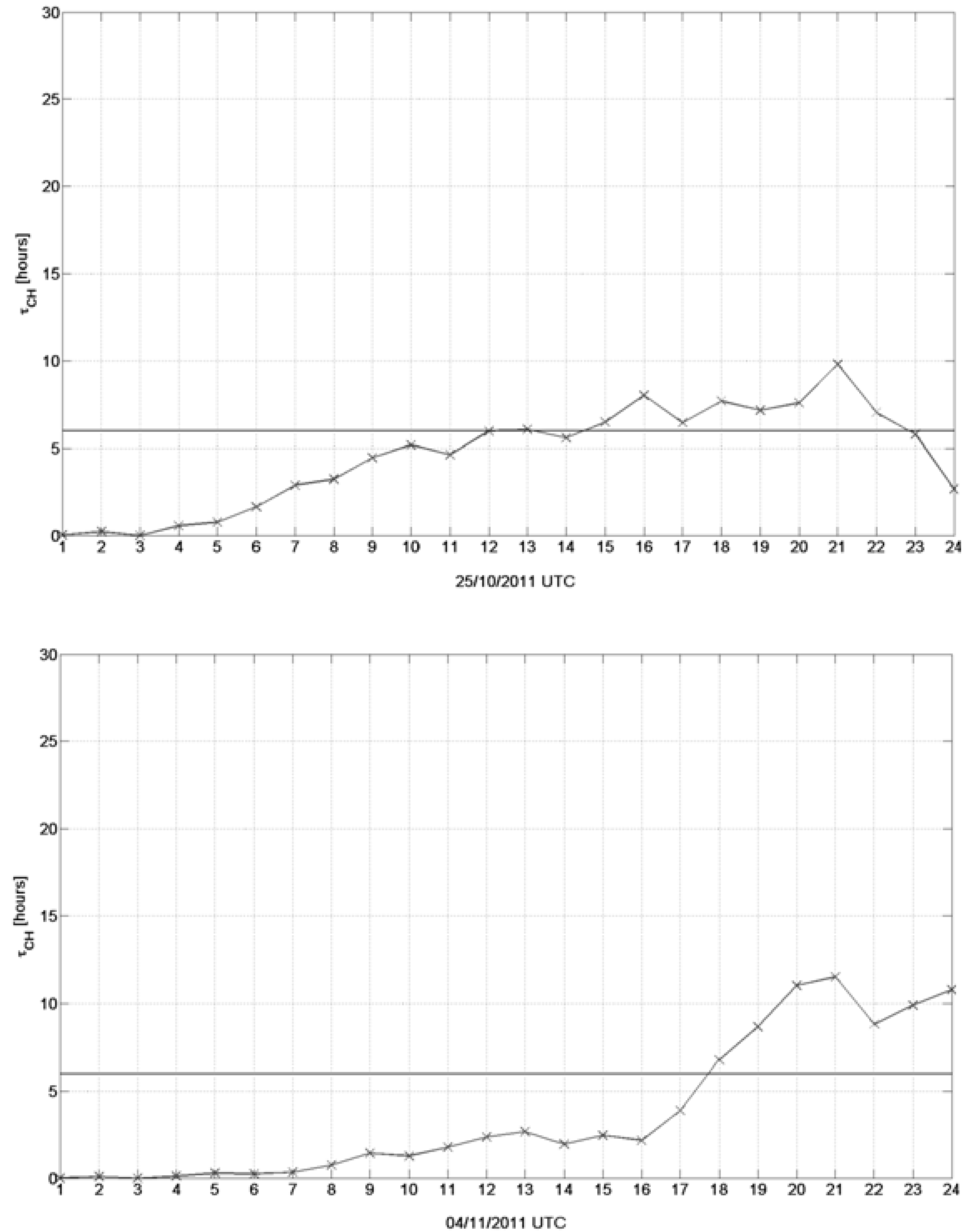

Figure 20. Temporal evolution of the convective adjustment time-scale (τ_{CH}) for the event of October 25th (upper panel, local time is UTC+1h) and November 4th (lower panel, local time is UTC+2h).

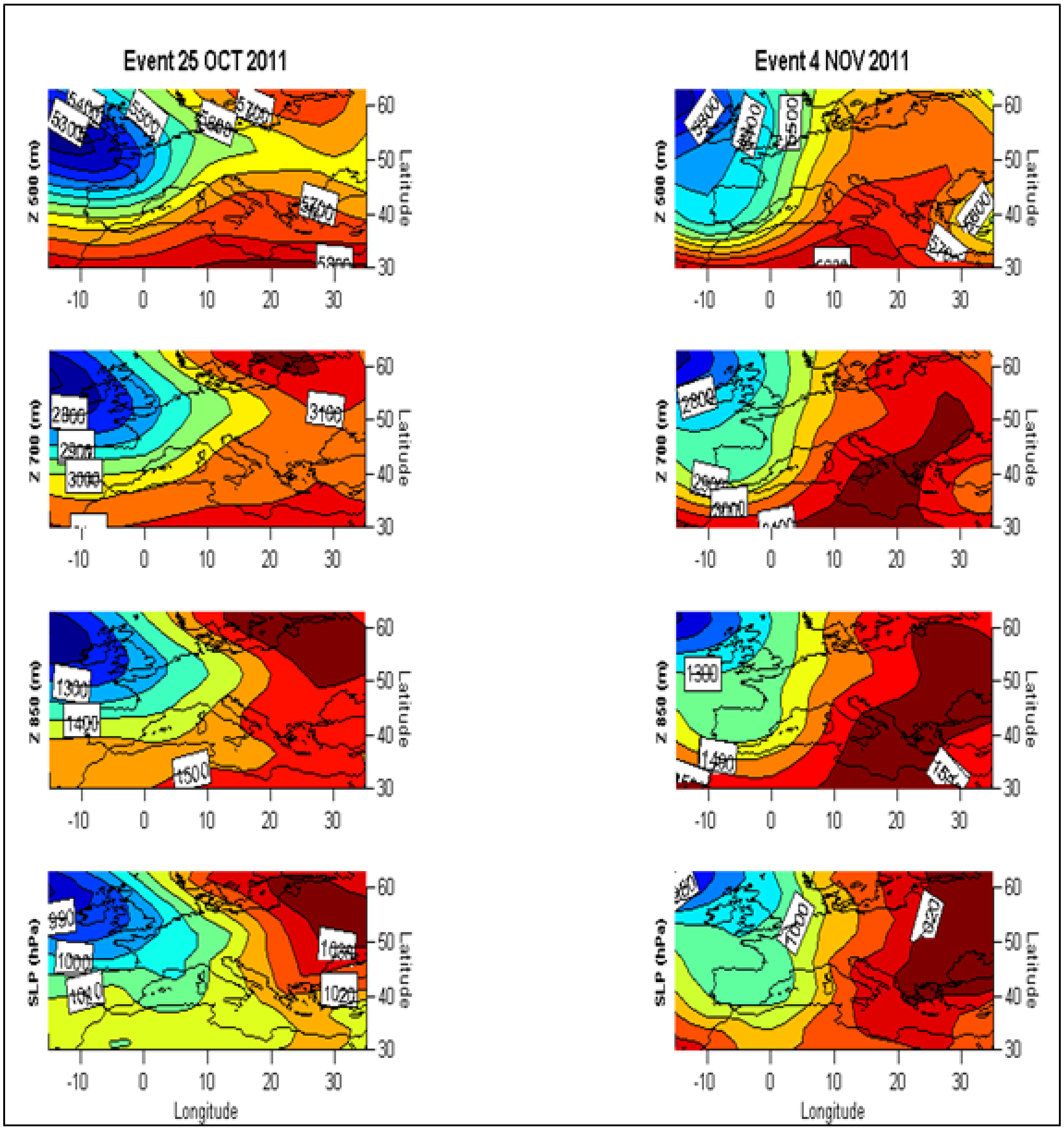

Figure 21. Reanalyses from NOAA/NCEP Model corresponding to 12UTC of October 25th (left column) and November 4th (right column). The marked low-mid troposphere positive vorticity is clear by comparing the geopotential height at 500hPa, 700hPa, 850hPa and mean sea level (courtesy of NOAA/NCEP).