

*Activité 3.1 : Poursuite des études liées à la tempête Alex / Attività
3.1 : Continuazione degli studi relativi alla tempesta Alex*

**Livrable 3.1.1 La cartographie des cumuls de pluie dans la vallée lors de la
tempête Alex**

ANALYSIS OF EXTREME PRECIPITATION DURING THE MEDITERRANEAN EVENT ASSOCIATED WITH THE ALEX STORM IN THE ALPES-MARITIMES: ATMOSPHERIC MECHANISMS AND RESULTING RAINFALL

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KEY WORDS

Heavy Precipitation Events (HPE), Extreme rainfall, Quantitative Precipitation Estimation, Rain-gauge, Radar, Flash flood, Weather model

ABSTRACT

On October 2, 2020, the Alpes-Maritimes was hit by precipitations of tremendous intensity, particularly in the inlands of Nice in the Tinée, Vésubie and Roya valleys, in the foothills of the Mercantour massif.

The fury of this rainfall is the result of a well-known phenomenon of a Mediterranean event: a convective multi-cell cluster with retrograde formation (back-building thunderstorms), which means new cells continuously take place of previous ones. This leads to heavy rainfalls over small areas and long durations, which can trigger flash-floods.

The spatial distribution of rainfall as shown by radar images, suggests several "corridors" crossing the department in a south-west to north-east axis, in accordance with synoptic winds. A meteorological analysis of the atmospheric mechanisms is proposed, supported by the outputs of the AROME model of Météo-France.

In addition, a cartography of the data collected by rain gauges in the area and from different networks is compared to the images obtained by radars (Météo-France products PANTHERE and ANTILOPE). The contribution of non-conventional rain gauges (outside of state networks) in this type of post-crisis feedback can be further evaluated.

We demonstrate that the AROME model has correctly anticipated the phenomenon, which allowed the authorities to emit a weather warning of highest level on the previous day. During the event, as telecommunication networks are broken and prevent transmission of surface reports, the radar images are the only available tool for decision makers. We also show that, in those mountainous lands, correcting radar imagery with rain gauges is essential for correct use of accumulation products, and finally river flows.

1. INTRODUCTION

The Mediterranean area is regularly impacted by High Precipitation Events (HPE), mostly during autumn. Those events can produce dozens to hundredths millimeters of rainfall in a few hours, frequently producing flash floods, inducing numerous casualties and material damage.

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In southern France, one can remember outstanding events like Vaison-La-Romaine on September 22th, 1992, with 300 mm in 24 hours [25], the Aude event on November 12th and 13th 1999, with 551 mm in 24h [29], or the case in the Gard department on September 8th and 9th 2002, with more than 600 mm in 24h [11]. More recently and closer to this case, the event of October 3rd/4th 2015 in the Alpes-Maritimes, with 175 mm in less than 2 hours in the Cannes area, a dense urban area [7, 22]. Those floods are even more remarkable when the topography of the area is abrupt, like the October 2nd, 2020 event in the Alpes-Maritimes (**Figure 1**).

Heavy rainfall in those events are typically a consequence of Mesoscale Convective Systems (MCS) [18], which tend to form in areas with high humidity in the lower atmosphere, while fed with warm air from the Mediterranean [14, 15, 18]. It has been shown that this process can be further accelerated by orographic lift [12–14], and is one of the ingredients that led to this disaster in the Alpes-Maritimes.

Section 2 shows an overview of the rainfall data used, and explanation of the data kept as a reference. Section 3 depicts a meteorological analysis of October 2nd, 2020, and its consequences over the Alpes-Maritimes. Section 4 compares several operational tools that are available before, during and after the event, to evaluate their relative performance. Finally, Section 5 discuss the results and concludes.

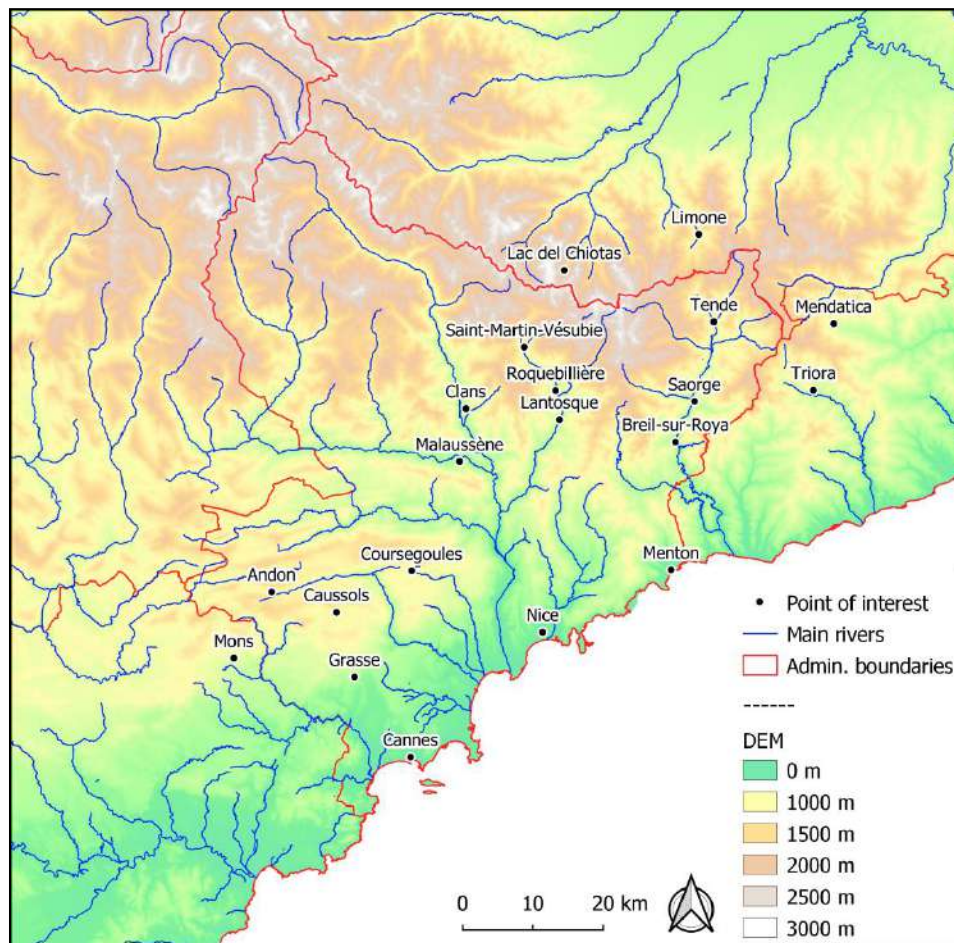


Figure 1: Location map of the main points of interest mentioned in the study
Data from OpenStreetMap, IGN and EU-DEM

2. METEOROLOGICAL DATA

In this section, the numerical weather prediction (NWP) system AROME, weather station observations, radar observations and finally derived products are presented.

2.1 Numerical weather prediction model AROME of Météo-France

AROME-France (AROME-FR) is a deterministic regional Numerical Weather Prediction (NWP) system, used operationally since 2008 by Météo-France, and continuously improved then [24]. The model boundary conditions are initialized from the ARPEGE model, while tri-hourly observation data is assimilated, from surface stations data to radar data, among other sources [4].

It was specifically designed for short-term prediction of hazardous phenomena, like HPE (over the Mediterranean and the Cévennes area). Its mesh allows explicit resolution of convection, unlike higher scale models that make use of implicit resolution by using parametrization.

Its initial resolution was 2.5 kilometers on 60 vertical levels, and, since 2015, was improved to 1.3 km with 90 levels [5]. The assimilation frequency was also increased to hourly data, leading to a significant improvement in the number of observations used [5]. Those improvements, and mostly the finer scale, allows a better predictability of intense convective events [16].

AROME-NWP is another product used in this study. It is a nowcasting model, based on AROME-FR, which is used as a source for its background and lateral boundary conditions. The main differences between those two models are the number of terms (up to +6h for AROME-NWC, +36h to +42h for AROME-FR), and a shorter cut-off time of 15 minutes for AROME-NWC (waiting time for observational data at model initialization). AROME-NWP is also simplified to allow more frequent runs, so that a complete run is available 45 minutes after the analysis time [1].

2.2. Surface observation

Surface data used in this study are mainly measured from automated rain gauges, combined to a few manual rain gauges. A major number of those rain gauges are managed by Météo-France networks (RADOME, SALAMANDRE, RIC,...), as part of its official mission of risk management, for safety of persons and property [8]. Those rain gauges, manufactured by *Précis-Mécanique*, are composed of two tipping buckets calibrated for 0.1mm or 0.2mm depending on the model, with a collection surface of 1000cm².

Other rain gauges are used in this study, and are provided by complementary networks:

- Outside of France borders, in Italy, data comes from the ARPA (Agenzia Regionale per la Protezione Ambientale for Piémont region) and ARPAL (Agenzia regionale per la protezione dell'ambiente Ligure), which use weather stations comparable to those of Météo-France (marked "IT" below).
- 5 rain gauges from the French electric utility company Electricité de France (marked "EDF"), which are also comparable to those of Météo-France (PG2000 from Précis-Mécanique, with 2000cm² collection surface [3]), and are regularly maintained.
- 29 rain gauges from the Métropole Nice Côte d'Azur ("MNCA"), which models are not precisely known.
- 5 rain gauges of the Géoazur lab, and 1 from the EDUMED network (marked "GEOAZUR")
- 7 rain gauges from non-profit organization Nice Météo 06 (marked "M06").

The last two networks ("GEOAZUR" and "M06") are semi-professional weather stations, well-known from the weather observation community, model "Vantage Pro 2" from manufacturer Davis Instruments. Their quality is here considered as good if they are regularly maintained (Chochon et al., upcoming publication) – some stations were indeed excluded due to uncertain quality.

Overall, those stations are reported as follows in this study:

- Standard Weather Stations (SWS) for weather stations from “official” institutes: Météo-France, EDF, and IT
- Personal Weather Stations (PWS), for other networks: MNCA, GEOAZUR and M06

A map of those networks is proposed in section 3.2, associated with observed rainfall accumulations from October 2nd, 2020.

When dealing with very severe events like October 2nd, 2020, it is not uncommon that communication networks, or even electrical grid itself, suffer from outages and are brought down. In this specific event, some of the weather stations used stopped reporting in the middle of the event, making real time data unavailable. For others, data could not even be retrieved afterwards.

In other cases, when a weather station is implanted close to a river or stream, it can be flooded or destroyed by heavy precipitation. This has been the case with SWS n°06127006 of Météo-France in Saint-Martin-Vésubie, as illustrated in **Figure 2**.



Figure 2: Aerial photography of Saint-Martin-Vésubie, before the 2020 flood (left picture), and a few days after the event (right). The marker at the center of the picture is the location of a Météo-France SWS, that has been destroyed by floods. Source: alex.ign.fr (IGN)

2.3. Radar observation

The French weather radar network, named “ARAMIS”, was deployed in the 1980’s by Météo-France, and exploited and extended since [19, 27]. Of 13 radars in 1995, the network is today composed of 33 sites, covering a major part of the French metropolitan territory. The mesh was greatly improved in the Southern and South-Eastern areas (Figure 3) over the previous decade, with the RHYTMME project, aiming at a better risk management of HPEs over mountainous regions [31]. Radars from this project are mostly X-band based, which have many advantages, but have a main drawback of being heavily attenuated by higher rain intensities, even using dual-polarization [27].

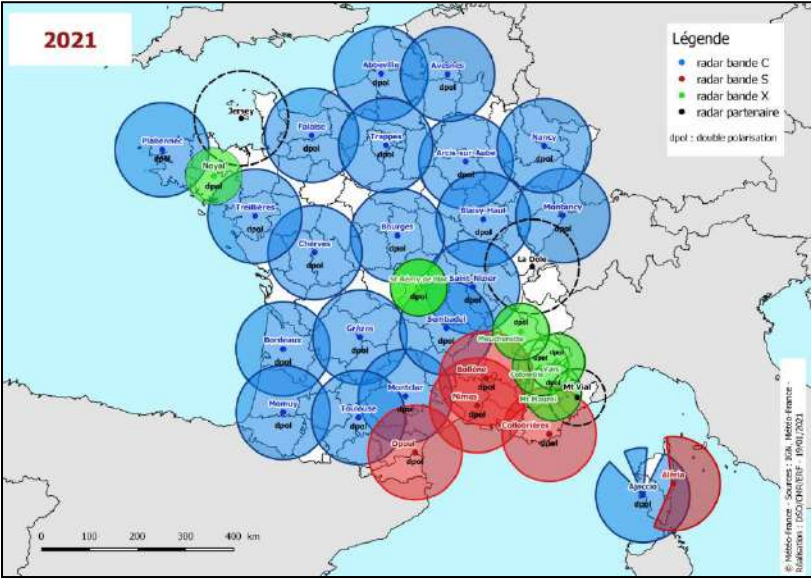


Figure 3: Météo-France weather radar network in February 2021. There are 20 C-band radars, 5 S-band radars, 6 X-band radars (+2 at Paris CDG and Nice airports). The network is extended with 3 partner radars, one of them particularly

interesting in our area of interest (X-band radar of Mont Vial, operated by the company NOVIMET), which allow a better coverage of the Mercantour area. Source: Météo-France

Weather radars work by measuring a variable called reflectivity: it is the proportion of electromagnetic pulses being scattered by hydrometeors. Those echoes can be produced by rain drops, hail, or interference caused by obstacles. The analysis of the signal can then infer position, intensity, and type of precipitation, and discard ground echoes or interference caused by relief [26].

Data from the ARAMIS network is being compiled every 5 minutes, allowing production of nation-wide imagery with a near-kilometer resolution, of instantaneous rainfall intensities estimation [27]. Those images are critical for many hydrological applications: they allow revealing spatial and temporal structures of precipitations at a finer scale than conventional surface observation [30].

Associated to fitting algorithms with surface rain gauge observations [28], this data allows generation of a merged value-added product of Quantitative Precipitation Estimation (QPE), named “PANTHERE”.

2.4. Fusion products

QPE products directly produced from 5-minute radar data, like PANTHERE (described in section 2.3) are known to underestimate rainfall accumulations, due to a limited data assimilation [20, 21, 26].

Météo-France, by merging data from the ARAMIS network (Section 2.3), and data from surface weather stations (Section 2.2), produces another QPE dataset, named “ANTILOPE”, correcting some of the bias and errors due to radar data, and integrated a broader surface dataset [8, 9]. **Figure 4** explains this principle of data merging of radar and rain gauges networks, allowing a better estimate of rainfall accumulations.

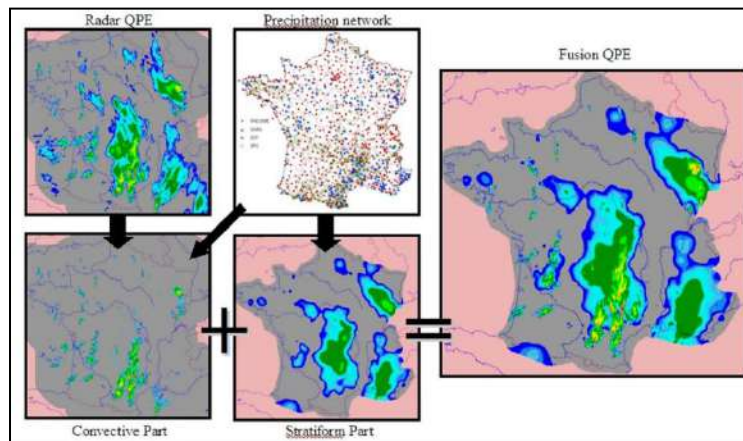


Figure 4: Data fusion principle, between radar network data and rain gauges observations (from Champeaux et al. 2011 [9])

Operationally, several versions of ANTILOPE are available. A first product is available hourly with a 20 minutes delay and a fitting using only a few rain gauges of the main network ; a second product is available 24 hours later, named “J+1”, integrating a greater number of rain gauges, which allows a better estimate of the rainfall accumulation. In this study, the second version of ANTILOPE is used: ANTILOPE J+1.

2.5. QPE reanalysis

In the context of feedback requested by public institutions of the Alpes-Maritimes, numerous rainfall observations have been gathered (see 2.2) over the area impacted by this event, in order to increase knowledge of the precipitations that fell.

Météo-France has then been able to produce a reanalysis of the ANTILOPE product for this event, by increasing the number of observations used in the product, using complementary networks mentioned in section 2.2. This ANTILOPE reanalysis, which is then a third version of the ANTILOPE product (see 2.4), is the best estimate available over the area for this event and is then used as a reference for rainfall over this study and named “ANTILOPE reanalyzed”.

3. CASE DESCRIPTION

3.1. Atmospheric mechanisms

At the synoptic scale, weather models are depicting a very low pressure area, centered over the English Channel. This low pressure area covers western Europe on October 2nd 2020 6h UT. Lowest pressure are around 970 hPa, and 500hPa geopotential heights close to 5200m, all with a strong pressure gradient, as more than 1000 hPa are observed over Gulf of Genoa with a 5600m altitude of 500hPa geopotential, 1200km away. This vigorous cyclogenesis led to strong winds over France, up to 186 km/h being reported at Belle-Île, South Brittany. Its trajectory during October 2nd is targeting southern France, with a relatively slow progress: at the end of the day, the center of Alex storm is positioned around Vendée coasts, 400km southern, over Bay of Biscay. This synoptic configuration is generating a strong south-west flow throughout the day of October 2nd, over the Mediterranean Sea, favoring arrival of warm and humid airmass on southeastern France. At this time, the Mediterranean still has warm water of more than 20°C (Météo-France buoy 6100001, 43.38°N / 7.83°E). Surface wind speed, 40 to 50 km/h on average, with 60 to 80 km/h gusts, combined to this warm airmass, contributes to increasing water vapor contents in the atmosphere. Dewpoints raise over 18 to 20°C off the Mediterranean coasts.

More locally, in the French Riviera, significant wind shear can be seen thanks to CNRM AROME 2.5km model: surface 10m wind is coming from the South, while from the South-South-West at 925 hPa and from South-West at 700 hPa. Surface observations from Météo-France, but also from M06 PWS, record 50 km/h average wind speed (74 km/h gusts) on the coasts, and 20-30 km/h (40 to 93 km/h gusts) inland.

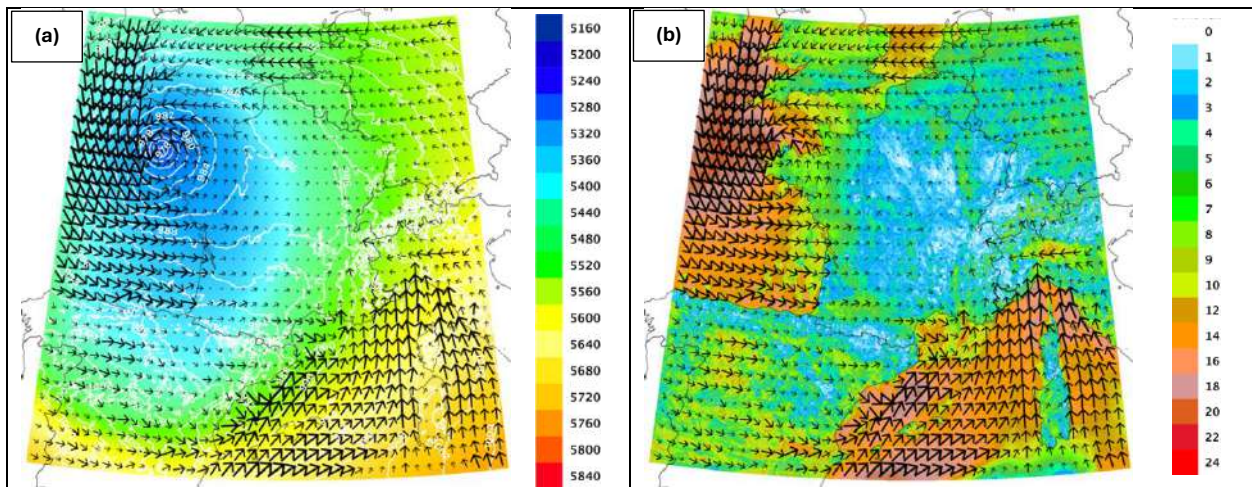


Figure 5 : Synoptic situation on October 2nd 2020 6h UT modeled by AROME 2.5km resolution : (a) Geopotential height 500 hPa (m), surface and flow pressure (hPa) ; (b) Wind speed (m/s) and direction at 1000 hPa

In high altitude, at 3000m, and mainly in the mountainous part of Alpes-Maritimes, the SW flow is strong, on average 90 to 130 km/h according to AROME model. The equivalent potential temperature at 850 hPa (θ_e), which depicts characteristic of the airmass, identifies warm and moist areas, with a θ_e up to 50-55°C throughout the day. The cold front arrival, around 2 to 3h UT on October 3rd, can be observed with a steep fall

of θ_e to less than 40°C . Convective Available Potential Energy (CAPE) values, calculated by the model, vary between 700 to 1200 J/kg near the shore. Vertical velocities at geopotentials 700 and 600 hPa raise up to 10 m/s on average on 6.25 km^2 areas (AROME grid size).

Higher in the atmosphere, at 300 hPa geopotential, a twisting and vigorous jet stream, positioned over southwestern France, blows at more than 200 km/h from the South. Also, a tropopause deformation is seen with very low altitude, less than 4000 m for the 1.5 PVU in West of France, with strong oscillations of thousands of meters during October 2nd, and over the Alpes-Maritimes.

The description of the atmospheric characteristics, at the surface, and higher in altitude, of October 2nd, assembles all the prerequisites for a multi-cell convective cluster with retrograde formation. A very dynamic atmospheric circulation, a conditionally unstable airmass, a warm moist air near the surface, orographically lifted, and a favorable wind profile, allows a decorrelation between location of cells genesis, and location of precipitation areas [29].

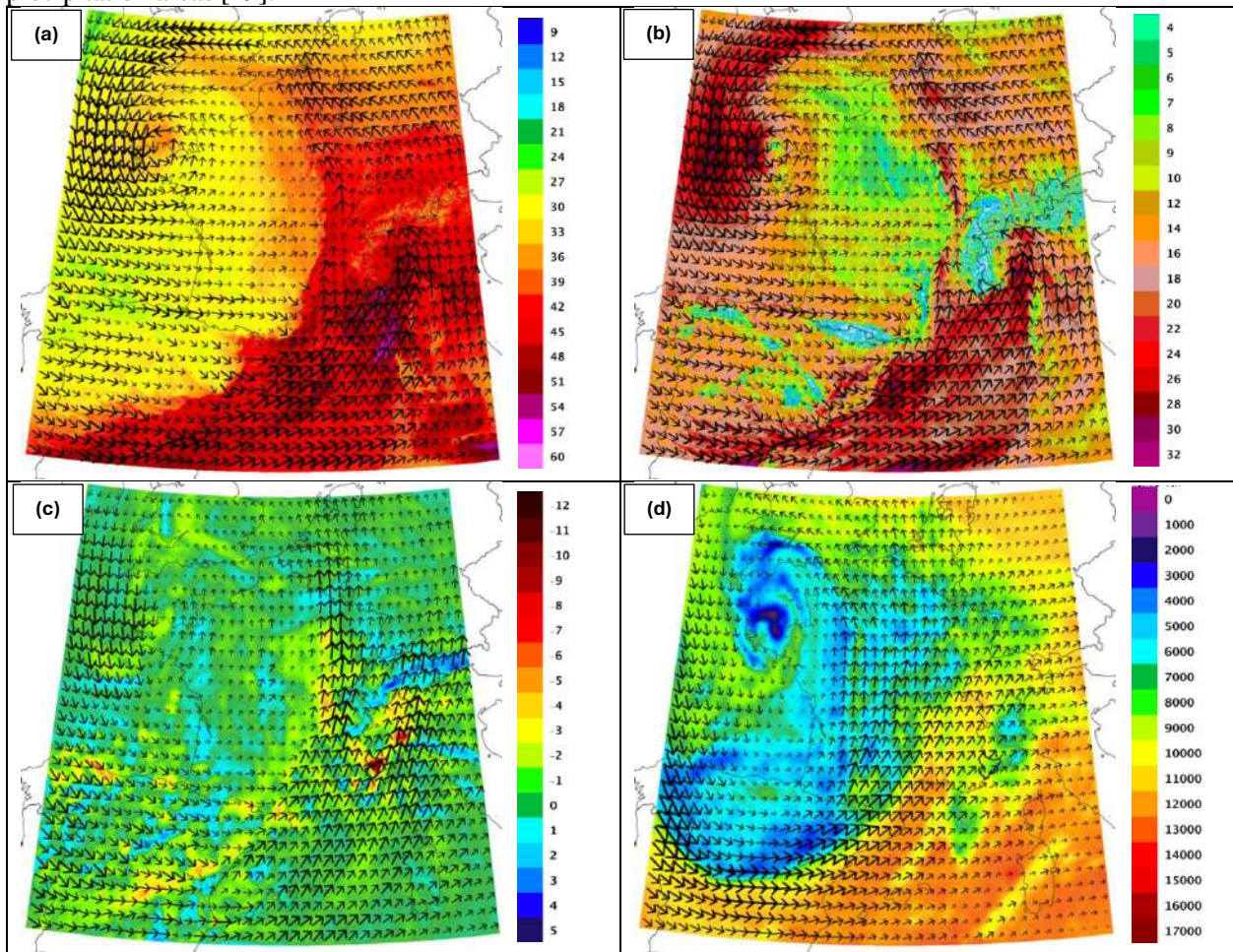


Figure 6 : Synoptic situation on October 2nd 2020 6h UT modeled by AROME 2.5km resolution : (a) Theta e ($^\circ\text{C}$) and flow at 850 hPa ; (b) Wind speed (m/s) and direction at 850 hPa ; (c) Vertical speed (hPa/h) and flow at 700 hPa ; (d) Height 1,5 PVU (m) and flow at 300 hPa

3.2. Resulting rainfall observed

A very basic approach to identify impacted areas is done using only surface observations, namely rain gauges mentioned in Section 2.2.

Figure 7 shows a map of accumulated rainfall over 24 hours, extracted from the ANTILOPE-reanalyzed product of Météo-France (a combination of radar and rain gauges data, as explained in Sections 2.4 and 2.5).

This QPE product is hereafter used as a reference: by combining several observing methods, corrected after several weeks of controls.

3.2.1. Observed

Figure 7 clearly depicts rain corridors, oriented from South-West to North-East, where the rain accumulations were the highest.

The first corridor is situated in western Alpes-Maritimes, over Grasse pre-Alps: the EDF SWS of Bas-Thorenc (Andon) reports 380 mm, and the Météo-France SWS of Col de Bleine 316 mm.

The second corridor, at the center of the map, shows heavier precipitation, over a large stripe from Grasse pre-Alps to higher summits of the Mercantour massif. Starting from the Caussols plateau (189 mm), the accumulations are rising rapidly when moving to the North-East, with 332 and 347 mm for Météo-France and EDF SWS of Coursegoules. To the North, on the foothills of the Mercantour, several stations are noteworthy:

- In the Tinée valley, around Clans, 356 mm are reported at the EDF SWS of Bancairon, while 428 mm are measured at the Clans village M06 SWS.
- In the Vésubie valley, the Saint-Martin-Vésubie SWS of EDF measures more than 500.3 mm in 24h, including 432.1 mm in 12h, 295 mm in 6h and 174.1 mm in 3h (**Figure 8**). This measure has been confirmed by a manual Météo-France SWS (N°06127001) in the surroundings, which reports 513 mm.
- Still in the Vésubie valley, the Météo-France SWS of Lantosque registers 243 mm.

Across the border, in Italy, the ARPA SWS of Diga del Chiotas measures 376 mm for this event, located North-East of Saint-Martin-Vésubie.

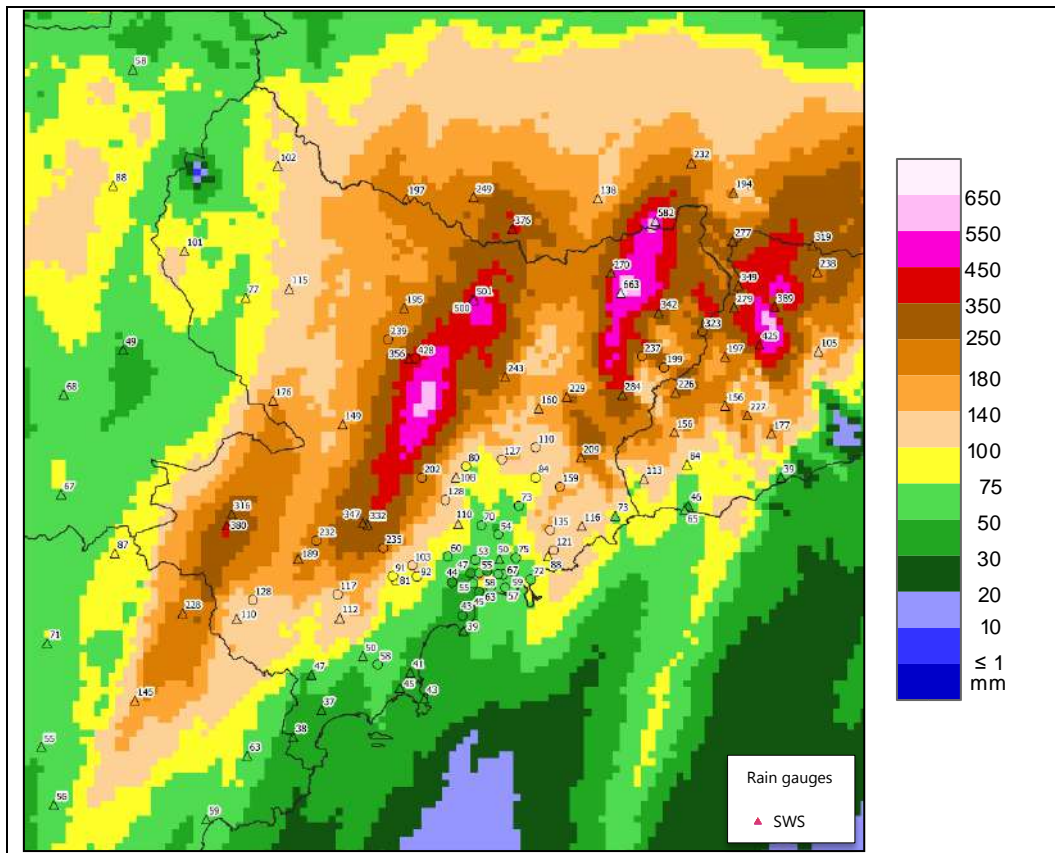


Figure 7: 24 h rainfall accumulation from ANTILOPE reanalyzed between 06:00 UTC on 02 October 2020 and 06:00 UTC on 03 October 2020. Labels show rain gauges measured accumulations.

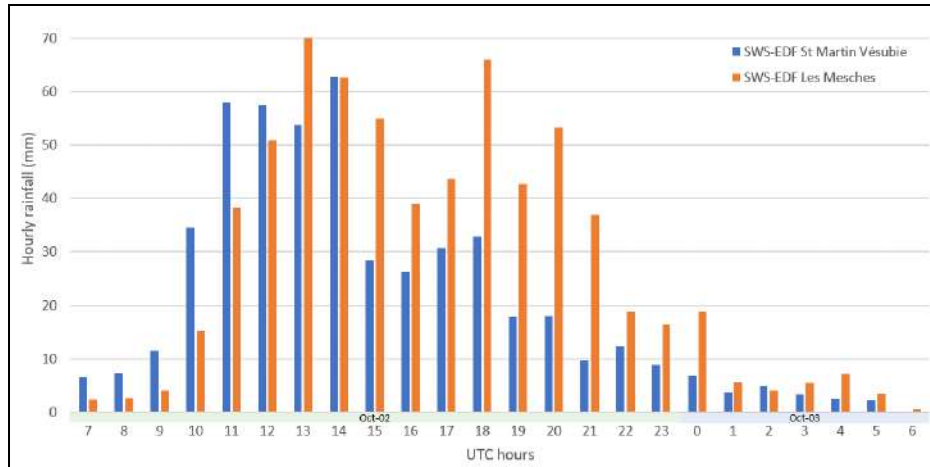


Figure 8: Hourly rainfall from EDF SWS of Saint-Martin-Vésubie in the Vésubie valley and Les Mesches in the Roya valley between 06:00 UTC on 02 October 2020 and 06:00 UTC on 03 October 2020.

A third corridor, East of the department, is located over the Roya valley, overlapping France and Italy. The French side seems more heavily affected. At the middle of the valley, Breil-sur-Roya village records 284 mm (Météo-France SWS). Upstream in the valley, near the Bendola vallon, GEOAZUR PWS are reporting 199 to 323 mm. Close to Saint-Dalmas-de-Tende, a Météo-France SWS measures 342 mm.

The Bieugne stream, which is a tributary flowing into the Roya at Saint-Dalmas-de-Tende, is coming down from the Mesches reservoir. EDF SWS records 663.2 mm, including 577.5 mm in 12 hours, 336.5 mm in 6h, and 187.3 mm in 3 hours (**Figure 8**). Finally, the ARPA SWS of Limone, North of Tende, records 582 mm. A fourth corridor can be seen in Italy, between Triora and Mendatica, which record 425 and 389 mm respectively.

3.2.2. Comparison with known extremes

According to Météo-France database of extreme precipitation events “Pluies Extrêmes”², the accumulations measured at Saint-Martin-Vésubie and Les Mesches (**Figure 8**) are clearly breaking the record of 6h, 12h, 24h sliding-window rainfall accumulations since beginning of meteorological records in the Alpes-Maritimes (**Figure 9**). The SWS of Les Mesches also breaks the local record of 3h-rainfall accumulation, with 187.8 mm against 177 mm on October 3rd, 2015.

Durée	6 min	15 min	30 min	1 h	2 h	3 h	6 h	12 h
Alpes-Maritimes	03/10/2015	07/06/2016	07/06/2016	03/10/2015	03/10/2015	03/10/2015	03/10/2015	31/10/2010
	22	44	81	115	175	177	194	248

Figure 9: Absolute records of rainfall accumulations for several durations (6 minutes to 12 hours), for Alpes-Maritimes departement, according to the « Pluies Extrêmes » Météo-France database.

Figure 10 depicts the absolute records over 1, 2 and 3 days, measured on the Alpes-Maritimes. Again, the two SWS cited above clearly break all records. The 663 mm in 24h observed at Les Mesches also seem to be the new national record (old one of 551 mm in 24h on November 12th, 1999 in Aude department).

	Janvier	Février	Mars	Avril	Mai	Juin	Juillet	Août	Septembre	Octobre	Novembre	Décembre	Annuel
1	11/01/1996	19/02/1972	13/03/1980	03/04/2019	18/05/2013	26/06/1994	04/07/2009	22/08/1965	08/09/2005	31/10/2010	14/11/2002	02/12/2005	31/10/2010
J	242 mm	138 mm	169 mm	136 mm	132 mm	200 mm	122 mm	137 mm	231 mm	332 mm	247 mm	236 mm	332 mm
2	10/01/1996	18/02/1972	13/03/1980	24/04/1993	09/05/2002	25/06/1994	13/07/2002	21/08/1965	29/09/1965	30/10/2010	14/11/2002	10/12/2017	30/10/2010
J	330 mm	219 mm	170 mm	201 mm	192 mm	208 mm	135 mm	172 mm	244 mm	366 mm	360 mm	265 mm	366 mm
3	10/01/1996	18/02/1972	18/03/1971	24/04/1993	09/05/2002	25/06/1994	13/07/2002	20/08/1965	06/09/2005	30/10/2010	14/11/2002	19/12/1958	14/11/2002
J	404 mm	269 mm	211 mm	235 mm	211 mm	208 mm	215 mm	173 mm	293 mm	395 mm	470 mm	294 mm	470 mm

Figure 10: Absolute records of rainfall for 1 to 3 days accumulations, for Alpes-Maritimes area, according to Météo-France « Pluies Extrêmes » database.

3.3. Human and property consequences

More than 5 months after the event, it is still difficult to precisely evaluate the consequences of this disaster. At least 8 people are still missing, and 10 casualties have been found, linked to the disaster³. Another victim was a volunteer firefighter, missing in action in the Vésubie, whose body was never discovered.

The French government declared 55 towns in state of emergency for natural disaster “flood and mudslide”⁴, allowing a systematic compensation for victims by their insurance. French insurers federation

² Website « Pluies extrêmes » of Météo-France : <http://pluiesextremes.meteo.fr/france-metropole/-Records-.html> (consulted on 21/02/2021).

³ According to an article in the regional daily Nice-Matin : <https://www.nicematin.com/faits-divers/tempete-alex-la-gendarmerie-plonge-ce-vendredi-a-la-recherche-de-victimes-640702> consulted on 22/02/2021

⁴ Extract from the Official Journal on website Légifrance concerning the declaration of the state of natural disaster (CAT-NAT) for 55 township of Alpes-Maritimes : <https://www.legifrance.gouv.fr/jorf/id/JORFTEXT000042407558>

(FFA) has estimated the cost of this disaster to 210 million euros for the Alpes-Maritimes, with 14.000 claims, of which 72% are for properties loss⁵.

Total cost estimates including public infrastructures damage, raise the bill to more than 1.5 billion euros, a number comparable to the cost of September 2002 disaster in the Gard [2, 18].

The Tinée valley, which has seen less damage to transportation and communication utilities, had a quick return to normal of its infrastructures. A few villages of the Vésubie were isolated for a few days or weeks at most. In contrast, a few towns of the Roya valley are still, after 5 months, inaccessible by road or railway (**Figure 11**).



Figure 11: Road access to the south of Breil-sur-Roya are destroyed, while a temporary unpaved road is being created (left picture). A house has been cut in half by the Roya floods (right picture).

As shown in Section 3.2, rainfall accumulations received in those valleys were hardly conceivable, and such disaster images were not making sense in collective consciousness before that, which makes the event awareness difficult. Some of those damages are clearly linked to the unbelievable amount of rain, but it was also seen that some constructions, located in the floodplain or flood-meadow, were already at risk⁶.

The decision of Météo-France to issue a “floods” red warning (highest level in French weather warning system) the day before led to a reduction of people travels, and probably had an impact on reducing casualties. The Prefecture decision to close the schools, announced the day before, has also been a factor by reducing the number of people on the roads, although strongly criticized by citizens.

Those decisions have been implemented quite in advance, thanks to a good previsibility of the event by the numerical models, as shown in the next section.

4. PERFORMANCE OF DIFFERENT OPERATIONAL TOOLS

During a crisis like this one, local authorities and emergency services sometimes have limited resources to precisely understand the amount of rainfall over a specific area and, therefore, the expected flood extent. It is

⁵ Claim estimate according to the French Insurance Federation : <https://www.ffa-assurance.fr/actualites/inondations-dans-les-alpes-maritimes-14-000-sinistres-estimes-pour-un-cout-evalue-210> consulted on 22/02/2021

⁶ Refer to the Pléiades images described by SERTIT 2020 : <https://sertit.unistra.fr/cartographie-rapide/?action=706> consulted on 22/02/2021

even more difficult during such serious event because some telecommunication means are destroyed, which prevent communication of real-time weather data, or even communication between rescue services.

As seen in Section 3, a heavy rain event was predicted and well anticipated by Météo-France – but it was tricky for citizens to imagine the impact of such rain accumulations, being intellectually challenging to conceive something that never happened in a living memory.

It is proposed thereafter an analysis and comparison of several tools which are typically used for prediction and real-time observation of such events.

4.1. Global analysis

As explained in Section 3.2, the ANTILOPE-reanalysed is used as a reference for the QPE field. An introduction to the different tools used below is presented in Section 2.

Figure 12 shows a panel of the different QPE products, with the same colorscale. The reference isolines for 200 mm precipitation (dashed line) and 400 mm (solid line) are overlaid on each product, extracted from the ANTILOPE-reanalyzed (a).

Figure 13 shows the absolute difference between each of the product with the ANTILOPE-reanalyzed reference.

The rainfall accumulation predicted by AROME 6Z on October 2nd, 2020 was already showing a similar spatial structure, modeling heavier precipitations on the foothills of the Mercantour massif, with a corridor organization. Some of the heaviest precipitation area over the Tinée valley is slightly shifted to the East. The maximum accumulations in 24h are up to 400 mm, which is already outstanding, but finally underestimated.

The IDW interpolation, while the easiest and quickest estimate available, is an imperfect spatialization product of the precipitation field, and then is only accurate on areas where density of rain gauges is high. Therefore, the center of the Tinée valley is clearly underestimating, due to lack of rain gauges in this area.

The PANTHERE QPE product is very accurate regarding the spatial repartition of the precipitations and is a very good estimate of the accumulations at low and moderate elevations, that is for the southern part of the Alpes-Maritimes. The drawback of such a product using primarily radar data is for areas that are obstructed by higher reliefs, which act as opaque obstacles to the electromagnetic pulses. Therefore, the rainfall accumulation is severely underestimated in upper areas, mainly the upper Roya valley. Although methods exists to try to compensate those drawbacks, like using higher elevation angles of the radar antennas, they come with other drawbacks, which make QPE tricky to construct on those areas.

The ANTILOPE J+1 product is better at correcting drawbacks of the PANTHERE estimate, by reducing the differences to the reference. This is very visible around Saint-Martin-Vésubie, and a bit improved also in the upper Roya valley, while perfectible. This product also highlights a risk of operational near-realtime fusion products: at the border of the Alpes-Maritimes and Var departments, the accumulations are highly overestimated near the village of Mons. The cause of this overestimate was discovered a few days later and was caused by a configuration error in Météo-France processing flow, which erroneously multiplied the Mons rain gauge values by 2.54 during the event. This kind of errors highlights the importance of quality controls and human analysis in operational use of derived products. This error was then corrected in ANTILOPE-reanalyzed, which is used in this study as a reference.

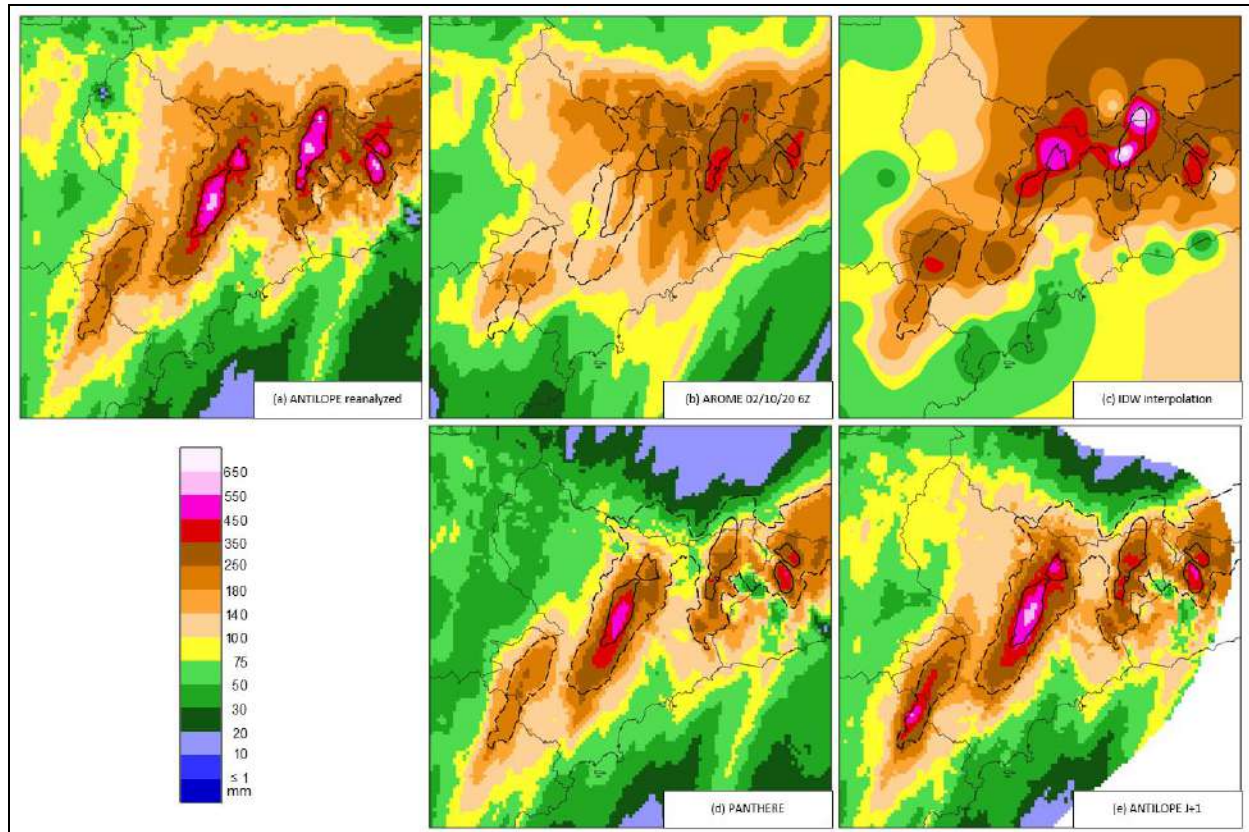


Figure 12: 24h rainfall observed by (a) ANTILOPE reanalyzed, (b) AROME HD 6z on 02 October 2020, (c) IDW interpolation of SWS and PWS observations, (d) PANTHERE, (e) ANTILOPE J+1. The reference isolines for 200 mm precipitation (dashed line) and 400 mm (solid line) are overlaid on each product, extracted from ANTILOPE-reanalyzed (a).

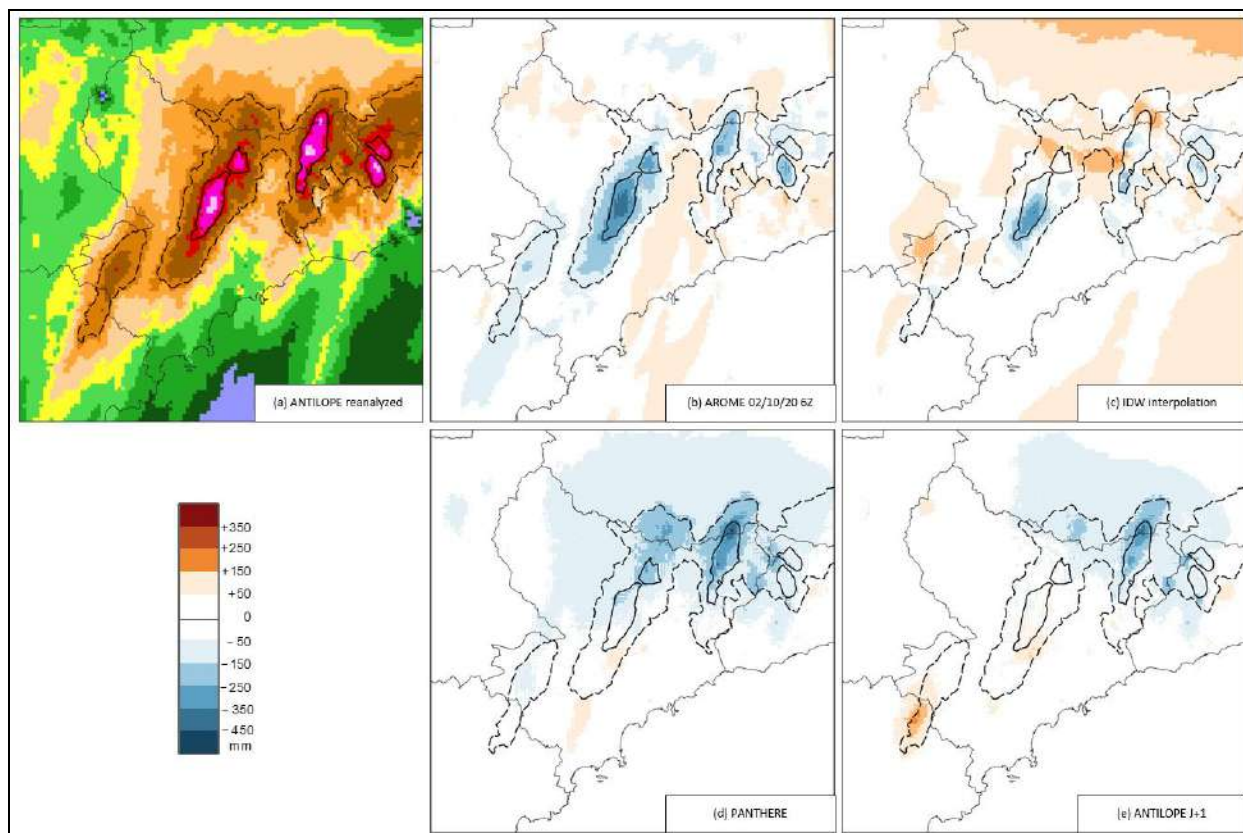


Figure 13: 24h rainfall observed by (a) ANTILOPE reanalyzed, and absolute difference with (a) for each product : (b) AROME HD 6z on 02 October 2020, (c) IDW interpolation of SWS and PWS observations, (d) PANTHERE, (e) ANTILOPE J+1.

4.2. Temporal analysis

In order to ease temporal analysis of this event, it is proposed to construct a specific region of interest (ROI), from which statistics will be extracted. **Figure 14** shows the region of interest that will be used thereafter to compare the different QPE products (predicted or derived from observations). This area is a 120km square, where the maritime area is being excluded due to lack of rain gauges measurements.

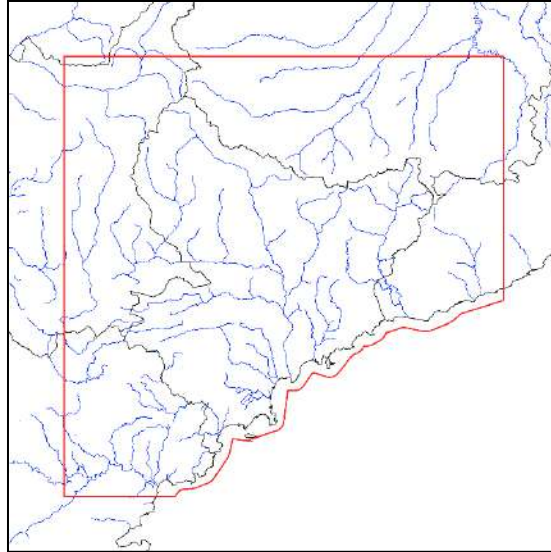


Figure 14: The red line indicates the region of interest used for statistics integration. Main rivers are marked as blue lines.

From a temporal point of view, **Figure 15** shows a clear underestimation of the PANTHERE product compared to the ANTILOPE-reanalyzed reference. Predicted hourly accumulations of AROME 6Z of October 2nd, 2020 shows variable results depending on the time step, but overall shows a very good accuracy.

Those comparisons show the interest of using “raw”, near-real-time QPE products like PANTHERE, or also simple interpolation of rain gauges, given a sufficient station density. This kind of derived products allows to quickly vision the spatial repartition of precipitations and their intensity but are not sufficient by themselves.

This also shows the confidence level to put in such products for risk management purposes. It remains extremely important to keep a dense network of measuring rain gauges, to confirm or calibrate radar estimated, while keeping a critical perspective even on stations measurements themselves: errors can also occur for rain gauges values (configuration error, transmission loss, or lack of maintenance leading to obstruction of the instrument [6, 10, 17]).

Finally, we also see the great improvement of spatial estimated by integrating Italian products in ANTILOPE-reanalyzed: in those areas, cross-border cooperation and operational real-time data sharing is critical.

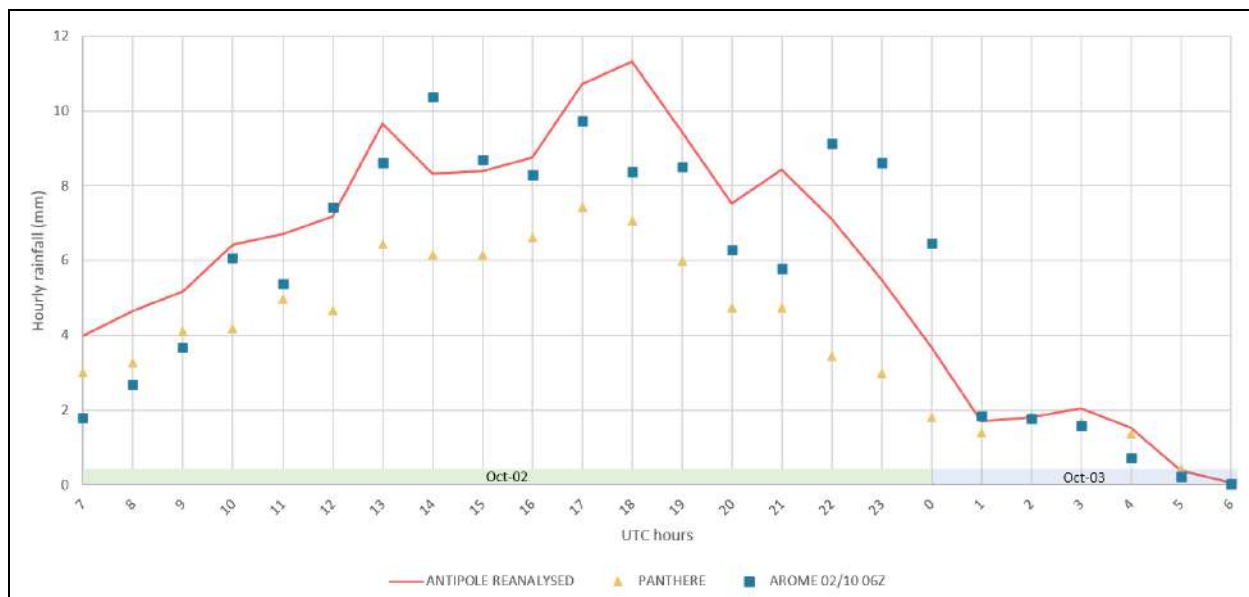


Figure 15: Hourly rainfall over ROI (defined in **Figure 14**) for ANTILOPE-reanalyzed (red line), PANTHERE (yellow triangles) and AROME 06Z of 02 October 2020 (blue squares)

4.3. Performance of predictions within different model runs

Previously was demonstrated the ability of AROME-FR to give a correct estimate of the event, a few hours before its paroxysm. **Figure 16** shows how AROME-FR performed the days before the event, and how simplified nowcasting tools like AROME-NWC have grasped the evolution of the event along the day (those models are described in Section 2.1).

For comparison purposes, AROME-NWC was extracted for initialization runs 06Z, 12Z, 18Z of October 2nd and 00Z of October 3rd, up to prediction step of +6h, intermediate hourly runs are not used. This method of accumulation is arbitrary due to availability of data and may hide performance of intermediate runs which may perform differently.

The nowcasting model AROME-NWC was extremely accurate at the beginning of the event for the Region of Interest, however it began to underestimate for the second part of the event, after 19/20h UTC, leading to a final 24h accumulation of 117mm, compared to the ANTILOPE-reanalyzed reference of 140 mm. An explanation for this sudden loss of performance of AROME-NWC after 19h UTC, is that the AROME-NWC of 18Z has its boundary conditions initialized from AROME-FR 15Z (whereas previous steps were from AROME-NWC initialized with AROME-FR 12Z). This means AROME-FR 15Z may have degraded performance for this event, leading to degraded performance of AROME-NWC.

The latest run of AROME-FR, on 6Z of October 2nd, 2020, depicts a very accurate temporality against observed rainfall, but constantly underestimates, leading to a final 24h accumulation of 132 mm over the ROI. This is however a closest prediction to previous AROME-FR runs of previous hours, which all converged to an accumulation of 117 mm, identical to the AROME-NWC accumulation, which is a 16% underestimation compared to the reference.

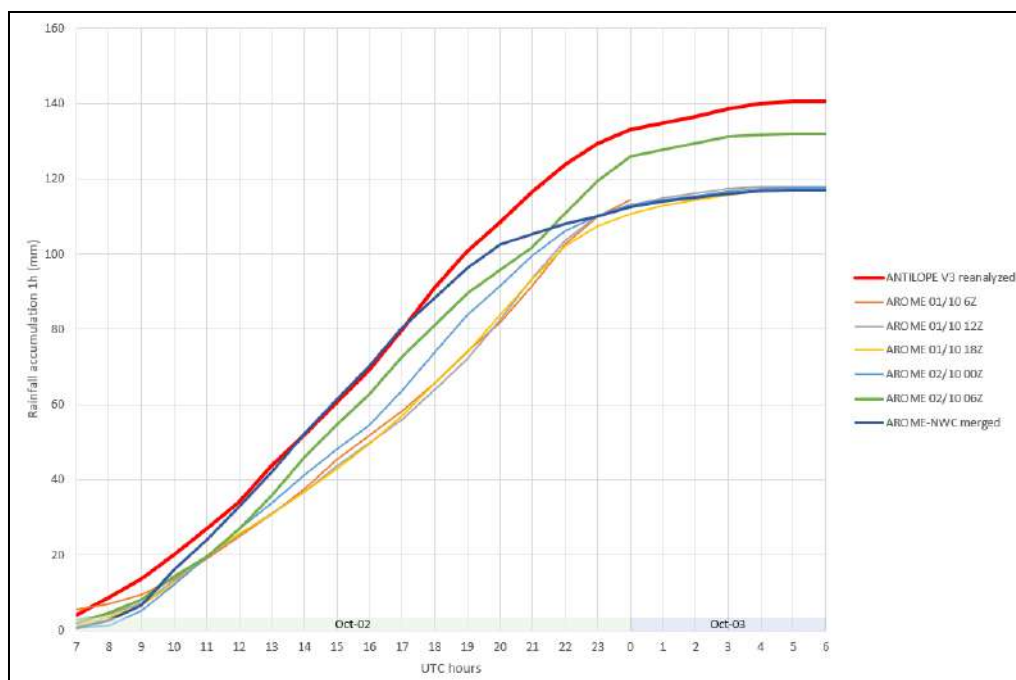


Figure 16: Accumulated hourly precipitations over the ROI (defined in **Figure 14**) for ANTILOPE-reanalyzed (red line), AROME-NWC (dark blue), and several runs of AROME-FR

4.4. Conclusion on performance

The day before the event, successive runs of the AROME-FR deterministic model are predicting an exceptional event over the Alpes-Maritimes, converging to a consequent amount of rain over the area.

On the morning of the event, the prediction of AROME-FR was the closest, among other runs, to the reference rainfall. While underestimating regularly throughout the day, the final accumulation is only 6% less than the observed reference, which is very accurate.

For the first part of the event, nowcasting system AROME-NWC offers a great accuracy on hourly intensities over the area.

Those comparisons are using the final rainfall variable of the model, which is an end-product of several layers of calculations and parametrization. Studying raw fields of the model (like hydrometeors mixing ratio) can further increase our understanding of behavior of the different model variants. Analysis of regional ensemble forecasting models, like AROME-PE, introducing local perturbations to compensate for sources of uncertainties, is also another angle of the problem that can be addressed.

More robust statistical indicators, that help analyzing spatial accuracy (Fractions Skill Score [23]), or local temporal performance using mean absolute errors calculations, could be used to further improve this analysis at a finer level.

5. DISCUSSION AND CONCLUSION

We hereby show that the main factors leading to Heavy Precipitation Events were correctly predicted by the AROME-FR regional model of Météo-France, at least a day before occurrence of the event.

The good previsibility of the event has probably been a factor in limiting the number of victims, even if the extent of the disaster was far from imagined.

The exceptional characteristics of this event is clear: with more than 600 mm accumulations in less than 24 hours, it is placed amongst the five strongest HPE experienced by the country. The specific topography and

maritime situation of the Alpes-Maritimes has played a strong role in the atmospheric situation and its consequences.

The geographic area impacted by the heavy rainfall is large, including areas where rain gauge density is poor, and where weather radars struggle to deal with rugged terrain, meaning even more higher rain accumulation may have been hidden.

The comparison of different QPE products shows the toughness to obtain real-time accurate rainfall data, whereas they come from conventional rain gauge networks that can be disrupted by the event itself, or spatialized products that can suffer from limitations inherent to their technology.

It is probable that better use of those products come from fusion products – in which many improvements have been done over the past years. Extending assimilation of data from other rain gauge networks, and radar data from neighboring countries is also an important line of work to improve those products and help local crisis management.

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