

Analysis of the 1 November 2015 heavy rainfall episode in Algarve by using weather radar and rain gauge data

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Abstract The trigger for the study presented in this paper was the extreme rain event of 1 November 2015 in Algarve region. The main objective was the analysis and improvement of the precipitation field using a radar–rain gauge merging method. Ordinary kriging with radar-based error correction has been applied to hourly values of precipitation from both sensors. The merging technique allowed keeping the better radar spatial pattern, being the respective estimates corrected by the rain gauges observations. The procedure led to a reduction in the errors of the precipitation estimates, evaluated by cross-validation, when compared to univariate interpolation of rain gauge observation or radar rain product. Finally, some discussion is also added on the problematic of flooding in urban areas, especially those with absent or deficient urban planning.

Keywords Precipitation · Radar · Rain gauge · Merging · Floods · Albufeira · Algarve

1 Introduction

Algarve is a region of Portugal with an extraordinary climate. It is the land of beaches with warm water, the place with the highest amount of sunshine hours per year, the region where everyone wants to have a home or vacation.

In spite of this, from time to time, Algarve is affected by severe weather conditions with great amounts of precipitation. 26 October 1997, 28 September 2008, 1 November 2015 or, more recently, 11 February 2017 are only some of the most remarkable examples of heavy precipitation, unfortunately most of the times with tragic consequences. The great majority of these episodes have been associated with low pressure systems extending their effects from the southern quadrant.

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These situations are responsible for several floods, sometimes flash floods, affecting people and goods as well as enterprises. Thus, socio-economic development and the occurrence of severe weather events, particularly heavy rainfall in short time intervals, require the supplying of as more accurate and fast weather information as possible, targeted to respond effectively to citizens, businesses and civil protection system. Accurate precipitation estimates, especially during intense and persistent precipitation events, are critical in meteorology and hydrology.

The main objective of this work is to analyse and discuss the precipitation episode that affected the Algarve region on 1 November 2015, especially between Portimão and Faro, where the influence of a low pressure system led to the occurrence of high precipitation values, namely in the period 0300–1500 UTC.

Firstly, the analysis of the meteorological conditions that trigger the occurrence of these effects is going to be performed. Then, particular attention will be given to the analysis of heavy precipitation values. On this concern, both the rain gauges and the closest weather radar will be used. On the one hand, rain gauges give the most approximate value of water reaching the surface, i.e. allow obtaining good observations of precipitation, but only representative of the place where they are located. In addition, they are not dense enough to capture the spatial variability of the precipitation field, namely during convective situations or orographic reinforcements. In fact, there is lack of precipitation information in between rain gauges. Most probably, the precipitation maximum will not occur at the rain gauge location. Anyway, the rain gauges are prone to several sources of error, most of the cases resulting in underestimation of the precipitation. On the other hand, radar is a remote sensing equipment, allowing obtaining a good spatial pattern of precipitation, but its point estimates are not as accurate as the rain gauge observations, i.e. although providing reliable patterns and spatial variability, radar estimates of precipitation have temporal and spatial variable bias values. Among the issues that can affect the radar estimates of precipitation, one may point out errors from the equipment (e.g. calibration biases), beam blockage, bright band effects, contamination from non-meteorological echoes, variability in the vertical profile of reflectivity and uncertainties in the Z–R relationship, for example (Zhang et al. 2016).

In addition, while the rain gauge observations are performed in the ground, the radar estimates of precipitation are obtained at a certain height above the ground, depending on the distance to the radar location, and many phenomena may happen while the drops fall towards the ground (e.g. microphysical changes, drift due to wind). One must also not forget that a rain gauge has a catching area of 200 cm², much less than the typical 1 km² area of a radar Cartesian cell, and that the radar precipitation estimate in this cell is a result of the average of several pulses and range bins previously done in polar coordinates. Therefore, considering the different and complementary nature of both types of observation, the best choice for getting a much proper precipitation field is the merging of the point values given by rain gauges with the spatial detail provided by the radar. With this procedure, it is possible to improve the rainfall estimates by correcting the radar bias, allowing obtaining an optimal precipitation field.

The combination of radar precipitation estimates and rain gauge observations has been a matter of research in the last decades. Several techniques were developed, ranging from the ones based on the application of a simple mean adjustment factor of R (radar)/G (gauge) to the radar field to the more sophisticated ones based on objective analysis, geostatistical techniques or the Kalman filter concept, for example.

In fact, several studies have proven that the improvement of precipitation estimates would be possible using radar–rain gauge merging methods (Alpuim and Barbosa 1999;

Goudenhoofd and Delobbe 2009; Sinclair and Pegram 2005; Schiemann et al. 2011; Vogel 2013 among others). In particular, geostatistical methods' best performance compared to simple bias correction techniques is referred by Goudenhoofd and Delobbe (2009), concluding that "there is a clear benefit of using spatial correction factor". Schiemann et al. (2011) tested various formulations of geostatistical combination methods, namely ordinary kriging and kriging with external drift, and suggested further work on the estimates uncertainty and on addressing "both the deterministic part of the geostatistical model and the spatial covariance of the stochastic part", despite providing a contribution to a solution based on the kriging with external drift method. Goudenhoofd and Delobbe (2009) also concluded that "the best method is the kriging with external drift which makes use of the radar as secondary information to improve the spatial interpolation of gauge's values. The kriging with radar-based error correction shows very similar performance while the computational cost is reduced". Vogel (2013) refers "merging radar and rain gauge data has been an intense field of research for many years and different combination methods have been suggested. Inclusion of radar information has been found to improve the skill of the quantitative precipitation estimates". In the exhaustive work done by Vogel (2013), several combined methods have been tested, including conditional simulation, and "the additional radar information in the combination and both spatial and temporal aggregation reduce the uncertainty in the precipitation estimates". It should also be noted that "the added value of the combination is sensitive to the rain gauge network density" and "a better representation of intense precipitation" is obtained by the combination.

2 Meteorological conditions

Most of the weather conditions that lead to the occurrence of heavy rainfall in Algarve are associated with the influence of low pressure systems from the south quadrant as happened on 1 November 2015.

Between 1200 UTC 31 October and 0000 UTC 1 November, there has been a deepening of the surface pressure field in North Africa associated with the development of a low with 1013 hPa in that region. This surface deepening was associated with the formation of a secondary nucleus in altitude, visible to the W of Sagres at 500 hPa. On 1 November, that deepening low displaced to NW, being located in Faro region by 1200 UTC, with 1008 hPa.

In addition, Algarve region was under the effect of a warm, humid and unstable SE air mass at the low levels of the troposphere. Due to both, this hot and unstable air mass and a strong convergence at surface, organized precipitation lines with SE-NW orientation have been generated, moving slowly to N and affecting especially the region at NW of Faro, with heavy and persistent precipitation, mainly in the 0300–1500 UTC period, sometimes with thunderstorms. It should be noted that in this 12-h period, precipitation amounts greater than 100 mm were observed in four automatic weather stations (Barbosa et al. 2016a, b).

During 1 November, afternoon and evening the low pressure system moved to the Atlantic SW of Cabo Raso, with 1005 hPa. As precipitation lines progressed to N, they gradually lost their activity, reaching the remaining zones of south and centre of Portugal with much less significant amounts of precipitation.

The activity of atmospheric electrical discharges began in S of Algarve at 0300 UTC, after which the electrical activity progressed in a range oriented from SE to NW towards

the W region of Algarve by 1200 UTC. Then, the electric discharges activity has spread to practically all Algarve region, maintaining the same standard in the orientation SE-NW. Lightning strikes affected the region between Albufeira and Aljezur, from 0900 to 1400 UTC, associated with the higher rainfall intensity band.

During this episode, the wind has been moderate to strong (with mean values between 40.0 and 51.8 km h⁻¹ in the automatic weather stations network), with gusts of 79.9 km h⁻¹ in Faro Airport at 1050 UTC (Barbosa et al. 2016a, b).

The analysis of satellite and Loulé/Cavalos do Caldeirão (L/CC) weather radar data has been also performed.

Four satellite images of the Cold Ring product are presented in Fig. 1. This product represents the brightness temperature in the channel 10.8 μm of the SEVIRI-MSG sensor, with a colour scale allowing to show that the clouds with colder tops (orange and red colours), i.e. higher tops, were initially at S of Faro. By the sequence of images, it can be concluded that the structure has moved slightly to N-NW.

On what concerns the L/CC radar, the reflectivity patterns obtained with the MAXZ product (projection of reflectivity maxima in dBZ) (Vaisala 2014) throughout the day have been analysed. It was easy to see the generation of the organized SE-NW orientation reflectivity lines that affected the zone between Portimão and Faro and inland.

The reflectivity values estimated with radar suggest some vertical development (Fig. 2), although not very expressive and occurrence of sometimes strong rainfall. Also visible is the band of higher reflectivity values, ranging from 32 to 48 dBZ, in the western Algarve, especially in the coast between Faro and Albufeira and inland.

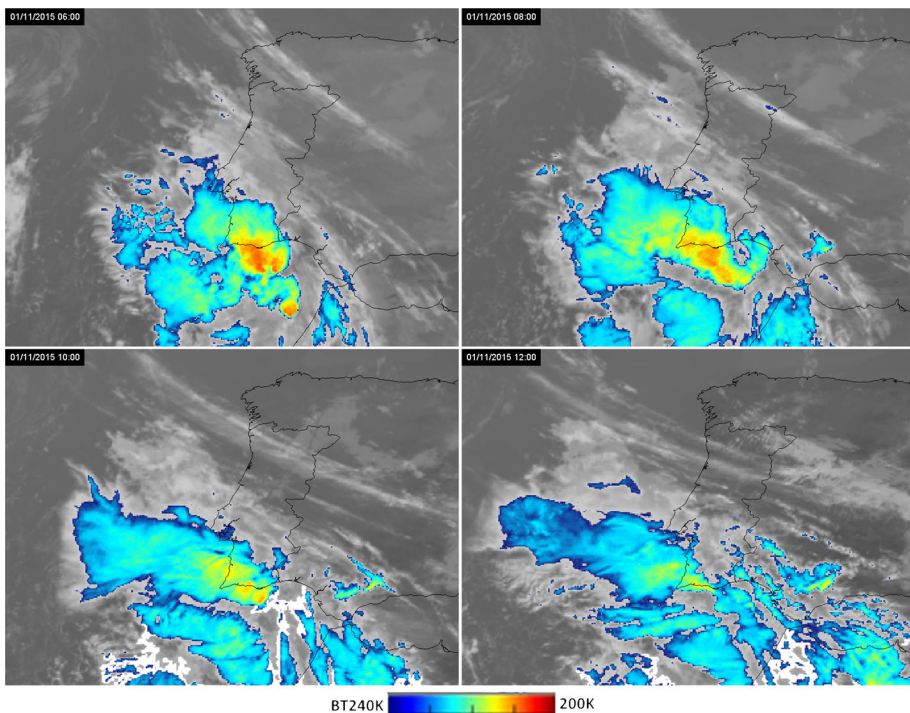


Fig. 1 Satellite images (Cold Ring product) at 0600, 0800, 1000 and 1200 UTC

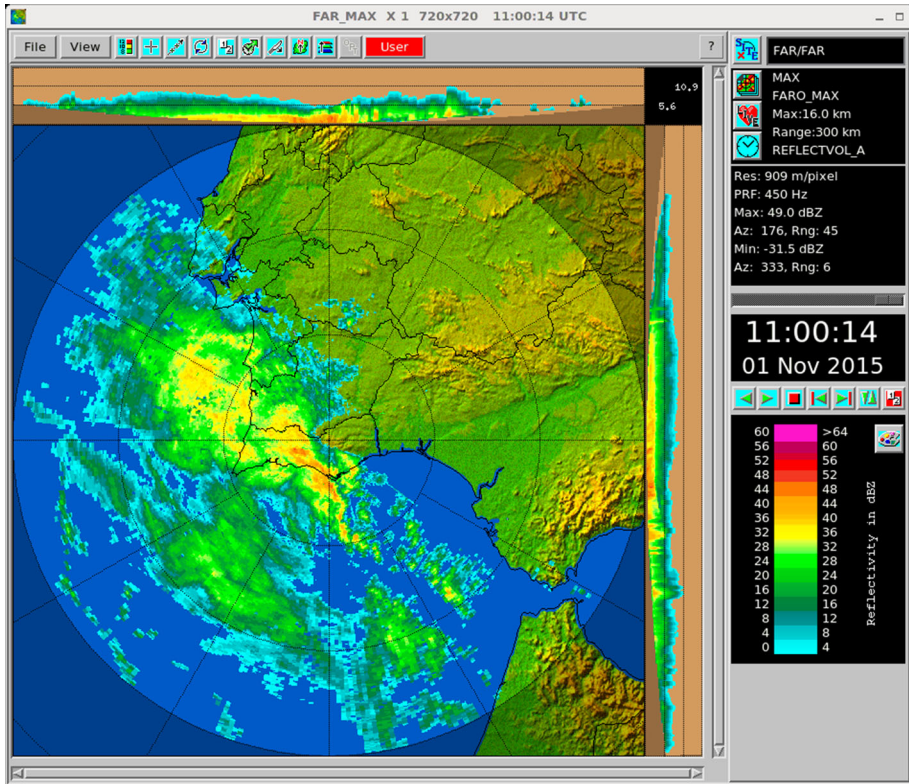


Fig. 2 Projection of reflectivity maxima (dBZ) at 1100 UTC

The generation of warning products derived from the emission and automatic identification of thresholds (Vaisala 2014) was also evaluated for this purpose, namely the warning products “PRECONV” (convective precipitation) and “PRECESTRAT” (stratified precipitation). These products result from the automatic combination of several fields observed with radar, associated with various types of severe weather conditions.

In the case of PRECONV warning product, the combination of fields that need to be checked for issuing a warning led to the following criteria in a threshold area of 9 km²:

$$\text{MAXZ} < 52 \text{ dBZ} \quad \text{and} \quad \text{VIL} \geq 10 \text{ mm} \tag{1}$$

On what concerns the PRECESTRAT warning product, it is issued when the following criteria is fulfilled in a threshold area of 90 km²:

$$\text{MAXZ} < 45 \text{ dBZ} \quad \text{and} \quad 2.5 < \text{VIL} < 8 \text{ mm} \tag{2}$$

According to the philosophy of these products, these conditions will be verified at the moment or will happen in the very short term.

This episode was largely marked by the issuance of radar warnings of stratified precipitation (PRECESTRAT), especially in the period 0750–1350 UTC. Nevertheless, the first warning was issued at 0240 UTC, still over the sea, and until 0725 UTC, several radar warnings were issued on the area under analysis. An example of radar warnings at 1220 UTC is shown in Fig. 3. Here, the spatial extension of stratified precipitation warnings is

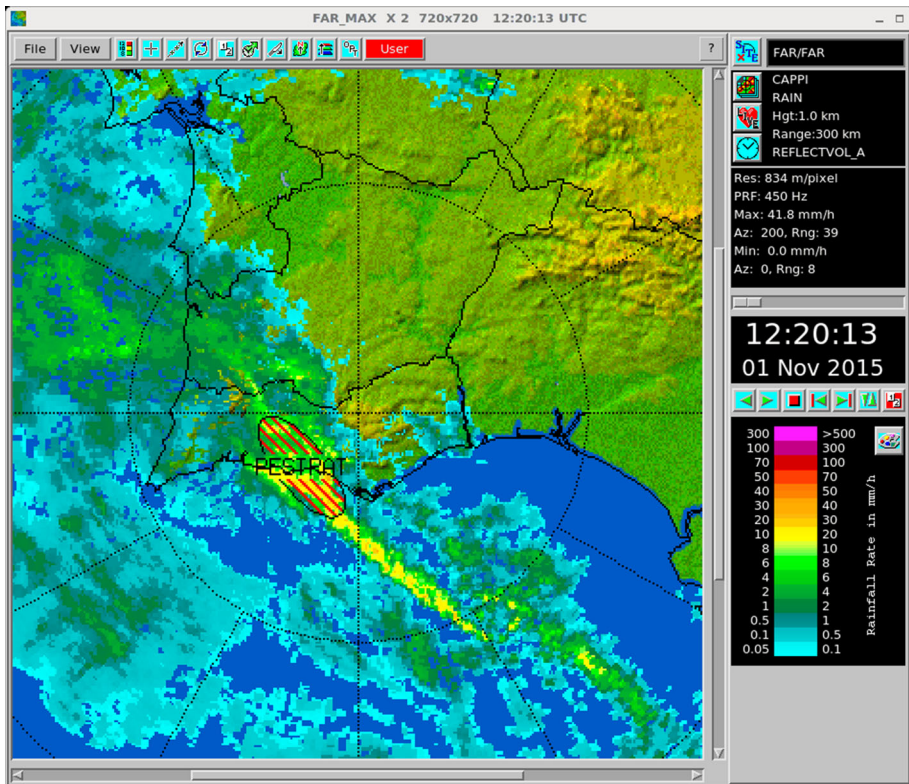


Fig. 3 Issuance of radar warnings of stratified precipitation at 1220 UTC

clearly visible. This has been the rule during several hours in the same region, thus reflecting the extreme accumulation of precipitation in this zone.

3 Precipitation field analysis

Hourly values of precipitation from the automatic weather stations networks of both the Portuguese Institute for Sea and Atmosphere (IPMA) and the Portuguese Environmental Agency (APA) have been analysed (Table 1 and Fig. 4). In addition, hourly accumulated estimates of precipitation obtained with the L/CC weather radar have been also considered in this analysis (Fig. 5).

Special emphasis has been given to the 12-h period from 0300 to 1500 UTC, in which higher accumulated values of precipitation have been observed (Table 2). In fact, during these 12 h, the precipitation amount exceeded 100 mm in four weather stations, namely Algoz (135.2 mm), Paderne (130.4 mm), S. Bartolomeu de Messines (104.7 mm) and Faro Airport (100.5 mm). These values represent a fraction between 93.4% (Algoz) and 98.9% (Faro Airport) of the precipitation amount for the whole day (Fig. 5).

The highest precipitation amounts have occurred in the period between 0300 and 1500 UTC, in particular in Algarve region and Baixo Alentejo coast, as can be seen in Fig. 6. The accumulated precipitation values in 24 h (0000–2400 UTC) and 12 h (0300–1500

Table 1 Automatic weather stations used and respective network and location

ID	Name	Network	Longitude (°)	Latitude (°)	Altitude (m)
1	Albufeira do Roxo	APA	− 8.080	37.929	135
2	Mértola	IPMA	− 7.552	37.758	190
3	Panóias	APA	− 8.306	37.757	164
4	Relíquias	APA	− 8.483	37.703	244
5	Zambujeira	IPMA	− 8.743	37.582	67
6	Neves Corvo	IPMA	− 7.972	37.577	225
7	Odemira	IPMA	− 8.729	37.547	76
8	Alcoutim	IPMA	− 7.769	37.438	290
9	São Barnabé	APA	− 8.164	37.359	249
10	Aljezur	IPMA	− 8.802	37.325	16
11	Monchique	APA	− 8.595	37.323	792
12	Fóia	IPMA	− 8.596	37.314	902
13	Catraia	APA	− 7.838	37.310	475
14	Mercador	APA	− 7.739	37.278	392
15	S.B. Messines	APA	− 8.276	37.246	126
16	Barranco Do Velho	APA	− 7.937	37.237	467
17	Castro Marim	IPMA	− 7.425	37.230	5
18	V.R.S. António	IPMA	− 7.416	37.187	11
19	Paderne	APA	− 8.209	37.167	55
20	Portimão	IPMA	− 8.583	37.148	24
21	Algoz	APA	− 8.298	37.139	85
22	Faro	IPMA	− 7.972	37.017	8
23	Sagres	IPMA	− 8.949	37.013	25

UTC) were very similar (Table 2). In this paper, particular emphasis is being given to this 12-h period, where the precipitation was strong and persistent.

It must be stressed that for some weather stations, the values of accumulated rainfall in that period were about 1.4 times higher than the November climatological values for the period 1971/2000. However, on what concerns the historical rainfall records in IPMA stations, the 12-h period values did not exceed the previous maximum. Nevertheless, the 24 h accumulated rainfall previous maximum was exceeded in both Algoz (105.5 mm on 4 December 1990) and Paderne (99.0 mm on 17 October 1972), with 144.8 mm and 134.8 mm, respectively.

Results for shorter periods, namely 3 and 6 h, were also considered and analysed. For a 6-h period (0800–1400 UTC), the rainfall amount in Algoz (107.9 mm) and Paderne (98.9 mm) represents about 74% of the daily amount (Fig. 5).

Furthermore, the weather stations that registered the largest amounts of precipitation, Algoz and Paderne, are the ones closest to Albufeira, which makes one think about the effects caused.

Precipitation values observed in automatic weather stations are point observations, which mean that are representative of the site where the observations are performed. Therefore, if this is the only information available, in rigour nothing can be said about what

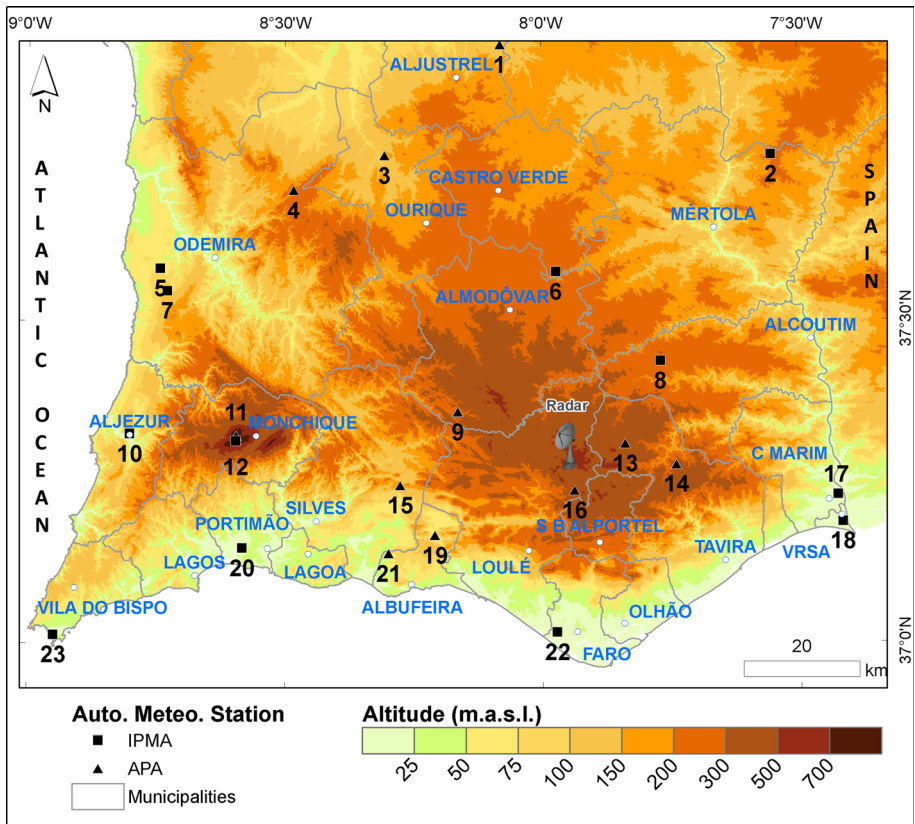


Fig. 4 Spatial distribution of used automatic weather stations from IPMA (2015) and APA (2015) networks and weather radar (radar symbol). Numbers represent station ID (Table 1). Name of the municipalities in blue

happen in between rain gauges, especially if there is a large space–time variability of precipitation. Thus, in order to have a better knowledge of the spatial distribution of precipitation, the data of the L/CC weather radar were also analysed.

In order to estimate the radar accumulated values of precipitation (mm) in periods of 1, 3, 6, 10, 12 and 24 h, the rainfall intensity estimates (mm/h) obtained using the Pseudo-CAPPI (Constant Altitude Plan Position Indicator) product, with a resolution of $1 \times 1 \text{ km}^2$, have been used as the basis. This product consists on a horizontal cut through the atmosphere, therefore requiring a PPI (Plan Position Indicator) volume scan at multiple elevation angles (Vaisala 2014). An altitude of 700 m has been chosen, as it is the closest possible to the surface and the one corresponding to the lowest underestimation of precipitation field. The radar hourly precipitation estimates were obtained with the radar RAIN1 (Hourly accumulated precipitation) product in mm. Analysis of these high-intensity precipitation values allowed to conclude that the period 1100–1400 UTC was the one where the effects were most felt. From the analysis of all data obtained for the various accumulation periods considered, it is possible to conclude that the spatial pattern corresponding to the maximum precipitation zone has a SE–NW orientation and, except for periods 0000–0600 UTC and 1800–2400 UTC, it is very similar in almost all other periods,

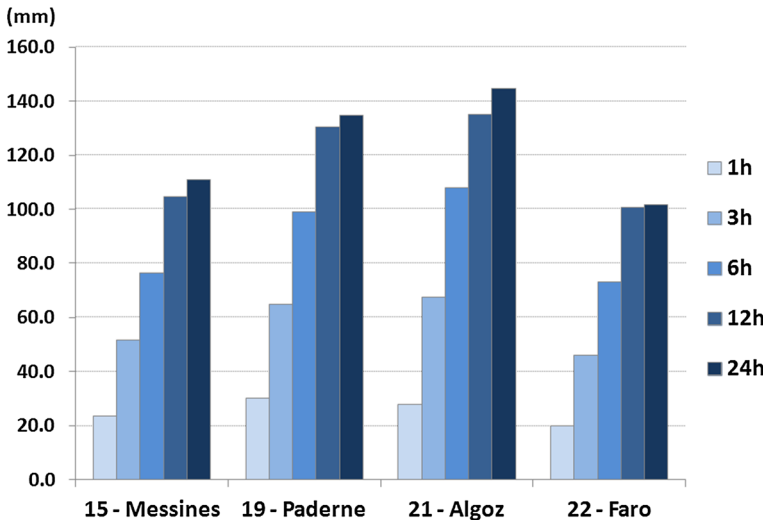


Fig. 5 Precipitation values for different hourly accumulation periods, in the four weather stations with daily precipitation values > 100 mm, on 1 November 2015

Table 2 Precipitation values for different hourly accumulation periods (rain gauges in Baixo Alentejo and Algarve regions, 1 November 2015)

ID	Precipitation (mm) 1 h maximum	Precipitation (mm) 0300–1500 UTC	Precipitation (mm) 0000–2400 UTC
1	0.1	0.1	0.1
3	4.6	18.5	24.0
4	7.4	43.0	50.6
5	10.6	66.8	69.5
6	9.1	14.2	24.3
7	10.5	69.1	71.6
9	13.5	68.3	69.0
10	13.1	68.5	74.0
11	11.2	83.3	97.6
12	12.2	76.2	88.4
13	17.7	35.9	38.1
14	12.1	25.6	32.2
15	23.5	104.7	110.8
16	13.2	48.2	51.7
18	10.2	12.8	24.7
19	30.0	130.4	134.8
20	10.7	79.8	89.3
21	27.8	135.2	144.8
22	19.9	100.5	101.6
23	10.2	45.3	79.1

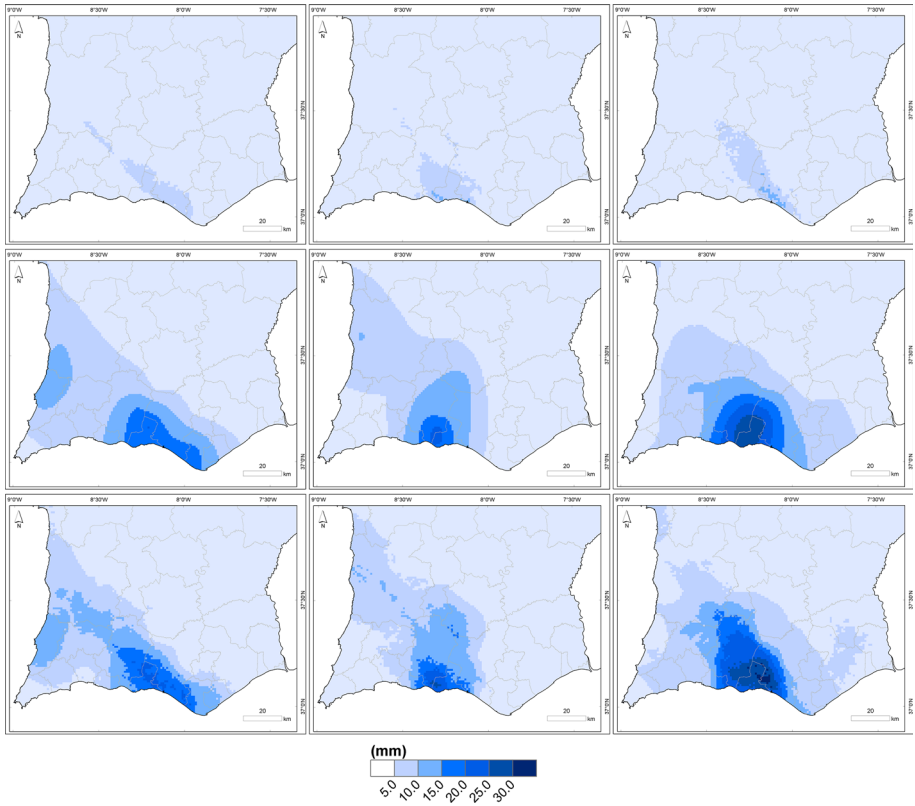


Fig. 6 Hourly rainfall estimates for 3 h, from 1100 to 1400 UTC (left to right), radar (top), rain gauge interpolation (middle), radar–rain gauge merging (bottom), 1 November 2015

which gives an idea of the phenomenon size, extending essentially throughout the coastal zone between Armação de Pêra and Faro and inflecting to N and NW in Albufeira region, clearly affecting the municipalities of Albufeira, in greater extent, as well as Silves and the Quarteira area. Regarding the 12-h accumulations, the 0000–1200 UTC, 1200–2400 UTC and 0300–1500 UTC periods were investigated. The above-mentioned behaviour has been verified for every period, although in a higher magnitude in the last one.

4 Improvement of the precipitation field

In Portugal, the use of radar data combined with in situ rain gauge observations to improve precipitation estimates has been applied for some intense precipitation episodes (Barbosa et al. 2016a, b; Narciso et al. 2015; Silva et al. 2008), mainly in urban areas, where the impacts of high precipitation values are more adverse and directly related to floods. Silva et al. (2008) applied residual kriging of linear regression between RAIN1 and rain gauge values, producing detailed precipitation maps for an intense precipitation event occurred on 18 February 2008, affecting Lisbon and Setúbal regions and Tejo river valley (Moreira et al. 2008).

Narciso et al. (2016) demonstrated that the combined radar–rain gauge method reduces the bias between observed and estimated precipitation values, thus reducing the estimation error. Several cases of intense rainfall occurring in Lisbon region were evaluated, and it was proven that the hybrid method improved the final validation results compared to solo radar estimates or rain gauge observations. Precipitation patterns and values were in accordance with the impacts (floods) occurred in various locations of the Lisbon city.

In the present work, radar–rain gauge precipitation merging is done using ordinary kriging with radar-based error correction, being the rain gauge observations considered the ground truth. The theoretical backgrounds and mathematical description of this geostatistical interpolation method were described by Goovaerts (1997), Burrough and McDonnell (2000). The kriging prediction values are a linear combination of measured values, weighted according to the variogram that describes spatial correlation between data. Intrinsic stationarity is one of the ordinary kriging main assumptions, but meteorological variables have sometimes a trend, that is why ordinary kriging is mainly applied on detrended variables, residuals or bias interpolation (as done in this study). Predicted value of random variable Z on location (x) is given by [Eq. (3)]

$$\hat{Z}(x) = m(x) + e'(x) + e'', \tag{3}$$

where $m(x)$ is a deterministic function describing a structural component of Z at x , $e'(x)$ is a random spatially correlated component and e'' is a residual, non-spatially correlated term or noise (nugget variance).

For each sampled point, the difference between rain gauge and radar precipitation values is obtained according to Eq. (4) and the computed values for the entire rain gauge network (automatic weather stations) are interpolated using ordinary kriging. In the ordinary kriging variogram modelling, the nugget effect was set to 0 and the used variogram type was exponential. Sill and range parameters were obtained by optimizing final error statistics. Both hourly L/C radar estimates of precipitation and hourly precipitation values observed in the relevant rain gauges of IPMA and APA networks have been used (Table 1 and Fig. 4).

$$Pd_i = Pu_i - Pr_i, \tag{4}$$

where Pd_i is the rain gauge–radar difference component, Pu_i is the hourly rain gauge precipitation observation and Pr_i is the hourly radar precipitation estimate (RAIN1).

The obtained difference precipitation grid is used to correct the radar precipitation estimates [Eq. (5)] and to produce a radar–rain gauge combined precipitation product—ROK.

$$ROK_i = Pr_i + Pd_i, \tag{5}$$

where ROK_i is the radar–rain gauge precipitation value at unsampled site, Pd_i is the interpolated precipitation difference between rain gauge and radar obtained by ordinary kriging and Pr_i is the hourly radar precipitation estimate (RAIN1).

This procedure was performed for all hours of 1 November. Validation was done using leave-one-out cross-validation (Dobesch et al. 2007; Goovaerts 1997) in order to compare errors from different estimation methods, namely radar rain product (RAIN), rain gauge univariate interpolation (IDW) and radar–rain gauge combined precipitation. The root mean square prediction errors (RMSE) and the r^2 (determination coefficient) between observed and estimated values are presented in Table 3, for the above-mentioned precipitation estimation methods. As can be seen radar–rain gauge merging method, ROK,

Table 3 Validation results of rainfall estimates (0300–1500 UTC on 1 November 2015), considering radar rain product (RAIN), rain gauge inverse distance weighted interpolation (IDW) and radar–rain gauge merging method (ROK)

	Maximum absolute error (mm)	RMSE (mm)	r^2
Radar–rain product (RAIN1)	93.4	49.6	0.73
Rain gauge inverse distance weighted interpolation (IDW)	34.6	16.6	0.83
Radar–rain gauge merging method (ROK)	26.1	11.4	0.92

presents lower error values and higher r^2 than the radar rain product or the univariate interpolation using IDW. The RMSE values for the 0300–1500 UTC rainfall estimates were 11.4, 49.6 and 16.6 mm, respectively. Also the r^2 values are quite different, 0.92 for ROK, 0.83 for IDW and 0.73 for RAIN1.

As it can be concluded from the observation of the several maps, the precipitation field obtained by interpolation of the rain gauge observations presents a much smoother pattern than the one based on the radar estimates. One of the great advantages of using radar–rain gauge merging technique, ROK, is to keep the better spatial pattern, depicted by radar, but allowing the respective values to be corrected by the in situ observations, using a spatial correction factor interpolated with ordinary kriging, maintaining a reduced computational cost and similar results as the more advanced methods like kriging with external drift (Goudenhoofdt and Delobbe 2009).

Figure 6 presents the hourly precipitation field obtained for the most relevant hourly period (3 h from 1100 to 1400 UTC), based on rain gauge values (top), on the L/CC radar information (middle) and using radar–rain gauge merging (bottom).

Figure 7 is obtained from the hourly radar–rain gauge adjusted precipitation estimation grids. For each pixel, the maximum on 3 and 6 h is calculated, providing useful information for different accumulation periods and allowing better characterizing and comparing regional values occurring at various times within the total event period. It is possible to conclude that Albufeira region was the most affected for all period accumulations.

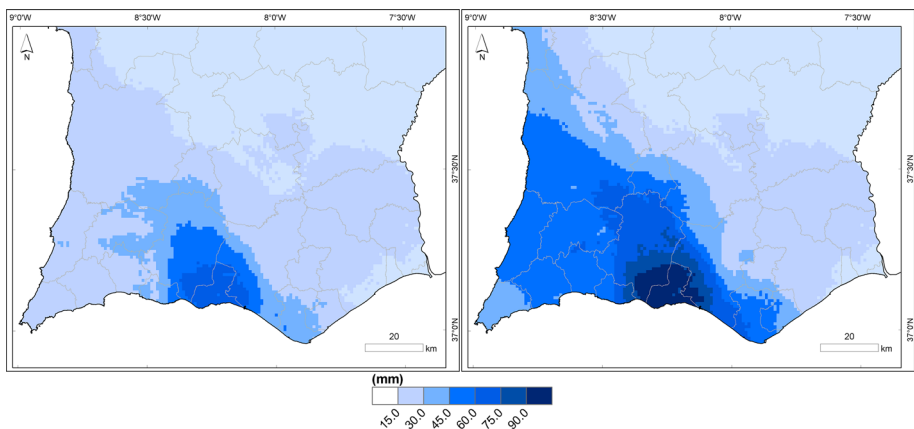


Fig. 7 Maximum accumulated rainfall in 3 (left) and 6 h (right) on 1 November 2015, obtained from hourly radar–rain gauge adjusted estimates

The accumulated precipitation field after the adjustment process is shown in Fig. 8, for the most intense precipitation period (0300–1500 UTC). This field is the result of the sum of every hour adjusted precipitation for the 12-h period considered. The area corresponding to the drainage basin of the Albufeira river (obtained from the digital model of the terrain) is indicated in dashed grey pattern. It can be concluded that the estimated values of accumulated precipitation for this 12-h period were higher than 110.0 mm in the entire basin, with a maximum of 137.0 mm. In this 12-h period, the average accumulated rainfall in the drainage basin was 129.0 mm.

5 Flooding in Albufeira urban area

The western part of Algarve is characterized by a coastline with cliffs and a relief with an irregular morphology. This aspect, coupled with a deficient real estate planning of the territory, allowing an unrestrained real estate growth in the last decades, led to the creation of situations of waterproofing of flood beds, with very harmful consequences.

In the last 70 years, there have been several floods in Albufeira caused not only by intense precipitation episodes. Effectively, the river basin of Albufeira has a very low

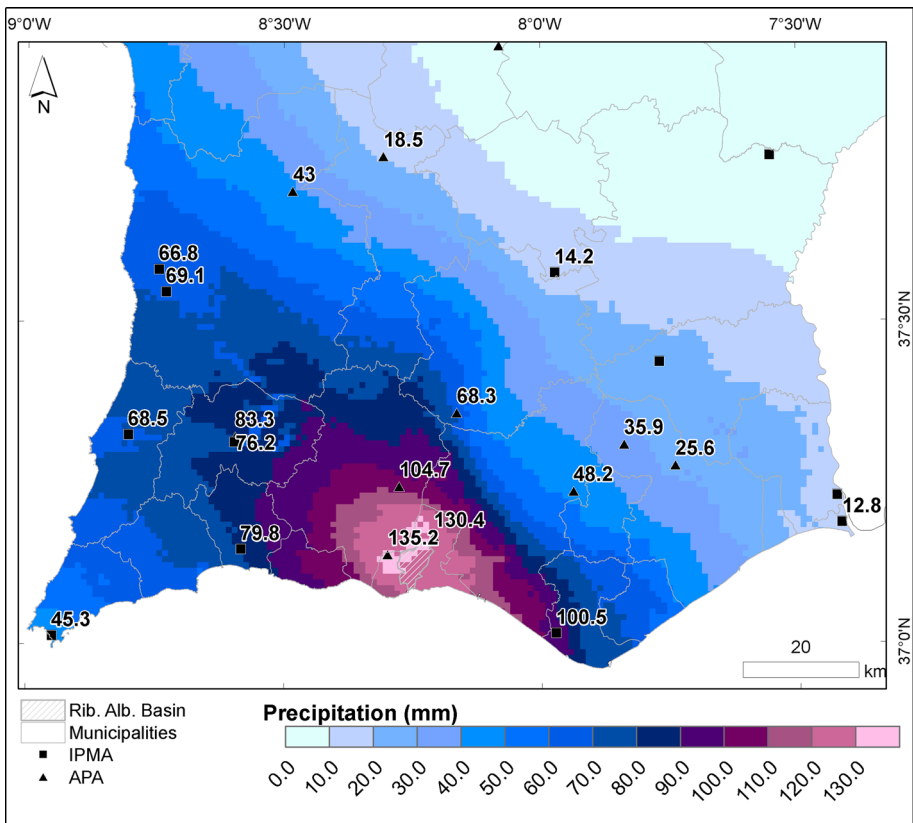


Fig. 8 Accumulated rainfall in the 12-h period from 0300 to 1500 UTC on 1 November 2015, (radar–rain gauge adjusted estimate)

concentration time. Adding the fact that Albufeira has grown around the river (Fig. 9), with use of the floodplain (Fig. 10), it is perceived that the water retention capacity due to its excessive waterproofing is currently very small. Very low concentration time and lack of retention capacity are factors responsible for flash floods, contributing to the fact that similar precipitation values occurred in areas of lesser vulnerability would not have the same impacts as in Albufeira, amplified by the relief morphology (Fig. 10).

The effects of soil waterproofing may be easily understandable by just watching the photographs on Fig. 9, with a difference of about 70 years from each other.

Thus, it is not surprising that on 1 November, the effects of high precipitation were quite different from site to site. Albufeira was clearly the place where the effects were most felt, with heavy damages in some dwellings and mainly commercial establishments, namely in downtown. In Quarteira, where the precipitation values were quite similar, there have been also damages in commercial establishments and housing, albeit to a lesser degree. Notwithstanding, in Armação de Pêra, where the amounts of precipitation were also quite high, as can be seen in Fig. 8, the effects were not felt in the same way.



Fig. 9 Albufeira in the 40s (top) and Albufeira nowadays (bottom). (Unknown author)

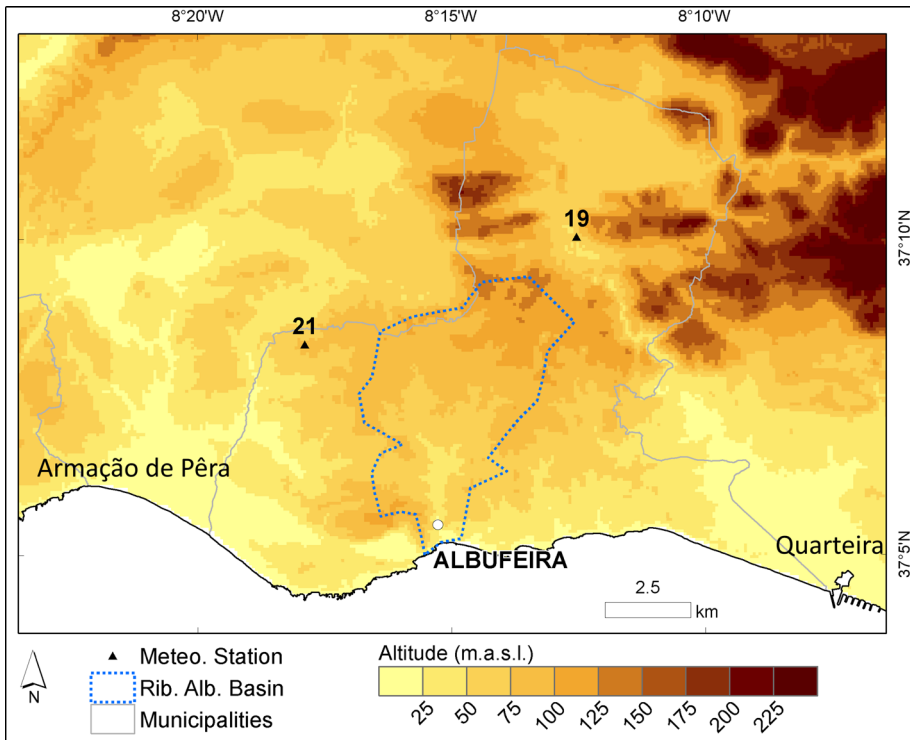


Fig. 10 Albufeira’s surrounding orography. White dot marks the place where photographs in Fig. 9 were taken

6 Conclusions

On 1 November 2015, the Algarve region has been subject to severe weather conditions, with strong and persistent precipitation.

The windward Algarve, namely the zone between Portimão and Faro, with particular incidence in the coastal zone between Armação de Pêra and Quarteira and heading inland to N and NW in Albufeira region, until about 25 km from the coast, has been subject to amounts of precipitation much higher than the normal values. The spatial pattern of the zone with higher values of precipitation presented a SE-NW orientation and had the peculiarity of maintaining this configuration for an extended period of time.

This pattern was fully confirmed by the analysis of the precipitation field obtained with the available observation instruments, rain gauges and the L/CC weather radar.

The application of a radar–rain gauge merging method confirmed that the SE zone of the municipality of Silves, the city of Quarteira and the municipality of Albufeira, in particular its river catchment, with an average value of accumulated rainfall of 129.0 mm between 0300 and 1500 UTC, were the most affected areas by heavy precipitation.

The application of the merging method led to a reduction in the errors of the precipitation estimates evaluated by cross-validation when compared to IDW or radar RAIN1 product, thus being completely justified.

Although the precipitation levels were quite high, the historical peaks were only exceeded in the Algoz and Paderne weather stations. However, changes in waterlines,

resulting from real estate growth without respect for land morphology, have had a decisive influence. Thus, despite the amount of rainfall that occurred, the effects of intense rainfall seem to indicate an excessive dependence on the terrain morphology and especially the use of the soil, contributing to a greater vulnerability of the affected area.

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