Nowcasting thunderstorms in the Mediterranean region using lightning data

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Abstract

Thunderstorms are often the cause of severe and disastrous flash floods. Lightning activity within these storms can be detected and monitored continuously from thousands of kilometers away and can therefore be very useful in improving forecasts and now-casts of severe thunderstorms. An improvement in the now-casting of such storms can assist in reducing damages and saving lives.

Using the ZEUS ground-based VLF lightning detection network and the Warning Decision Support System – Integrated Information (WDSS–II) software, we performed now-casting simulations using 1 year of lightning data over the Mediterranean area. Thousands of thunderstorms were observed and now-cast 30, 60, 90 and 120 min ahead. Statistical analysis was then done by calculating the hit, miss and false-alarm rates, as well as the POD, FAR and CSI scores in order to determine the success of the now-casting.

The results show that the algorithm is overall successful in now-casting the location of the lightning clusters, especially when applied to strong and consistent lightning events (it is these events which also have the strongest connection to flash floods). The probability of detection (POD) values range between 0.46 for 30 minute now-casts and 0.25 for 120 minute now-casts. The critical success index (CSI) values are quite similar, but slightly lower. The now-casting has a low false-alarm rate, 0.03 for 30 minute now-casts, which is also beneficial for operational use.

This method has been implemented for the use in real-time now-casting and is used in the EU FLASH project to seek and track areas of thunderstorm risk according to lightning intensity. The experimental now-casts appear on the project website (www.flashproject.org/).

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1. Introduction

Severe and extreme weather such as severe thunderstorms, hail, wind storms, tornadoes, hurricanes, floods, etc. have always presented dangers and threats to human life while causing destruction and damage in their path. Sectors and activities impacted include agriculture, aviation, infrastructure (roads, bridges), homes, and even sporting events.

In recent years there is growing evidence that due to climate changes, extreme weather events are becoming more common in the eastern Mediterranean region (Alpert et al., 2002) and in Europe (Ashton, 2003). In addition, growth in population itself causes more people to be at risk, while the resultant expansion of urbanized areas creates favorable conditions for extreme events such as floods (Davis, 2001), and along coastlines raises the risk for damages from hurricanes. These two aspects together, the increased frequency of extreme weather events and the growth of the population, contribute to the increase of damages and losses.

Among extreme weather events, flash floods are a serious problem in the Mediterranean region in particular, and in Europe in general (Porcu et al., 2003). After droughts, floods are the most important meteorological hazard that affects the
Mediterranean countries, followed by wind storms and hail (Llasat-Botija et al., 2007).

Flash floods are characterized by their short lived nature and any flood that occurs at a certain location within a few hours after the causative rainfall is considered a flash flood (Georgakakos, 1986). Because of their unexpected nature, flash floods are in general difficult to predict.

The most obvious and dramatic feature of the convective process is lightning, producing electromagnetic radiation in the very low frequency (VLF) band (5–15 kHz). The radiation can be detected from thousands of kilometers away from the parent thunderstorm, and therefore most operational regional lightning detection networks detect VLF radiation, providing information about the lightning flash (time, location, peak current, polarity, multiplicity, etc.).

It is known that both lightning and rain processes are related to cloud microphysics and that strong updrafts impact both phenomena. Furthermore, precipitation plays an important role in separating electric charge in thunderstorms to produce lightning (Williams, 2001; Williams et al., 1989). Many studies give evidence of a relation between lightning and rainfall and show that in most cases an increase in rain rate corresponds to an increase in lightning (Battan, 1965; Carte and Kidder, 1977; Gungle and Krider, 2006; Pessi and Businger, 2009; Tapia et al., 1998; Zhou et al., 2002). This correlation is generally better for higher precipitation amounts (Katsanosa et al., 2007). Studies aimed to quantify this relationship reveal that this relationship changes according to a number of factors such as, the stage in the life cycle of the storm (Tapia et al., 1998), the storm type, which also relates to geographic location (Petersen and Rutledge, 1998), the climate regime (Soriano and De Pablo, 2001) and the lightning type (Soula and Chauzy, 2001). Differences between ocean and land storms were also found (Takayabu, 2006). In addition, cloud-to-ground (CG) lightning was found to be spatially correlated with the area of high precipitation (Carte and Kidder, 1977; Soula, 1998; Soula and Chauzy, 2001; Tapia et al., 1998) and temporally, it was found that rainfall generally lagged behind the occurrence of lightning by a few minutes (Gungle and Krider, 2006; Piampass et al., 1982; Soula, 1998). Strong correlation was also found in larger temporal scales, such as monthly and seasonal variations (Price and Federmann, 2006).

The strong relationship between lightning and extreme rainfall is also evident from several studies in which lightning data was shown to provide additional information for the decision making process when facing the possibility of severe weather (Gatlin and Goodman, 2010; Goodman et al., 2005; Montanya et al., 2009; Schultz et al., 2009; Wiens et al., 2005; Williams et al., 1999).

The devastating effects of thunderstorms, described earlier, are the reason that now-casts are so greatly needed. Now-casting is defined by forecasts in time that refer to periods less than a few hours (Wilson et al., 1998). Today the primary tools for detecting convective storms are weather radars, lightning detectors and satellite imagery. For short period forecasts, the most prominent of these is radar reflectivity echoes (Wilson et al., 1998), although radars are limited in range to approximately 250 km.

Extrapolation techniques based on radar data were the earliest now-casting techniques developed. These include the cross-correlation method (Rinehart and Garvey, 1978) that calculates a motion vector field and provides information on larger areas of reflectivity and the centroid-type method (Crane, 1979) that tracks individual isolated storms effectively. Examples of systems based on the latter method are the Thunderstorm Identification, Tracking, and Nowcasting (TITAN) (Dixon and Wiener, 1993) and the Storm Cell Identification and Tracking (SKIT) (Johnson et al., 1998). (Hering et al., 2004; Hering et al., 2005) used a radar based tracking method called Thunderstorm Radar Tracking (TRT) to identify and track storms in complex terrains. S-PROG is another advection-based now-casting system (Seed, 2003) that improves the prediction by now-casting different features at different spatial scales. The NCAR auto-now-cast system (ANC) (Mueller et al., 2003) also has the ability to now-cast storm initiation and dissipation. A recent method for tracking and now-casting of convective cells was suggested by (Kober and Tafferner, 2009).

Several studies have used satellite data in the context of tracking and now-casting algorithms (Bolliger et al., 2003; Carvalho and Jones, 2001; Feidas and Cartalis, 2005; Zinner et al., 2008). The usage of satellite data enables a much larger spatial coverage than ground-based data, although the discontinuity that arises from the orbits of the satellites restricts the usage of the data to specific events. Some studies have made use of lightning data to improve now-casts (Betz et al., 2008; Goodman, 1990; Papadopoulos et al., 2005; Rossi and Mäkelä, 2008; Steinacker et al., 2000). Methods for tracking thunderstorms using lightning can also give valuable information regarding lightning flashes in thunderstorms, such as flash rate, density, polarity and amplitude. Cells defined by radar data can also be defined by lightning data. Both data sources can be used for the recognition of the stage of the life cycle of the convective cell.

The work discussed in the present paper was conducted in the frame of the European Union FP6 project FLASH (www.flashproject.org). The main motivation for the FLASH project was to improve our understanding and forecasting ability of flash floods in the Mediterranean region. The FLASH project is a combined effort of 5 countries — Spain, Italy, Israel, Greece and Cyprus, to contribute to the research on flash floods with the aim to improve public awareness and provide warnings of these severe weather phenomena.

The goal of the study is to improve the analysis and short term forecasting of intense convection using only lightning data. There are a number of reasons why this is beneficial: it greatly simplifies the usage of a now-casting model (lightning data are simple to use); allows for real-time usage; and it can cover areas that are not observed by radar. Therefore now-casting using lightning data can be very useful for predicting floods over large spatial scales. It also gives a short term prediction of lightning, which is by itself a dangerous natural phenomenon. The paper is ordered as follows: the Section 2 gives an introduction of the lightning data used and of the WDSS–II software with which the now-casts of the lightning clusters were produced. The Section 3 describes the now-cast verification process. The Section 4 presents the results of the research. The Section 5 is a summary and discussion of the results and the Section 6 presents ideas for future work.
2. Method and data

2.1. Lightning data

The ZEUS (named after the Greek god of lightning) network is an experimental long-range lightning detection system (Anagnostou, 2006). The system consists of a network of six Very Low Frequency (7–15 kHz) radio receivers located across the European continent: Birmingham [UK], Roskilde [Denmark], Iasi [Romania], Larnaka [Cyprus], Lisbon [Portugal] and Athens [Greece].

The ZEUS locating algorithm relies on the Arrival Time Difference (ATD) technique (Lee, 1986). The ZEUS system with current receiver configuration can detect lightning activity over Europe, North Africa and part of the Atlantic and West Asia. One of the greatest advantages in using lightning data is that it is near real-time data. Lightning data from the ZEUS network can be received in minutes from the time of their occurrence. This is particularly advantageous when performing 1–3 hour now-casting simulations.

The ZEUS system provides continuous measurements of lightning activity over a very large region with high locating accuracy and detection efficiency. In a comparison between the ZEUS and the Lightning detection NETWORK (LINET) networks over Western Europe (Lagouvardos et al., 2009), the location error of ZEUS was calculated to be 6.8 km (The LINET system has a much smaller error), with a detection efficiency of 25% of total lightning and a characteristic under-detection during nighttime.

2.2. WDSS–II – software algorithm

The Warning Decision Support System–Integrated Information (WDSS–II) was developed by the National Severe Storms Laboratory and the University of Oklahoma (Lakshmanan et al., 2007). It is the second generation of a system of tools for the analysis, diagnosis, and visualization of remotely sensed weather data. WDSS–II provides a number of automated algorithms that operate on data from multiple sources to provide information with high temporal resolution and spatial coverage. After receiving the raw data, the software grids it into a density matrix and using a hierarchical k-means clustering method is able to define storm clusters at different scales (Lakshmanan et al., 2000; Lakshmanan et al., 2002). The hierarchical clustering method uses additional information to assign pixels/data to a cluster — the Euclidean distance and a contiguity measure. The technique provides nested partitions, in which the identified storm structures are strictly hierarchical, where the larger scale is composed of multiple clusters from smaller scales. The motion of the storm clusters is then estimated by comparing two consecutive frames, objectively matching clusters over time, thus finding the movement that minimizes the absolute error between the two frames. The now-casting is performed based on the motion estimates, growth and decay of the current data.

2.3. Experimental setup

In this research, WDSS–II was used with lightning data received from the ZEUS lightning network to produce lightning density, to identify cells, to track storm clusters and to produce now-casts.

In order to test the now-casting skill of WDSS–II with ZEUS data, we used 1 year of lightning data, for Jan–Dec 2008, producing now-casts every 15 min for lead times 30, 60, 90 and 120 min. The study area includes the entire Mediterranean and Europe region, from latitude 32°N to 50°N, and longitude of 8°W to 35°E. The lightning density was gridded into 0.1°×0.1° boxes.

The now-casts produced refer to lightning density; however, in order to evaluate the now-casting skill we looked at the lightning clusters produced, comparing the location of the now-cast clusters with the location of the observed clusters.

When using WDSS–II algorithms it is possible and usually required to set some of the initial parameters to values that are tuned according to the overall performance of the now-casting system. First, the time step of the lightning density was calculated every 15 min over a period of 30 min. Second, the number of K segments into which the image is segmented was set. This divides the lightning density into K segments according to the value of the pixel, defines a minimum value, under which the data are discarded, and a maximum value, over which the value is regarded as the value of the maximum. We found that a coarser division works better, as the lightning data can sometimes be missing. The minimum density threshold was set to be 1 flash per 15 min/pixel (100 km²) and values smaller than this were discarded. In order to reduce the influence of extreme values, a maximum threshold was set to 5 flashes/15 min/pixel and values above this threshold were set to this maximum value. Finally, the minimum cluster size for each scale is also defined. We defined scale 0 to be a minimum of 1 pixel, which is 100 km². Scale 1 to be a minimum of 10 pixels, which is 1000 km², and scale 2 to be a minimum of 20 pixels, which is 2000 km². This is done according to the type of data and the resolution needed.

3. Verification

As described in the contingency table (Table 1), the verification was done in the following way — if at (t + dt) a cluster was now-cast and a cluster of overlapping pixels above a certain threshold was detected in the observation, this is considered as a hit. If a cluster was detected in the now-cast but not observed, this was considered as a false alarm, and if a cluster was observed but not now-cast, this was determined as a miss. We then counted the total number of hits, misses and false alarms. The percentage of hits was calculated by dividing the number of hits by the total number of clusters now-cast. The percentage of false alarms was also calculated by dividing the total number of false alarms by the

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total number of now-cast clusters. The percentage of misses was calculated by dividing the number of misses by the total number of observed clusters. A hit was determined if there was at least 1 pixel overlap between the now-cast cluster and the observed cluster (corresponding to an overlapping area of 100 km²). In addition, the analysis was done taking into account a range of ‘effective radii,’ defined as an area around the predicted cluster in which to search for the observed cluster (Fig. 1). This was done because the more basic analysis does not take into account situations of ‘near hits,’ when storms are correctly predicted to occur but the predicted location is slightly missed. For this reason the effective radius can improve and refine the results.

Another statistical evaluation made was the calculation of the probability of detection (POD), the false-alarm ratio (FAR) and the critical success index (CSI), also known as the threat score (TS) (Schaefer, 1990). The definition of each index is given in Eqs. (1), (2) and (3) below. Each index can give slightly different information regarding the success of the now-cast. The CSI is one of the indicators of the value of a forecast warning, and assumes that an event that was neither now-cast nor observed is of no consequence. A perfect score of a CSI would be 1. Other variations of the score have been developed to also take into account correct negative forecasts, such as the equitable threat score, true skill score and Heidke skill score (Doswell et al., 1990; Schaefer, 1990). The Heidke skill score can be used when the correct now-casting of null events is known, i.e. when the verification of the now-cast is done per pixel. However, in the cluster by cluster analysis done here, this is not the case. These clusters can have different shapes and sizes and so the comparison is never between identical spatial structures. This does not allow for calculation of the null events. Therefore, we present only the CSI values. The POD is the ratio between the number of correct forecasts (hits) and the total number of events and shows the percentage of events now-cast. The false-alarm ratio is the ratio between the number of unsuccessful now-casts (false alarms) and the total number of the now-cast events and is a measure of the failure of the forecast to exclude non event cases.

\[ \text{POD} = \frac{\# \text{ Hits}}{\# \text{ Hits} + \# \text{ Misses}} \quad (1) \]

\[ \text{FAR} = \frac{\# \text{ FalseAlarms}}{\# \text{ FalseAlarms} + \# \text{ Hits}} \quad (2) \]

Fig. 1. An example of hits, misses, and false alarms for a 60 minute now-cast. (a) With an effective radius of 0. (b) An effective radius of 5 pixels. (c) The actual cluster at that time. (d) Real lightning density.
CSI = \frac{\# \text{ Hits}}{\# \text{ Hits} + \# \text{ Misses} + \# \text{ FalseAlarms}} \tag{3}

4. Results

In order to examine the now-casting ability of the method used in this study, it was applied on a number of case studies of flash floods that occurred in Europe. Here we will discuss two such cases, the first is from Barcelona and the second is from Rome. Both cases were chosen for analysis in the FLASH project because of the extent of the event and the availability of data.

4.1. Case study: 12–14/09/06 – Barcelona

This case study affected the whole region of Catalonia and was characterized by flash floods, tornadoes, lightning and landslides. Recorded rainfalls between the 12th and 14th of September were between 100 and 250 mm in 24 h. There was a maximum accumulated rainfall of 267 mm in the south of Catalonia, and 256 in the north. One person died. Besides damages to agriculture and urban area, a traffic jam brought Barcelona city to a standstill, 40,000 people were affected by railway cuts, Reus airport was closed and long delays were recorded at Barcelona airport. The CCS insurance company paid out €55,993,194 for damage generated by floods and landslides and €3.15 million for damage produced by tornadoes (Llasat et al., 2010).

Fig. 2 shows now-casting of one of the storms passing over Barcelona on the 13/09/2006; the now-cast showing the north-east movement of the storm. At 09:45 (all times are in UTC) three of the four clusters were able to be now-cast, all showing the same movement.

An analysis of the now-casting ability is seen in Fig. 3. The ability decreases with increasing lead times, with fewer hits and more false alarms. It is interesting that the 60 minute now-cast produced a greater number of clusters. This is due to the fact that the now-casts are based on the motion estimation which is done only according to the previous frame, so each now-cast is based on a different time frame. The 60 minute now-cast is made based on the motion estimation between times 10:30 and 10:45, so it is possible that at that time there was momentarily an increase in lightning activity leading to a greater number of clusters. Two of the storms were successfully predicted in all times. One storm was successfully predicted for the 30 minute and 60 minute now-cast but was not predicted in the 120 min, perhaps indicating a dissipating storm.

4.2. Case study: 15/06/2005 – Rome

In order to show the versatility of the now-casting method, another case study is presented. This flash flood event occurred on June 15, 2005, in the region of Lazio, including Rome. Although this event brought considerable flooding to the area, there is no documentation on the losses and damages.

Now-casting for specific lead times was performed. Fig. 4 shows tracking of clusters for a period of 45 min (gray/black) and the now-cast of these clusters for lead times of 30, 60, 90 and 120 min (colors). The storms can be seen to be moving north-east. The storms are correctly now-cast to move north-east, entering the affected Lazio region, particularly over Rome where the flooding occurred.

The storm cluster moving towards Rome is seen clearly in Fig. 4 at 05:15, and the 90 and 120 minute now-casts place it above Rome where heavy precipitation was observed at this time. The lightning data at 7:15 (corresponding to the

Fig. 2. Now-casts for a flash flood event that occurred in Barcelona for 13/09/06 09:45 UTC. The actual clusters are shown in black, a 30 minute now-cast in red, a 60 minute now-cast in yellow, a 90 minute now-cast in green and a 120 minute now-cast in blue.
120 minute now-cast) is shown in Fig. 5. Another interesting feature of this event is the splitting and merging of the now-cast clusters, which can be seen in the zoomed-in area of Fig. 4. At the initial time there are three clusters, but 30 min later it is predicted that all three will merge, while 60 min later this big cluster will split again into two and at 120 min one of these

![Fig. 3](image-url) (a) Actual cluster at 11:45, compared with now-casting ability for (b) 30 minute now-cast, (c) 60 minute now-cast and (d) 120 minute now-cast. The number 1 indicates a hit, the number 2 indicates a miss and 0 indicates a false alarm.

![Fig. 4](image-url) Example of clusters being tracked from 04:30 until 05:15 UTC (gray clusters) and then now-cast — 30 (red), 60 (yellow), 90 (green), and 120 (blue) min ahead.

![Fig. 5](image-url)
clusters will dissipate. This demonstrates the advanced ability of this software to deal with splits and merges of clusters which often happens in the observed lightning activity.

Fig. 6 shows the level of the now-casting skill for each lead time (30, 60 and 120 min). In all three now-casts, two clusters were successfully predicted. These storms were probably longer lived, more constant and with intense lightning activity, having a maximum lightning density of $0.02 \times 10^{-2}$ flashes/km$^2$/s (Fig. 5). In all now-cast lead times one cluster was missed. This cluster could have been new or not intense enough to be tracked. All three lead times also predicted a cluster that was not observed at the given time, resulting in a false alarm. It is most likely that this was a decaying storm, even though the now-cast predicted that it was growing.

![Diagram](image)

**Fig. 5.** Real lightning density 120 min after initial now-cast, to be compared with the blue contours in Fig. 2.

![Diagram](image)

**Fig. 6.** (a) Actual cluster at 05:15, compared with now-casting ability, (b) 30 minute now-cast, (c) 60 minute now-cast, and (d) 120 minute now-cast. The number 1 indicates a hit, the number 2 indicates a miss and 0 indicates a false alarm.
4.3. Now-casting scoring

The technique to determine hits, misses and false alarms, as described in Section 3, has been applied to 1 year of lightning data (year 2008) that was input into the WDSS–II software. Now-casts were produced, starting every 3 h in order to avoid multiple assessments of the same cluster. One thousand time intervals were used in the evaluation, consisting of about 6000 storms. Results (Fig. 7) are shown for Scale 2, for four lead times — 30, 60, 90 and 120 min, with the effective radius ranging from 0–5 pixels, which corresponds to 0–50 km around the storm, and for a minimum overlap threshold of 1 pixel which is 100 km$^2$.

From Fig. 7 it is evident that the hits percentage is fairly high, ranging from 90% for 30 minute now-casts to 60% for 120 minute now-casts, for an overlap threshold of 1 pixel. If we include 5 pixels around the now-cast cluster, the hits increase to 95% at 30 min and 75% at 120 min lead time. For the storms that are detected and tracked, the ability to now-cast is high. However, the percentage of misses begins at 60% which means that at least half of the storms are not detected or cannot be tracked and therefore, cannot be now-cast. This could relate to smaller or less intense storms, or perhaps new storms, that are more difficult to detect. The false-alarm rate is quite low, beginning at 10% for 30 minute now-casts and increasing to 50–60% for 120 minute now-casts.

The results were analyzed also according to the POD, CSI and FAR indicators, shown in Fig. 8, as a function of lead time and effective radius and for an overlap threshold of 1 pixel. The probability of detection decreases with lead time and increases with effective radius, as expected, giving between 40–50% for lead times up to 60 min, and 20–40% for lead times up to 120 min, suggesting as was seen before, that for a lead time of 30 min, about 50% of the storms are predicted, this decreases to 30% for a lead time of 120 min.

Looking at the POD in Fig. 8a, two of the most obvious features are the decrease of POD with increasing lead time and an opposite trend with an increase in effective radius. It should be also noted that the increase of POD with increasing radius is more pronounced for the longer lead times. A similar trend can be seen in Fig. 8b, with the CSI values. There is also very little difference between the POD values and the CSI. This is because the occurrence of the false alarms is very low. In Fig. 8c, the effect of the effective radius becomes more apparent, with the increase greatly improving the results with longer lead times. This suggests that the false alarms are more a matter of errors in calculating the location of the storm, rather than in the prediction that a storm exists. Because of the difficulty to predict the dynamics of the clusters, increasing the area of the now-cast can increase the possibility of a successful prediction.

Fig. 7. The vertical axis shows the range of the effective radius (in pixels), the horizontal axis shows the lead times, and the colored contours correspond to the percentage of hits (top panel), percentage of false alarms (middle panel) and percentage of misses (bottom panel). A hit implies an overlap threshold of at least 1 pixel between the now-cast and the observations.
4.4. Cluster attributes

Using the WDSS–II algorithms to track spatial and temporal attributes, we calculated statistics regarding the storms of the 2008 data analysis. We looked at the number of clusters observed and now-cast, the average size of the storms that were accurately now-cast (hits) and the average size of the storms that were missed in the now-cast, as well as the maximum lightning density for each cluster. This analysis assisted in understanding which storms are easier to track and now-cast. Table 2 shows that about half of the observed clusters are now-cast. The size of the clusters now-cast is larger than the size of the cluster missed but the difference in size is not significant. The average size also increases with lead time, which suggests that larger clusters have a longer life time. There is quite a big difference in the lightning density between the now-cast clusters and the clusters missed at the shorter lead times (30 and 60 min). The clusters that were more difficult to track were also less intense. Since the clustering and tracking algorithm is greatly dependant on the intensity, it is reasonable that less intense clusters are more difficult to track. Furthermore, there is less need to track less intense storms, since it is the intense storms that cause the greater destruction.

4.5. Statistics of storm attributes throughout the year

Next, we calculated storm attributes, such as lightning density (Fig. 9a), number of storms (Fig. 9b), size of storms (Fig. 9c) and speed of cells (Fig. 9d), throughout 2008. The analysis was done as a function of the months of the year, in order to examine if there are trends and significant changes during the different seasons.

Previous studies show that in the Mediterranean and central Europe the most intense convective storms occur in the summer (Areitio et al., 2001; Christian et al., 2003; Correoso et al., 2006). This is supported by the findings in Fig. 9a, which shows that the highest maximum density of lightning occurs between June and August. The lightning density is at a minimum during winter months. The lightning density ranges between $0.005 \times 10^{-2}$ flashes/s/km² to $0.03 \times 10^{-2}$ flashes/s/km² which corresponds to about 5 flashes/15min/pixel (100 km²) to 30 flashes/15min/pixel (100 km²). A similar trend can be found in Fig. 9b, which shows that the number of thunderstorms during the summer is significantly greater, amounting to a total of 13,600 storms in the months of June, July and August. In the winter this number decreases by two orders of magnitude to a total of 670 storms in the months December, January and February.

The trend in the size of the storms is shown in Fig. 9c. The size of the storms is quite uniform throughout the year, although the scaling of the clusters can effect these results, since a minimum of storm size was set to 400 km², thus excluding smaller storms. Finally, there are also differences in storm speed between the winter and summer storms, as seen in Fig. 9d. Average storm speed in the winter is 6.2 km/h and in the summer increases to 16.5 km/h. This might be in contradiction with the assumption of faster storms in the winter due to the strengthening of the jet stream at this time, however, it suggests that these storms are convective in nature and therefore more intense and fast during the summer.

Note that due to inter-annual variations in the characteristics of the storms in the Mediterranean and Europe, the above analysis might be somewhat different if performed on several years of data (which is beyond the scope of this study).

<table>
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<tr>
<td>Forecast time 30 60 90 120</td>
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<tr>
<td>Average number forecast 2802 2716 2685 2651</td>
</tr>
<tr>
<td>Average number observed 6130 5996 5852 5673</td>
</tr>
<tr>
<td>Average size [pixel] — hits 37.92 38.24 39.59 41.35</td>
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<tr>
<td>Average size [pixel] — misses 33.36 34.32 35.66 36.45</td>
</tr>
<tr>
<td>Max lightning density — hits $2.99 \times 10^{-4}$ flashes/km²/s</td>
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<tr>
<td>Max lightning density — misses $0.76 \times 10^{-4}$ flashes/km²/s</td>
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**Fig. 8.** (a) POD as a function of lead time and effective radius. (b) CSI as a function of lead time and effective radius. (c) FAR as a function of lead time and effective radius.
Fig. 9. Storm characteristics as a function of the month of the year: (a) maximum lightning density, given in $10^{-2}$ flashes/km$^2$/s. (b) Number of identified clusters. (c) Average storm size, given in km. (d) Average storm speed, given in km/h.

Fig. 10. The results of the analysis used to define a statistical threshold of an 80% probability (blue line) for correctly now-casting an intense thunderstorm.
4.6. Experimental real-time now-casting

A method for real-time now-casting was developed, based on the results of the skill statistics from 2008, and taking into account the decreasing now-casting ability that corresponds to the increasing lead time. A statistical threshold can be defined (Fig. 10), according to which there is at least an 80% probability to correctly now-cast the occurrence of an intense lightning storm. At 30 min, radius zero implies 95% success rate, at 60 min, radius one implies 85% success rate, at 90 min, radius three implies 80% success rate and at 120 min, radius eight implies 80% success rate.

Fig. 11 shows how this can be used to create a forecasting cone; each circle is drawn with a radius equal to the effective radius for that lead time around the now-cast position of the cluster.

This method is currently being used experimentally in real-time and the results of the now-casting are published on the FLASH website: http://www.flashproject.org/. Fig. 12 shows an example of the use of such a real-time now-casting algorithm to predict storms, depicting a now-cast of the storm that affected Rome on 15/06/05. The numbers represent the different clusters or thunderstorm cells.

5. Summary and conclusions

The motivation for this research that was conducted in the framework of project FLASH was to develop an experimental continental-scale real-time now-casting system based only on lightning data. This is in contrast to all existing now-casting systems today that greatly rely on radar and other meteorological data received by local meteorological systems and are therefore limited by the restricted spatial availability of such data. This could be partially overcome using satellite observations, but the discontinuous nature of these observations makes them inappropriate for usage in continuous real-time mode. Lightning, on the other hand, has the advantage of being able to be detected thousands of kilometers away from its source. In addition, many of the areas affected by devastating flash floods do not have the advantage of radar coverage and/or sufficient availability of early warnings. Furthermore, even in areas with adequate data, flash floods are very difficult to predict because of their dynamic nature and surprising appearance.

Both spatially and temporally, a relationship exists between lightning and rainfall, and this relationship can be quantified, especially in strong convective systems. For these reasons, in this research we investigated the possibility of now-casting thunderstorms only using lightning data.

The lightning data used in this research was from the ZEUS network based in Athens. ZEUS is a VLF lightning detection network, with 6 sensors across Europe and primarily detects cloud-to-ground lightning. In order to now-cast convective cells, the lightning data from ZEUS were used by the WDSS–II software, which is a collection of algorithms created specifically to analyze and create forecasts using weather data.

We tested the now-casting system on a few flash flood case studies, including those that occurred in Italy during June 2005 and in Spain in 2006. The results were promising; with storm clusters in the affected regions identified and tracked and their movement now-cast to coincide with the actual observed storms.

The now-casting skill was verified by statistical methods — using data from an entire year: from January 2008 to December 2008, creating now-casts every 3 h for the entire Mediterranean region. The now-casts were evaluated by comparing the location of the now-cast clusters to the actual observed clusters, defining hits, misses and false alarms. This assessment was done for different thresholds of overlapping between now-casts and observations. For an entire year of data, about 1000 time frames of now-casts were generated and analyzed with a total of 6000 different clusters.

Now-casts were generated for lead times of 30, 60, 90 and 120 min, and the now-casting skill was assessed for each lead time. The now-casting skill was also assessed for an effective radius ranging from 0 to 5 pixels, which corresponds to an area of 0 to 50 km around the now-cast cluster. This effective radius defines the area around the now-cast cluster in which to search for the observed cluster.

The results from the 2008 data demonstrated a success rate (percentage of hits) that ranges between 95% for 30 minute lead time to 60% for 120 minute lead time for an overlap threshold of 1 pixel and effective radius of 0. These scores decrease when increasing the pixel overlap threshold and increase when increasing the effective radius, especially

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**Fig. 11.** A now-casting cone, built from the results of the now-casting analysis. Areas of possible activity are defined according to the effective radius and at least 80% likelihood of hits.
for the longer lead times. The percentage of misses begins at 50% and increases, meaning that 50% of the observed clusters are actually now-cast. This can be attributed to the fact that the system is not able to now-cast new, small and less intense storms.

A further analysis was done by calculating the probability of detection (POD), false-alarm ratio (FAR) and critical success index (CSI) for the 2008 data now-casts. The POD values range between 0.465 for a lead time of 30 min and effective radius of 0 to 0.519 for effective radius 5, and 0.252 for a lead time 120 min and effective radius of 0 to 0.389 for effective radius of 5.

The CSI score takes into account the false alarms as well and can therefore give a more accurate description of the now-casting ability. The CSI values are quite similar to the POD, but slightly smaller: 0.46 for a lead time of 30 min and effective radius of 0, and 0.2 for a lead time of 120 min and similar effective radius. It is not possible to compare this score with another; however, it can give information regarding the dependence on the effective radius and the reason for the false-alarm rate. The similarity between the POD values and the CSI values are due to the low false-alarm rate — ranging from 0.018 to 0.033, for a 30 minute lead time. It seems that the greatest effect on the CSI scores stem from the number of misses, meaning the number of clusters not now-cast, which are at least 50%, as was mentioned before. Mostly these are clusters that are inconsistent in movement and/or intensity, which are difficult to track.

There is greater variance in the false-alarm ratio values between the lead times, increasing by an order of magnitude between lead time of 30 min and lead time of 120 min. The effect of the effective radius is also greater for longer lead times, suggesting that the false alarm is less due to the miss prediction of a cluster and more related to errors of the exact location of that cluster.

The cluster attributes of size, lightning density and speed, were also tracked and a comparison of these attributes was made according to the months of the year. As expected, it was found that there are more storms during the summer months, and these storms are more intense in lightning activity and speed than those during the winter months. This is in line with the known meteorological features during the summer and winter in the Mediterranean region.

This now-casting system and the results of its evaluation are used in the FLASH project to issue real-time warnings of thunderstorm activity across the Mediterranean and Europe. Usage of the statistical threshold for the 80% success rate allows us to predict areas with a greater than 80% chance of thunderstorm activity with warnings out to 180 min.

It should be stressed that research of this type, now-casting with the use of only lightning and applying it to a large region such as the entire Mediterranean region, has not been done yet. Furthermore, the verification using 1 year of now-casts over the entire region has never been done before. The existing now-casting systems are assessed usually based on a number of case studies and for small, local regions to which these systems are specifically modified. Therefore, the information given here can be valuable to improve the now-casting procedure, allowing for a more general now-casting possibility and a more constant now-casting ability.

It is quite difficult to assess the ability and value of a forecast. However, the analysis done in this research shows promising results as to the ability to predict intense thunderstorms with the use of lightning data only, which can be utilized and improved in the future. There are other ways of evaluation, which can’t be quantified, such as the usefulness the now-casting can have for users in their decision making process (Murphy, 1993). Lightning data can provide information in areas and/or times when there is no other data to rely on. Also, we believe that it can give additional
information, which can assist in the decision making process, when facing the possibility of severe weather. Finally, it gives new information regarding thunderstorm characteristics viewed only from the perspective of lightning data.

6. Future work

A very relevant continuation of this research related to flash flood forecasting is to develop reliable lightning-rainfall relationships for the Mediterranean region and to incorporate these relationships within the now-casting system, in order to provide now-casts of precipitation. This is currently being conducted with promising results and will be continued throughout the coming years. Further research can also be done by combining satellite IR images with lightning data, using cold cloud area and cloud top temperatures as additional parameters in the now-casting algorithm.

Another improvement that can provide more accurate forecasts is the use of more accurate and voluminous lightning data. In 2016 the Meteosat Third Generation (MTG) geostationary satellite will be launched as part of the GMES program, and for the first time this weather satellite will include the Lightning Imager (LI) to continuously monitor lightning activity from space, allowing the possibility to continuously track and study thunderstorms over Europe and Africa. The LI will have an optical sensor that will detect efficiently both in-cloud and cloud-to-ground lightning discharges.

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