Answer to the reviewer 1 comment of NHESS-2018-319.

We acknowledge the reviewer for the fast and complete review of the paper. In the following we show the actions taken to improve the paper quality. The Author Replies (AR) to the Reviewer Comments (RC) are in blu.

Before discussing in details the RCs, it's import to outline that the subject paper contained two typos. The first refers to the length scale of the background error matrix in the x and y directions that varies between 14 and 25 km and not , between 20 and 30 km, as erroneously reported in the manuscript. The second refers to the correct lightning number for each day are 82 331 for the 9 September, 291 164 for the 10 September (170 000 is written into the manuscript) and 105 467 for the 16 September (60 000 written in the manuscript). Despite the typos, the results shown in the paper were obtained using the correct number of flashes and the correct length scales in the background error matrix.

In the first submission, we stressed the improvement given by the data assimilation at the local scale on the precipitation VSF (Very Short term Forecast, 0-3h). To highlight this point, we showed several ways to improve the forecast by the assimilation of lightning, radar data or both, as it's evident for the Serano case study, for which the radar assimilation impacted the forecast of the first phase (03-06 UTC) whereas lightning impacted the second one (18-21 UTC).

Notwithstanding, given the comments of reviewers 1 and 2 and the results section (Section 4) underwent a substantial rewriting. In particular, in the revised version of the paper, we deleted Section 4.1.2 (second phase of the Serano case study) and Section 4.2.1 (first case of the Livorno case study). The results of Section 4.2.1 are now shortly commented in Section 5 (Discussion and conclusions) to highlight that there is space for improvement. Following the comments of the reviewer #2, the scores of the phases commented in the paper were summarized in three tables (Tables: 4-6) for specific thresholds (1, 6, 10, 20, 30, 40 mm/3h and, for Livorno, also 50 mm/3h). This limited the number of precipitation thresholds considered but increased the readability of the paper.

The space gained by deleting the aforementioned sub-sections was used to extend the discussion about the adopted assimilation methodologies. In particular, we extended the section "Lightning data assimilation" to include a discussion on the useful comments raised by the reviewer 1; we extended the section "Radar data assimilation" to show an example of 3D-Var assimilation of the reflectivity factor (this should also answer to few comments of the reviewer 1).

Finally, we added supplemental material to the paper discussing the following two points: a) the relative contribution to the total water mass given by lightning and radar reflectivity factor data assimilation (Section S1); b) the sensitivity of the precipitation VSF to the nudging formulation (Sections S2). In addition, the supplemental material provides different plots of Figures 15-17 (Section S3, as requested by reviewer 1) and the forward radar operator used in RAMS-3DVar (Section S4), as requested by the reviewer 3.
The important points considered in the supplemental material weren't included into the paper to avoid exceeding the length limit. However, the supplemental material is recalled in several parts of the paper to help the reader to consider it for reading.

Reviewer's preamble

Summary: The authors utilize a cloud-scale functional relationship between lightning and water vapor mass mixing ratio published in the literature and applied it to a homegrown 3DVAR framework at the convection-allowing scale to evaluate the analysis and short term forecast of two selected high impact weather events over Italy.

Recommendation: reject and, eventually, re-submit.

Main Comments:
While the manuscript could eventually offer some merit for this journal, I found the analysis generally very rudimentary with the authors going at length in describing in excruciable level of details individual figures/panels in a repetitive and redundant manner without distilling the content into concise arguments/hypotheses. Given its repetitive nature, the entire results section could, in fact, easily be condensed into a 2-3 pages. Most importantly, the manuscript (hereafter, m/s) lacks rigor and rationales for the set ups and methods put forth for each, respective DA approaches. Salient Major issues are itemized below.

RC(1). As far as the scientific content is concerned, the core ideas and notions of this lightning data assimilation (LDA) method are conceptually similar to those from many existing studies, which fundamentally aim at promoting convective development through the introduction of latent heating within a prescribed neighborhood region/column centered at observed lightning locations. Past works from Benjamin et al. (2004), Alexander et al. (1999), Chang et al. (2001), Papadopoulos et al. (2005), Pessi and Businger (2009), have used empirical relationships between lightning-rainfall rates-latent heating or lightning- reflectivity rates-latent heating [e.g., in the HRRR]. Following a similar idea, recent works such as Machand and Fuelberg (2014), Lynn et al. (2015), Lynn (2017), Fierro et al. (2012; 2014, 2015), Wang et al. (2017, 2018) proposed LDA means that essentially boost the local thermal buoyancy where lightning is observed. A very limited portion of these techniques, however, offer alternative approaches to address spurious convection (i.e., removal) – which is a far more challenging problem to tackle. For completeness and given the relatively limited advances in LDA relative to radar DA, the authors should do a better job in discussing and including all the aforementioned references in their text. I was in fact astonished to notice that the integrity of the Results section in section 4 is completely devoid of references to previous works.
In particular, since they opted to borrow an LDA method from one of these investigators, comparisons with their study should be performed more systematically throughout the m/s. For instance, the works of Federico et al. 2017b is invoked when referring to multi-day forecast statistics using the Fierro et al. method without mentioning that, such a study, was already conducted by the same author over a larger domain and using nearly three times more forecast days/cases (Fierro et al. 2015 study). Given this omission, their study (Federico et al. 2017b) inadequately state that such multi-day statistics for this LDA have never been conducted. In a similar manner, it is of relevance to underline whenever appropriate that, in this work: (i) radial velocity is not included (specify why), (ii) only cloud-to-ground lightning data are considered and (iii) spurious convection is not addressed. In the light of (i) and (ii), one on the recent studies they cite (Fierro et al. 2016) not only assimilated level II radar data (radial velocity + reflectivity factor) but used total lightning data. This needs to be clearly stated, for completeness (Cf comment 3 below for rationales).

AR: In the revised version of the paper we extended the discussion of the LDA in the introduction, in the data and method section and in the discussion of the results in order to include most of the mentioned references.. The problem caused by the missed reference in Federico et al. (2017b) study was corrected in the reviewed manuscript.
Regarding the specific comment (i): it’s worth mentioning that we are working on the assimilation of the radial velocity but the operator is not yet implemented in the 3D-Var. Besides, while the reflectivity factor measured by the radar network is operationally available, the radial velocity is not

operationally processed. Currently, it needs further research to manage some issues (complex orography, scan strategies optimized for rainfall estimation). For these reasons, we focused on the assimilation of the reflectivity factor. These motivations are discussed in the revised version of the paper in Section 3.3 by writing:

“Radial velocity is not assimilated within the RAMS@ISAC model because it is not operationally processed , the scan strategy being optimized for QPE purposes. Furthermore, the implementation of a radial velocity data assimilation scheme is under development in RAMS-3DVAR and it is not currently available for testing. For these reasons, we didn’t consider the assimilation of this parameter. “

Regarding point (ii) in the paper we wrote that total lightning is assimilated, not only CG. For the events analyzed in the paper the fraction of IC strokes to the total number of strokes detected by LINET is about 30% (22% on 09 September, 30% on 10 September and 35% on 16 November). There are cases when the IC strokes recorded by LINET are more than 50% of the total number of stokes over Italy. In general, the Section on LDA has been extended to consider this point and others; (iii) The spurious convection is not considered by the LDA but it is considered in the assimilation of radar reflectivity factor. We specified better this point in the revised version of the paper, but the comment is already present in the first submitted version.

RC (2). In term of DA methodology, I found one major drawback, which is never discussed, nor evaluated. Given that both the LDA and their “RAD” experiment make adjustments to the relative humidity (RH) field, it is expected that both techniques will overlap in their adjustments over all the (many) grid points characterized by observed lightning flash rates exceeding zero. This is because changing RH is equivalent to adjusting Qv as RH ~ Qv/Qv_saturation. A more self-consistent DA approach would adjust the pseudo- observations for the Qv or RH field in a manner that eliminates any possibility of overlap during the minimization. Toward that end, the authors should include soundings and/or horizontal cross sections of RH/Qv that shows, quantitively, how the RH field is adjusted by each respective DA approach (radar vs lightning).

Second, given that lightning is a cloud-scale observation, I cannot find any justifications for not conducting the 3DVAR analysis on the innermost, higher resolution domain. Instead, the method minimizes the cost function on the intermediate domain and, later, projects the innovations on the coarser-scale domain. This needs to be addressed.

AR: First: we added a complete new section (Section S1 of the supplemental material) to address this point. In this section, we show the evolution of the accumulated precipitation and total water mass in the atmosphere (i.e. water vapour mass+mass of hydrometeors) as a function of time (including the spin-up period).

Second:

Data assimilation is not performed on domain D3 (R1) because the use of this domain is exceptional and we don’t have background error statistics for this grid.

The background error statistics for the domain D2 is computed by the NMC method, which, for this paper, is based on HyMeX-SOP1 simulations. The Appendix A and B of Federico (2013) show the details of the application of the method, which requires a large number of simulations (see Barker et al., 2004 for the general discussion). These simulations are not available for the innermost grid of the Livorno case, which was introduced to better resolve the precipitation at the local scale and to show how precise can be the impact of lightning and radar data assimilation on the VSF. These motivations have been clarified in the revised version of the paper.

It is worth specifying that this limitation refers only to the assimilation of the radar reflectivity factor because flashes are assimilated by nudging. Nevertheless, we could not compare simulations with or without data assimilation for a specific domain assimilating lightning in the innermost domain and for this reason we assimilated flashes over the D2 only.

In the revised version of the paper, we specified better the role of the domain D3 and the reason for not assimilating lightning and radar reflectivity factor over the domain D3.

It is specified in section 3.1 (RAMS@ISAC and simulations set-up) as follows:

"The third domain covers the Tuscany Region, has 4/3 km horizontal resolution (R1), and it is used for Livorno to represent with higher spatial detail the precipitation field over Tuscany. The fine structures of the precipitation field are smeared out over Tuscany using only domains D1 and D2. The operational implementation of the RAMS@ISAC model uses the domains D1 and D2 and no refinements for specific areas of Italy are used because Italy is a complex orography country and grid refinements for a specific event can be done only a-posteriori, i.e. after the occurrence of the event."

And few lines below:

"It is noted that data assimilation is performed over the domain D2 (R4) only, and the innovations are transferred to domain D3 (R1), for the Livorno case, by the two way-nesting. The domain D3 is used for the Livorno case to refine the resolution of the precipitation field over Tuscany and to show the spatial and temporal precision of the precipitation forecast over Tuscany using data assimilation. However, its usage is exceptional because, as stated above, Italy is a complex orography country and grid refinements over specific areas are used only after the occurrence of an event. For these reasons the domain D3 is usually not used in RAMS@ISAC and statistics about the background error aren't available for this grid. The background error in RAMS-3DVar is computed by the NMC method (Parrish and Derber, 1992), which requires a number of simulations (at least two-weeks) verifying at the same time but starting with a lag of 12 h. These simulations are not performed in this paper and background error statistics for the domain D3 are not available.

Being lightning assimilated by nudging, they could be assimilated over the domain D3. Nevertheless, to preserve the rationale of the paper, i.e. comparing simulations with or without data assimilation for specific domains, we didn't assimilate lightning over the domain D3.

Because lightning and radar cloud scale observations, their assimilation at higher horizontal resolution is foreseeable in future works."

RC Third, the radius of influence/decorrelation length scale chosen for radar reflectivity factor (50 km) is far too large for convective scale applications and would incur unrealistically large amount of Qv mass added into the domain – which will undoubtedly yield to spin-up issues and the generation of convective-scale gravity waves that will degrade longer term (>= 3h) solutions (please provide plot of perturbation pressure in your response). In that regard, the authors should indicate and contrast the total amount of Qv mass added by RAD and LIGHT.

AR: The 50 km length is not a distance to spread the innovation introduced by the radar reflectivity factor data assimilation. It represents a search radius to compute the pseudo-profile of relative humidity used in 3D-Var. A discussion about this point was introduced in the new section on radar reflectivity factor data assimilation (Section 3.3).
In particular, we wrote:

"It is important to point out that the 50 km length-scale of the above step doesn't represent the horizontal correlation length-scale of the background error, which determines the horizontal spread of the innovations in the 3D-Var data assimilation (the latter length-scale is between 14 and 25 km depending on the level). The 50 km length-scale is used to set a square for computing the pseudo-profile of relative humidity (Eqn. (2)). This profile is given by a weighted average whose weights are determined by the agreement between the simulated and observed reflectivity factor. The larger the agreement the larger the weight. This distance seems appropriate because the spatial error of meteorological models in simulating meteorological features, for example fronts, can be of this order. The control simulation for the two events considered in this paper confirms this choice."

RC (3). In the context of forecast improvements, the Qv-based method they borrowed/adapted was scaled for total lightning data (> 50% detection efficiency of intra-cloud [IC] flashes). I was surprised to find that absolutely no information on the detection efficiency and geolocation accuracy of the lightning network used (LINET) is provided in the text [no figures either]. Given the large area covered by this study, it is thus very likely that the geolocation accuracy of this network remains very poor for low amplitude flashes and for all flashes over oceanic regions. Given the low sferics amplitudes of IC flashes, the VLF portion of the sensor will miss nearly all these flashes, while the VHF portion only is able to detect some of the IC flashes within a few tens of kilometers away from the station [e.g., Rison, MacGorman works]. Thus, it is relevant to state and underscore that LINET only detects a very small portions of the total IC flashes in the study domain (likely < 5%). Motivation for scaling the F12 method for IC flashes (in lieu of cloud-to-ground [CG] flashes), lies in the well-documented finding that, in contrast to CGs, ICs are well correlated with thunderstorm kinematic and microphysical evolution (updraft strength, updraft volume, graupel mass etc, see Wiens et al. 2005, Schultz et al. 2011 among many others). CGs, on the other hand, were found to be correlated with the descent of reflectivity cores and the onset of the demise of the storm's updraft core [MacGorman and Nielsen 1991, MacGorman et al. 1989, Rutledge and Lang's seminal works etc]. Not surprisingly, ICs were found to lag CG by an average of 15 min [see one of the recent MacGorman study]. Moreover, Boccippio et al. 2001 and Medici et al. 2017 found that in deep continental convection, IC flashes always outnumber CGs by a ratio sometime exceeding 10:1. Based on these facts, it becomes clear why the Fierro method emphasized the use of IC flashes [or total lightning] for their application. Further motivation arises from the recent successful launches of the GLM instrument aboard GEOS-16/17, which will provide continuous day/night coverage of total lightning at ~90% detection efficiency (DE) over a large domain covering the Americas (Gurka et al. 2006; Goodman et al. 2012, 2013, Rudlosky et al. 2018). Note that GLM will provide flash extent information of lightning, while the metric derived from the (limited) point flash data in this study can only provide a very rough surrogate for CG flash location density at best. Similar space-borne technology to detect lightning have been developed by China (Feng-Yun-4, yang et al. 2016) with these data being assimilated in recent works by Wang et al.

(2017, 2018) – which were never referenced either. Apart from their propensity to detect total lightning at a high DE, the chief advantage of this technology lies in its ability to retrieve lightning over remote oceanic regions.

AR. LINET has been started and used operationally since 2004. Since then, more than 100 publications provided evidence about both DE and location accuracy (LA). In particular, since the beginning in 2004 LINET exhibited a statistical average location accuracy of some 100 m. Because a minimum of 5 sensor reports are exploited for each stroke solution, the LA does not deteriorate within several 100 km from a sensor. Thus, the LA is excellent all over the present study region.

LINET Europe comprises more than 200 sensors and provides more extensive stroke data than any other VLF/LF system in the region.

LINET detects and records stroke signals down to currents of a few kA (CG normalization). This is the reason why LINET ranges are large enough to exploit >=5 sensors for geolocation without reducing the typical baselines of 250-300 km. The resulting DE is good enough to detect any CG. Over the Mediterranean the stroke DE diminishes due to larger baselines. However, the flash detection is less sensitive because of the stronger strokes that characterize a flash.

Like any other VLF/LF system signals are recorded whether CG or IC. Thus, the detected IC portion is certainly not lower than in any other VLF/LF system. As a consequence, total lightning is reported at least as efficient than in any other VLF/LF system, and will be beneficial for the purposes in the present paper.

IC discrimination of LINET is based on TOA analysis. The advantage is a unique discrimination when the detection geometry is within certain ranges; the disadvantage is decreasing discrimination power when the distance to the closest sensor become too large, because of too small TOA differences between CG and IC at the same 2D location. Thus, over water far from land the identified IC fraction decreases, though total lightning counts remain relevant.

It is true that leader steps signify discharge processes (see, e.g., well-known LMA results). However, it is well-proven that VLF/LF detects pulses from IC activity that are very similar to CG strokes; this is why CG-IC discrimination is very challenging for VLF/LF systems. We think, though, that any VHF issue is not relevant here, because there is no large-scale VHF system that covers Italy and the surrounding sea with baselines of a few 10 km.

Observations from global networks or satellites may be a point of future concern, but do not represent any focus in the present paper; also, IC discrimination is either not yet possible or poor. It may be mentioned that GLM lightning data is not yet an issue; interestingly, Eumetsat/NASA on behalf of NOAA have selected LINET to carry out the first evaluation of the new lightning data source. This has been communicated in Science Team Meetings and conferences (see GLM Cal/Val 2017 Ground Validation Field Campaign 2017).

The discussion about the LINET network has been extended in the revised version of the paper.

RC (4) The following key information pertaining to the respective DA methods are missing/never discussed:
(a) What are the background/observation errors for reflectivity/lightning? (b) What statistics are used for model error?

AR. Lightnings are assimilated by nudging and no error is associated with them. The error matrix for model error has been clarified in the section on the radar reflectivity factor data assimilation (Section 3.3).

RC (c) How is the adjoint for the lightning data assimilation operator derived?
AR. The derivation of the adjoint of lightning data assimilation was performed using two case studies of the HyMeX-SOP1 (unpublished work) as commented in Federico et al., (2017a). We commented about this point in the new section on lightning data assimilation. Also, the supplemental material (Section S2) shows the sensitivity of the rainfall VSF scores (POD and ETS) to the nudging formulation.

RC (d) What assumptions are made for grid points with zero lightning or zero reflectivity observations ? Does the radar DA or LDA treat those as missing observations or equate those to the background values to reduce spread ?
AR. Lighting are assimilated by nudging and this comment doesn't apply. In the case of radar, grid points with zero reflectivity factor and zero simulated reflectivity factor are assumed missing observation, and the innovations can spread according to the background error matrix. This has been clarified in the revised version of the paper (Section 3.3).

RC (e) What Gaussian decorrelation length scales are assumed for each observation? Please specify/justify/explain. How would the selection of a given length scale value, influence the results ?
AR. The observation error matrix for radar reflectivity is diagonal (this was already stated in the first submission of the paper). We acknowledge that the sensitivity tests proposed by the reviewer are interesting, nevertheless they are left for future studies. The importance of this point is discussed shortly in the revised version of the paper. We wrote:

"The observation error matrix R in Eqn. (4) is diagonal and observations' errors are uncorrelated. This choice is partially justified by under sampling the radar reflectivity factor observation by choosing one point every five grid points in both horizontal directions of the radar observations Cartesian grid (Rohn et al., 2001). However, correlation observations errors have significant impact on the final analysis, as shown for example in Stewart et al. (2013), and different choices of the matrix R will be considered in future studies.
The value of the elements on the diagonal of R depends on the vertical level and are 1/4 of the diagonal element of the B_z matrix at the corresponding height. By this choice, we give more credit to the observations than to the background and analyses strongly adjust the background towards observations."

RC (f) Is spurious convection addresses by either DA method ? Please elaborate.
AR. Yes, in the radar reflectivity factor data assimilation, but not in lightning data assimilation. The point is already present in the discussion paper, but it has been clarified in the revised version of the paper in the section dedicated to the radar data assimilation (Section 3.3).

RC (g) Does the variational minimization set use a multi-scale approach ? If yes, what influence radii are chosen and how many cycles ?
AR. We don't use the multi-scale approach. This has been clarified in the paper in the section dedicated to the radar data assimilation (Section 3.3).

RC (5) Why did the authors not include the fractions skill score FSS as the main evaluation metric for their forecast? Several works have posited that, in contrast to ETS, FSS does not penalize

displacement errors as much and, arguably, FSS offers a more accurate measure of skill on convection-allowing grids (Mittermaier et al. 2013).
Additionally, more recent studies evaluating forecast performance have been making usage of the so-called performance diagrams, which conveniently merge several key contingency table elements into one single diagram (Roebber 2009). The authors should show such diagrams to provide a more complete and succinct view of the overall forecast performance of the case they selected.

AR. Considering POD and ETS gives the possibility to show the many facets of a forecast, and this is important. These scores are also widely used in the bibliography and this make the results of this paper comparable with other papers. We, of course, acknowledge that there are other interesting measurements of the model performance, as FSS, that could be considered. Taking into consideration this comment and the comment of the reviewer 2 about the score we propose the following solution: we consider three neighborhood radii to take into account for displacement errors; nearest neighborhood (as in the first submission), 25 km and 50 km. We put the scores in three tables (Tables 4-6 of the revised paper) following a remark of the second reviewer.

RC (6) The case studies selected are cherry-picked given the confession that CTRL generally failed to provide reasonable forecast estimates of precipitation for both cases herein. For good measure, fairness and to better underscore the performance of the DA method, the authors should show the results for one case in which CTRL did not perform well and contrast it to one case where CTRL did preform reasonably well.

AR. The events were selected because they were missed by several forecasts and, for this reason, they are challenging. Moreover, they had important consequences because nine people died and damage to properties was extensive. We stressed this point in the introduction by writing:

"The forecast of severe events at the local scale still remains a challenge because of the multitude of physical processes involved over a wide range of scales (Stensrud et al., 2009). The Serano case, being localized in space, poses challenges in forecasting the exact position and timing of convection initiation; the Livorno event involves the interaction between a high impact storm with the complex orography of Italy, which is difficult to simulate at the local scale. For the above reasons the forecast of both events was challenging, as confirmed by the poor forecast of RAMS@ISAC. The difficulty to forecast timely and accurately the precipitation fields of the two events is the reason for choosing them as test cases."

RC (7) The authors omit to mention that the degradation of the forecast at >= 3h is mainly due to saturation of the model solution by errors and biases within the initial / boundary conditions derived from large scale models or re-analysis datasets. This needs to be shown for both cases, especially given the unrealistically large (50 km) decorrelation length scale used for radar reflectivity factor.

AR. Agreed, we considered this point in the revised version of the paper. However, the model errors play also a role in the degradation of the forecast in addition to IC/BC. Again 50 km is not the decorrelation length scale for radar reflectivity factor.
Section 5 (Discussion and Conclusions) was updated by adding the following statements:
"Another important point to study is how long the innovations introduced by data assimilation lasts in the model forecast. While in this study we consider the VSF at 3h, future studies must explore longer time ranges. This kind of study was performed for lightning data assimilation (Fierro et al., 2015; Federico et al., 2017b; Lynn et al. 2015 among others) and for radar data assimilation (Hu et al. 2006; Jones et al. 2014, among others), using a rationale similar to that used in this paper.

In general, the performance of the forecast and the impact of lightning and radar data assimilation decrease with forecasting time because of the propagation of boundary conditions inside the domain and because of model errors. Improving the data assimilation system also contributes to a longer resilience of model performance. The studies cited above showed that lightning and radar data assimilation can have an impact up to 24h depending on several factors (model, data assimilation, quality of the data, meteorological conditions, initial and boundary conditions).
A study considering both radar reflectivity factor and lightning should be performed to understand the resilience of the innovations introduced by data assimilation. ”

RC (8) Title: Revise to include that: (i) primarily CG flashes are assimilated and (2) the model vehicle is RAMS.

AR. We included in the title that RAMS@ISAC is the model vehicle. As stated above, the IC flashes for the case studies considered in this paper is about 30%, which is not a small fraction of the total lightning. The discussion on the method assimilating lightning has been widened to consider this and other points. Considering the comments of the reviewer 3 we decided to include the word “preliminary” to the paper title. The new title is:

“Preliminary results of the impact of lightning and radar data assimilation on the very short term rainfall forecasts of RAMS@ISAC: application to two case studies in Italy”

RC Because these issues are collectively substantial and would require thorough rewriting of the manuscript in many places, I opted not to dwell on editorial comments for the time being. Additionally, the level of English remains, in my view, unacceptable for publication.

AR. We revised the English of the paper, also according to the comments of the reviewer 2 in the PDF file. The copy-editing service of the journal will also improve the quality of the English.

RC Figures:
Figures 5, 6, 8, 12a, 13a, 14a, 15a, 16a, 17a, 18a: The use of colored dots makes it very difficult to effectively compare the observations with those of the simulations: For consistency, either both sets of plots should show colored dots or shaded contours. For lightning, the authors should effectively show the gridded lightning data that were used to create the Qv or RH pseudo-observations.

AR. Agreed. It is always difficult to choose the right representation of the precipitation field when comparing model output with raingauges. We acknowledge that the solution suggested by the reviewer is a good one, however we also like our representation because: a) rainfall at the raingauges is not interpolated, avoiding errors introduced by the interpolation process; b) the rainfall predicted by the model shown as a field gives the possibility to see the behavior of the model also in parts uncovered by raingauges. We propose the following solution: a) redrawing the RAMS@ISAC rainfall field changing the colorbar to match exactly the raingauges colorbar; b) adding the representation suggested by the reviewer as supplemental material to the paper (Figures S3-S5 of the supplemental material); c) recalling the supplemental material when discussing the second VSF of Livorno to highlight the wet frequency bias when assimilating radar reflectivity factor (see Figure S5 of the supplemental material).
Ok for the Figures about lightning. They have been redrawn according to the reviewer remark.

RC Additional comments:

General comment: What is the main rationale for using a model that is marginally known by the community (RAMS) versus a more commonly used, battle tested, publicly available model such as WRF-ARW ? The authors not only seem to re-invent the wheel here but render any potential future work dedicated to reproducibility of the results - to the least - very challenging.

AR. RAMS@ISAC is used/maintained/developed at ISAC-CNR since several years (and it is also operational over Italy since 2000, in different versions/adaptations etc), and it is important for us to test our tool for challenging cases, as those considered in this work.
Also, we are WRF users too (see, for example, Avolio and Federico, 2018) and for the cases of this paper no substantial differences were found for the performance of WRF and RAMS@ISAC models (using the same initial and dynamic boundary conditions). The performance of the WRF model for the Livorno case is shown, for example, in Ricciardelli et al. (2018). The reviewer can verify that the comments given in this paper about the performance of RAMS@ISAC for the most intense phase of the Livorno case can also be applied to the WRF model (see specifically their Figures 11 and 12 for the most intense phases in Livorno). It has to be noted that Ricciardelli et al. (2018) used ECMWF IC/BC, which are different from that used in this paper. So, the results of this paper could be even more valuable because they are "more general" and not linked to the specific modelling tool.

To clarify this point we added the following sentence in Section 4.2.3:
"Considering the evolution of CTRL rainfall forecast for the two VSF of Livorno, we concluded that CTRL was able to predict abundant rain over Livorno, but the rainfall forecast was delayed compared to the real occurrence. A similar behaviour was found in Ricciardelli et al. (2018) using the WRF model, showing that the results of this paper for Livorno are likely not tied to the specific model used."

RC (1) Bottom, page 2: what are "conventional data" ? Why are radial velocity data not used ? Line 70: the main advantage of using 3DVAR vs 4DVAR, EnKF or hybrid methods lies in their already low computational burden. Thus, I do not agree with this justification. Also, variables are not "perturbed"; but adjusted by VAR methods.

AR. See reply to the RC on the same topic, i.e., assimilation of Doppler velocity. We changed the paper according to the reviewer suggestion for the other parts of the comment.

RC (2) Pages 3 and 4: Please refer to Major Comments 1 and 3. Lines 105: Given that "Federico et al. (2017a) implemented the methodology of Fierro et al. (2012) ...", how come on line 112 "We use the method of Federico et al. (2017a) to assimilate lightning..." ? Please revise accordingly.
AR. Ok for this comment. We added the reference to Fierro et al. (2012). The comment of line 112 come from the fact that we intended to cite the adaptation of the methodology, that is discussed in Federico et al. (2017a). We clarified that conventional data are SYNOP and RAOB.

RC (3) Line 124: c.f. end of Major Comment 1.
AR. We wrote "total lightning".

RC (4) Line 240: RAMS used diagnostic relationships (vs explicit) to forecast lightning as it does not explicitly solves for the 3D electric field. Line 243: "Fourth"
AR. For the first comment we wrote: "Second, it predicts the occurrence of lightning following the diagnostic methodology of Dahl et al. (2012),…."

RC (5) Line 290: Delete equation set as these are considered basic/common knowledge.

AR. In some papers, where we omitted the equations, we had the opposite comment. However, for this paper, to reduce length and to give more space to the important points raised by the reviewers the equations were deleted.

RC (6) Section 3.2, lines 300-312: Explicitly state and indicate that equation (2) is from Fierro et al. (2012, 2015) and not from Federico et al. Line 305: Please explain the rationales behind the choices of these constants: In particular, how are the forecast metrics affected for a 20% change in A, which has been shown to exhibit the most notable influence on the forced convection?
AR. Ok for the reference. The functional form is of the same as in Fierro et al. (2012, 2015), but the coefficients were adapted to RAMS@ISAC as shown in Federico et al (2017a). In Federico et al. (2017a) it is clearly stated that the method is that of Fierro et al. (2012), the only difference being the adaptation to RAMS@ISAC model. A sensitivity test to the nudging formulation is shown in the supplemental material (Section S2).

RC (7) Line 316-317: c.f. Major Comment 2.
AR. We clarified better the ability of LINET to detect both IC an CG.

RC (8) End of page 11: c.f. Major Comment 2
AR. Not applicable to the revised version.

RC (9) Line 356: do the authors refer to the LFC or the LCL, (which may I add is an idea borrowed from Marchand and Fuelberg 2014 and Fierro et al. 2016). What is the top of the adjustment layer for lightning ? Please elaborate.
AR. It is the LCL. The idea is of Caumont et al. (2010), we didn't add the reference to this point of the paper because the whole methodology is taken from Caumont et al. (2010), already cited several times. The top adjustment for lightning is -25°C. However, this is already stated in the paper (Lines 314-315 "The check and eventual substitution of the water vapor is performed every five minutes and it is made only in the charging zone (0 °C, -25°C).").

RC (10) Line 410 and elsewhere. This is similar to the results of Fierro et al. 2016. C.f. Major Comment 1. Please establish comparisons with previous works throughout the manuscript.
AR. We integrated better the results of this paper with those of previous works.

RC (11) Line 669: This statement is incorrect. The DE of ground based sensors levels off very rapidly with distance from land. This is where space-borne lightning detection systems such as the GLM or Feng Yun-4 can fill the gap.
AR. Ok, however the good coverage of the LINET network for some important areas, as between Corsica and Italian mainland (both Liguria and Tuscany) makes this point "less problematic" for the Livorno case, while the Serano event occurred over the Italian mainland.

RC (12) Lines 716-725: c.f. Major Comment 1.
AR We added the references. (Fierro et al., 2015; Federico et al., 2017b; Lynn et al. 2015, Hu et al., 2006; Jones et al., 2014).

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Answer to the reviewer #2 comments on NHESS-2018-319.

We acknowledge the reviewer for the useful comments on the paper, both in the general comments section and in the pdf file. Our answers are in red. The Author Replies (AR) to the Reviewer Comments (RC) are in blue.

AR: Before discussing in details the RCs, it's import to outline that the subject paper contained two typos. The first refers to the length scale of the background error matrix in the x and y directions that varies between 14 and 25 km and not , between 20 and 30 km, as erroneously reported in the manuscript. The second refers to the correct lightning number for each day are 82 331 for the 9 September, 291 164 for the 10 September (170 000 is written into the manuscript) and 105 467 for the 16 September (60 000 written in the manuscript). Despite the typos, the results shown in the paper were obtained using the correct number of flashes and the correct length scales in the background error matrix.

RC: Extracted from the general comments:

This manuscript addresses an interesting and challenging topic, moreover represents a substantial contribution to the understanding of natural hazards and their consequences matching the scope of NHESS. However, the scientific and presentation quality are poor, above all because the results are presented in a "repetitive and heavy" manner and the English language needs a deep revision.

Specific comments: please see the notes on the pdf for each section and also for each figure's caption, moreover please deeply motivate the reason why: a) radial velocity is not assimilated: the operator is not implemented or the data are not available?; b) data assimilation is performed in the domain D02 only; c) you used a background error matrix of fall 2012 for case studies of late summer 2017. Technical corrections: please see the notes on the pdf for each section and also for each figure's caption.

AR: Comment "…in a repetitive and heavy manner". In the first submission of the paper we stressed the important improvement given by the data assimilation at the local scale on the precipitation VSF (Very Short term Forecast, 0-3h). To highlight this point, we showed the many ways in which the forecast is improved by the assimilation of lightning, radar or both data. For example, the two stages of the Serano case show that the radar (first phase 03-06 UTC on 16 September) or lightning (second phase of the event, 18-21 UTC on 16 September) were the key observation to assimilate in order to improve the precipitation VSF. Also, other stages had specific aspects that we discussed.

Our attempt, however, was not successful, considering the comments of reviewer #1 and reviewer #2 and the results section (Section 4) underwent a substantial rewriting. In particular, in the revised version of the paper, we deleted Section 4.1.2 (second phase of the Serano case) and Section 4.2.1 (first case of the Livorno case). The results of Section 4.2.1 are shortly commented in Section 5 (Discussion and conclusions) to highlight that there is space for improvement. Following the comments of the reviewer #2, the scores of the phases discussed into the paper have been put in three tables (Tables: 4-6) for specific thresholds (1, 6, 10, 20, 30, 40 mm/3h and, for Livorno, also 50 mm/3h) and, following the remarks of the reviewer #1, different neighborhood radii have been used to compute ETS and POD scores.

The space gained by deleting the two sub-sections stated above and by other corrections was used to extend the discussion about the methods of assimilating lightning and radar in the 3D-Var model. These sections should be clear in the revised version of the paper.

Finally, to avoid the repetitive discussion, we added supplemental material to this paper to show how lightning and radar data assimilation works together, presenting the evolution of the total water averaged for all VFS of the two cases and including in this discussion the assimilation stage (Section S1).

The supplemental material shows also sensitivity tests of the precipitation scores (POD and ETS) to the nudging formulation (Section S2). Section S2 requested new simulations with different model settings (see Table S1 in the supplemental material).

Also, the supplemental material contains some plots requested by the reviewer #1 and the formula used to compute the reflectivity factor (dBz) of RAMS@ISAC requested by reviewer #3.

We didn't include the supplemental material in the paper, as stated in the discussion phase of this paper, to avoid excessive length. However, the paper has few references to the supplemental material to help readers to decide if they are interested to this material.

"...the English language needs a deep revision". We revised the English of the paper, also according to the remarks of the reviewer #2 in the PDF file. Also, the copy-editing service of the journal will improve the quality of the English before the eventual publication of the paper.

AR: Specific question a) We are working on the assimilation of the radial velocity but the operator is not yet implemented in the 3D-Var. Also, while the reflectivity factor measured by the radar network is operationally available, the product of radial velocity is under development. At the moment, it needs further research to solve some issues (complex orography, operations of the radars not optimal for the Doppler retrieval and others). For these reasons, the attention was on the assimilation of radar reflectivity factor. These motivations are discussed in the revised version of the paper in Section 3.3 by writing:

"Radial velocity is not assimilated within the RAMS@ISAC model because it is not operationally processed, the scan strategy being optimized for QPE purposes. Furthermore, the implementation of a radial velocity data assimilation scheme is under development in RAMS-3DVAR and it is not currently available for testing. For these reasons, we didn't consider the assimilation of this parameter. "

Specific question b) Data assimilation is not performed on domain D3 (R1) because the use of this domain is exceptional and we don't have background error statistics for this grid. Background error statistics for the domain D2 are computed by the NMC method, which, for this paper, is based on HyMeX-SOP1 simulations. The Appendix A and B of Federico (2013) shows the details of the application of the method, which requires a number of simulations (see Barker et al., 2004 for the general discussion). These simulations are not available for the innermost grid of the Livorno case, which was introduced to better resolve the precipitation at the local scale and to show how precise can be the impact of lightning and radar data assimilation on the VSF. These motivations are clarified in the revised version of the paper.

Of course, this limitation is only for radar reflectivity factor because flashes are assimilated by nudging. Nevertheless, we couldn't compare simulations with or without data assimilation for a specific domain assimilating lightning in the innermost domain and, for this reason, we assimilated flashes over the domain D2 only.

In the revised version of the paper we specified better the role of the domain D3 and the reason for not assimilating lightning and radar reflectivity factor over the domain D3.

We wrote in section 3.1 (RAMS@ISAC and simulations set-up)

"The third domain covers the Tuscany Region, has 4/3 km horizontal resolution (R1), and it is used for Livorno to represent with higher spatial detail the precipitation field over Tuscany and to show better the precision of the rainfall VSF using data assimilation at the local scale. The fine structures of the precipitation field are smeared out over Tuscany using only domains D1 and D2. The operational implementation of the RAMS@ISAC model uses the domains D1 and D2 and no refinement for specific areas of Italy are used because Italy is a complex orography country and grid refinements for a specific event can be done only a-posteriori, i.e. after the occurrence of the event."

And few lines below:

"It is noted that data assimilation is performed over the domain D2 (R4) only, and the innovations are transferred to domain D3 (R1), for the Livorno case, by the two way-nesting. The domain D3 is used for the Livorno case to refine the resolution of the precipitation field over Tuscany and to show the spatial and temporal precision of the precipitation forecast over Tuscany using data assimilation. However, its usage is exceptional because, as stated above, Italy is a complex orography country and grid refinements for specific areas are used only after the occurrence of an event. For these reasons the domain D3 is usually not used in RAMS@ISAC and statistics about the background error aren't available for this grid. The background error in RAMS-3DVar is computed by the NMC method (Parrish and Derber, 1992), which requires a number of simulations (at least two-weeks) verifying at the same time but starting with a lag of 12 h. These simulations are not performed in this paper and background error statistics for the domain D3 are not available.

Being lightning assimilated by nudging, they could be assimilated over the domain D3. Nevertheless, to preserve the rationale of the paper, i.e. comparing simulation with or without data assimilation for specific domains, we didn't assimilate lightning over the domain D3.

Being lightning and radar cloud scale observations, their assimilation at higher horizontal resolution is foreseeable in future works. "

Specific questions c) We chose the background error matrix computed for HyMeX-SOP1 because the period was characterized by several convective events over Italy, as documented in Ferretti et al., (2014), while the period preceding the convective events of this paper was characterized by fair weather, typical of the summer Mediterranean season. For this reason, we believe that the matrix for the HyMeX-SOP1 is more representative of convective events compared to the matrix computed for the period of the storms occurrence. We wrote to comment on this point:

"The background error matrix is computed using the NMC method (Parrish and Derber, 1992; Barker et al. 2004) applied to the HyMeX-SOP1 (Hydrological cycle in the Mediterranean Experiment – First Special Observing Period occurred in the period 6 September-6 November 2012; Ducroq et al., 2014). This choice is motivated by the fact that HyMeX-SOP1 contains several heavy precipitation events over Italy and the background error matrix is representative of the convective environment of the cases considered in this paper. In particular, 10 out of 20 declared IOP (Intense Observing Period) of HyMeX-SOP1 occurred in Italy (Ferretti et al., 2014). On the contrary, the period of September 2017, especially before the events selected in this study was characterized by fair and stable weather conditions over Italy and the background error matrix for September 2017 is less representative of the convective environments that characterise the events of this paper."

RC: PDF file with technical corrections:

AR: Considering the pdf file, all corrections were accepted. There are, however, few points that need a short discussion. They are listed below.

Elements of novelty of the paper: we highlighted better the elements of novelty of this paper in the introduction. We wrote:

"This paper presents for the first time the assimilation of the radar reflectivity factor in the RAMS@ISAC model and shows how the assimilation of the radar reflectivity factor works together with lighting data assimilation. Also, this paper shows how accurate in space and time can be the forecast of the precipitation field using cloud scale observations over complex terrain, contributing in this way to a number of works on the same subject."

Comment on Line 276: The frequency bias was not shown to keep the discussion concise. However, was important to point out that the model has a wet bias, especially when assimilating radar reflectivity factor. For this purpose, we introduced the score that was used to highlight that the model has a wet bias, nevertheless we didn't show any figure to keep the discussion more concise. In the revised version of the paper the wet bias of the model is highlighted better and a discussion on how to reduce the wet bias is added in the "Discussion and conclusions" section (Section 5).

In particular in the "Discussion and Conclusions" section we wrote:

"The wet bias of RAD and RADLI forecast is the main drawback of the results of this paper. To reduce the moisture added by radar and lightning data assimilation further research is needed and different approaches are possible (Fierro et al., 2016). In particular: a) assimilating for a shorter time period (0-6h in this paper); b) reducing the length-scales of the 3D-Var in the horizontal directions to limit the spreading of the innovations or assuming an innovation equal to zero for grid points without lightning and with zero reflectivity factor observed and simulated; c) reducing the amount of water vapour added to the model (for example reducing the values of A and B constants for lightning data assimilation or relaxing the request of saturation when radar reflectivity is observed in areas where the model has zero reflectivity); d) adding moisture to a shallower vertical level.
It is also noted that a combination of heating and moistening could provide the same buoyancy with less water vapour addition (Marchand and Fulberg, 2014)."

While in the supplemental material (Section S2) we wrote:

"It is finally noted that RAD and RADLI have high POD values for all thresholds, nevertheless their ETS is below that of LIGHT and SAT up to 32 mm/3h (RADLI) and 42 mm/3h (RAD). This behavior is caused by the larger number of false alarms given by assimilating radar reflectivity factor compared to simulations assimilating lightning. This result shows again that RAD and RADLI configurations have a wet frequency bias. In particular, the frequency bias of RAD and RADLI configuration is about 3 between 20 and 40 mm/3h."

Line 306: There was a typing error into equation 2 (equation 1 in the revised version of the paper). The correct equation is:

$$q_v = Aq_s + Bq_s \tanh(CX)(1 - \tanh(Dq_g^{\alpha}))$$

and q_g is in the last term. We also note that the number of lightning assimilated by the model is larger than that reported in the first submission of the paper for both cases for a mistake we did in checking the numbers. The correct number of assimilated flashes is reported at the start of this answer. The results, however, were obtained using the correct number of flashes.

Line 314: “The check and eventual substitution of the water vapor is performed every five minutes and it is made only in the charging zone (0 °C, -25°C).” To better explain this choice, we reformulated the sentence adding references to the charging zone:

“The check and eventual substitution of the water vapor is performed every five minutes and it is made within the mixed phase layer zone (0 °C, -25°C), wherein electrification processes are the most active (Takahashi 1978, Emersic and Sounders, 2010; Fierro et al., 2015).”

Line 314: the comment is: could you add some more details about this quality control?

We added two references. We wrote:

“The processing chain aims at identifying most of the uncertainty sources as clutter, partial beam blocking and beam broadening. The radar observations are processed according to nine steps detailed in Vulpiani et al. (2014), Petracca et al. (2018) and references therein.”

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ANSWER to the Reviewer #3

Review of the manuscript
„The impact of lightning and radar data assimilation on the performance of very short term rainfall forecasts for two case studies in Italy"
by
Stefano Federicio, Rosa Claudia Torcasio, Elenio Aviolo, Olivier Caumont, Mario Montopoli, Luca Baldini, Gianfranco Vulpiani and Stefano Dietrich
The study discusses the impact of the assimilation of lightning and radar reflectivity data on the performance of very short-range rainfall forecasts for two convective case studies in Italy. They showed that especially the combined assimilation of both observation types has a clear and positive impact on the forecast performance.
The manuscript is interesting and tackles a very important subject, since the forecast of severe precipitation is still a major weakness of current forecast systems. However, you have to provide more information on how the two observation types are assimilated. The equations and the text you provide are not enough to convince the reader that the methodology with all its coefficients is scientifically justified. Furthermore, I am concerned about the coarse vertical resolution you applied for the simulations.
Therefore, major revisions of the methodology section are necessary before I can suggest the publication of the manuscript.
In the following, I spilt my judgement into major and minor comments.

We acknowledge the reviewer for the useful comments on the paper, both in the general comments section and in the pdf file. Our answers are in red. The Author Replies (AR) to the Reviewer Comments (RC) are in blue.

AR: Before discussing in details the RCs, it's import to outline that the subject paper contained two typos. The first refers to the length scale of the background error matrix in the x and y directions that varies between 14 and 25 km and not , between 20 and 30 km, as erroneously reported in the manuscript. The second refers to the correct lightning number for each day are 82 331 for the 9 September, 291 164 for the 10 September (170 000 is written into the manuscript) and 105 467 for the 16 September (60 000 written in the manuscript). Despite the typos, the results shown in the paper were obtained using the correct number of flashes and the correct length scales in the background error matrix.

We acknowledge the reviewer for the interesting remarks, which helped to improve the paper. In general, we note that both lightning and radar reflectivity factor data assimilation sections have been expanded, as requested by the reviewer, and the "Data and Methods" section should be much clearer in the revised version of the paper. In the following there are important points raised by the reviewer (the choice of the background error matrix, or superobs for example), which we can only comment without performing again the simulations. Because they are important for the data assimilation system and we can only comment on them, we prefer to add the word "preliminary" to the title of the paper. In this way we highlight that important points of the physical options of the software are still to be fully tested.

The new title proposed is: “Preliminary results of the impact of lightning and radar reflectivity factor data assimilation on the very short term rainfall forecasts of RAMS@ISAC: application to two case studies in Italy”

The revised paper has supplemental material where we investigate the following two points: a) the relative contribution of lightning and radar data assimilation to the behavior of total water mass in the simulation; b) the sensitivity of the rainfall VSF to lightning data formulation.

RC: Major comments

- You show the horizontal dimensions and resolutions of your domains. However, for the vertical dimension you only write that it covers the troposphere and the lower stratosphere. How many levels do you use up to which height? How many of these levels are in the boundary layer? These are important information strongly influencing your results. This needs to be mentioned in the text. I found the total number of vertical levels and the model top height in the table you provide. However, to my opinion a horizontal resolution of 1 km combined with only 36 levels up to more than 22 km height is way too coarse to adequately describe the developing processes.

AR: The set-up of the RAMS@ISAC in this paper is the same as the operational setting, with the exception of the usage of domain D3 for the Livorno flood. In the operational setting a compromise must be chosen between the grid resolution and the computational time. While a future release of the operational setting will use more vertical levels (42), for the current year we are still using 36 levels. Among them 10 are below 1 km, 15 below 2 km and 18 below 3 km. The level 21 is at 5200 m in the terrain following coordinates used by RAMS. Above 6 km the model levels are more than 1000 m apart, with a maximum of 1200 m for the vertical layer at the model top.
Of course more vertical levels are useful to resolve important processes in the vertical as, as in cases of fronts, Planetary Boundary Layer processes, clouds etc., nevertheless a compromise between vertical resolution and computing time is necessary. Note, also, that this vertical grid was used with success in several heavy precipitation events over Italy. We wrote (Section 3.1):

“The resolutions and the extensions of the grids in the vertical direction is the same for the three domains. The vertical grid covers the troposphere and the lower stratosphere. Vertical levels have different spacings and are more packed close to the ground. Among the 36 levels used in this paper 10 are below 1 km, 15 below 2 km and 18 below 3 km. The first vertical level is at 24 m above the surface in the terrain following coordinates used by RAMS@ISAC, the level 21 is at 5200 m. Above 6 km the model levels are about 1000 m apart, with a maximum of 1200 m for the vertical layer at the model top.“

RC: You write that the R10 simulation is applied as lateral boundary condition for the inner domain simulations and that you use assimilation in the inner domains. O.k. so far – but do you adjust the lateral boundaries provided by R10 to the new situation after the assimilation? If not they may negatively influence your forecast. If you think that this is not necessary for your short-term forecasts, this has to be mentioned in the text.

AR: This point is related with the operational setting of RAMS@ISAC. Updating the R10 domain to the new situation after data assimilation is beneficial for the simulation.

Nevertheless, this would require additional simulations of the R10 model increasing the computing time for the whole chain. We added the following comment (in Section 3.1): "The R10 run is not updated after the acquisition of new data by the analysis system and this is a limitation of the results shown in this paper."

RC: The description of the lightning data assimilation is too short. The reader has no chance to understand equation (2) with all its coefficients without further explanation. In the text, you mention graupel mixing ratio qg, but the equation only contains qs. What is qs or should it be qg? The way you present it sounds like "Voodoo".

AR: Lightning section was mostly rewritten in the revised version of the paper and extended to consider this and other comments of the reviewers. In the revised version of the paper it should be more readable. The correct form of Equation (2) (Eqn. (1) in the revised version of the paper is):

$$q_v = Aq_s + Bq_s \tanh(CX)(1 - \tanh(Dq_g^{\alpha}))$$

and now q_g is present.

RC: How do the assimilation system deals with sharp gradients along the vertical profile when you only adjust the profile in a certain height region?

AR: Lightning data assimilation as well as radar data assimilation can produce sharp gradients in the vertical directions. For lightning data assimilation a nudging is performed to avoid a direct insertion of the data in the model, while in the case of radar the data are directly introduced in RAMS@ISAC. Nevertheless, our experience with RAMS@ISAC shows that, at least for the setting of this paper, the sharp gradients introduced in the model do not produce incorrect results or blowing up of the model. We highlighted this point into the paper (Section 3.3):
"Lightning and radar data assimilation may produce sharp gradients in vertical direction caused by the addition of water vapour to specific layers. In the case of lightning, the water vapour is added by nudging to reduce the sharp gradients. However, radar data assimilation, which accounts for the largest mass of water added to RAMS@ISAC (see Section S.1 of the supplemental material), directly inserts the water vapour into the model. Our experience with RAMS@ISAC, however, shows that results are reliable and the sudden addition of water vapour doesn't cause shocks to the model simulation, despite the notable gradients of specific humidity."

RC: You only adjust qv? How do you make sure that this results in more precipitation? Do you tune this with the coefficients? If yes – you have to include the information in the text.
AR: The increase/decrease of the water vapour depends on the data assimilation. Lightning can only increase the water vapour while radar can increase or decrease the water vapour. However, if the added/removed water vapour determines more/less precipitation depends on the physical and dynamical processes occurring in RAMS@ISAC and no specific tuning is done. The only exception is that if, after the data assimilation, the model is oversaturated, the water vapour is reduced to the saturated value (at the RAMS@ISAC temperature).
We added the following sentence at the end of Section 3.3 "Data and Methods": "It is finally noted that the data assimilation increase/decrease the water vapour into the model depending on the cases. The eventual increase/decrease of the forecasted rainfall

depends on the physical and dynamical processes occurring into the meteorological model, without any specific tuning."

RC: I understand why you reduce the resolution of the radar data. But is a pure sampling the best method? Usually one uses a kind of "super obbing" to avoid the implementation of errors (e.g. by insects) or extremes. Please comment on this and add explanation why you choose sampling.

AR: This is an aspect that need to be improved in future version of the software. Using superobs does a better job compared to the sampling of the data for the reasons stated by the reviewer and superobs improve the performance of the data assimilation. The only point that favours the sampling method compared to superobs is that the latter could increase the correlation among the observations' errors. We highlighted the point in Section 3.3 by writing:
"It is important to note the pure sampling of the data could result in implementation of errors (for example reflectivity given by insects or birds) or extremes. Creating superobservations would reduce this problem, the main drawback being the missing of very localised phenomena. While the aim of this paper is to present the update of the data assimilation system of RAMS@ISAC and its application to two challenging cases, the problem of using superobservations will be considered in future studies because it impacts the results."

RC: The error value of 1 to 3 dBz seems to be too small, making the system very sensitive to the radar data. Especially when combining this with a pure sampling of the radar data sounds dangerous to me. Please explain why you use this error value.

AR: The choice of a small error for the reflectivity factor is motivated by two reasons: a) the data are carefully checked by the Civil protection Department; b) the performance of the control simulation, not assimilating any data, is rather poor for the case studies. Nevertheless, the choice could not be optimal for other cases. We highlighted this point in Section 3.3 by writing:
"The error of radar data is assumed small (1dBz) for two reasons: a) reflectivity data are carefully checked by the Civil Protection Department; b) the performance of the control simulation, not assimilating any data, is rather poor for the case studies. This setting, however, could not be optimal for cases when the control forecast performs better and different choices should be done for those cases."

RC: You mention that cross correlations between the variables are neglected in this study. Do you neglect them in the observation operator only or in the assimilation system? Every assimilation system needs cross correlations between the variables e.g. to spread the information of the observations horizontally and vertically.

AR: The expression we used is not correct. We neglect cross correlations among different variables. In the current form, the data assimilation system uses the variables: (u=zonal velocity, v=meridional velocity, T=temperature, q=water vapor mixing ratio). For the results of this paper we neglected cross correlations in the **B** matrix among different variables (specifically (u,q), (v,q) (T,q)), while we maintained the error correlations among different levels and in the horizontal plane of q to spread the innovations in the vertical and horizontal directions (the latter being shown in Figure 14b of the revised paper). This

is a point that need to be improved in future versions of the software, by considering also cross correlations among different variables. We will precise better this point adding the following sentence (Section 3.3):
"Cross correlations among different variables of the data assimilation system are neglected in this study and the application of the RAMS-3DVar affects the water vapour mixing ratio only. Cross correlations among different variables can improve the performance of data assimilation system, and an example of their impact in the RAMS-3DVar is shown in Federico (2013). Nevertheless, the impact the cross correlations among different variables of the 3D-Var in the precipitation VSF will be explored in future works.".

RC: - Mention not only that the forward operator for reflectivity is from the WSM6 scheme of WRF – also mention the equation of the forward operator.

AR: We added the expression of the forward radar operator in the supplemental material (Section S4) to avoid excessive paper length. A reference was put into the paper to the reference material (Section 3.3).

RC: Minor comments

- Although the text is well readable, the language can be improved. Although, I am not a native speaker, I stumbled over several things. Here some examples:
- Page 4, line 113: ... case studies occurred in September 2017 ...
- Page 5, line 135: ... developed to the lee ...
- Page 5, line 151: Also notable is the feeding ...
- Page 5, line 158: ... is also clearly seen in the radar ...
- Page 5, line 163: ... can be noted over central-northern Italy.
- Page 6, line 165: ... cloud system was active for several ...
- Page 6, line 168: ... were recorder during the day; ...
- Page 6, line 170: ... from 00 UTC ...
- Page 6, line 186: ... occurred within a few hours.
- Page 6, line 192: illustrated better than represented? We chose illustrated.
- Page 6, line 195: ... interaction between the air-masses and the Western Alps generated a depression ...
- Page 7, line 197: ... it is noted that divergent ...
- Page 7, line 198: ... it is apparent that the equivalent ... We wrote "it is evident the equivalent...'
- Page 7, line 201: ... low pressure system ...Not applicable in the revised version of the paper.
- Page 7, line 204: From a synoptic point of view, ...
- Page 7, line 206: ... more intense than the Serano case ...
- Page 7, line 211: ... recorded over Italy, following ...
- Page 7, line 213: ... for the Serano case.
- Page 7, line 215: ... it is well evident that the cloud system ...

AR: All the above points were corrected, with the exceptions indicated in blu.

RC: Abstract: Lines 29 to 31. Do you need this sentence? To my opinion, the sentence above is enough.

AR: Deleted.

RC: Abstract: Merge lines 32 to 34 with the paragraph above.

AR: Done.

RC: Mention once in the text why you use the term “reflectivity factor” instead of reflectivity.

AR: Ok. We added the following footnote to express the point, the first time the term “reflectivity factor” is introduced in the paper (excluding the abstract). “Throughout the paper we use the expression radar reflectivity factor, which is the quantity provided by the radar (and expressed in mm^6m^{-3} or dBz) after conversion from the received power. The radar reflectivity factor is different from reflectivity and is obtained in the special case of Rayleigh approximation. Reflectivity is not the quantity that radars usually provide and display on their screens although most of people refer to it.”

RC: For me “Probability of dectetion” and “Hit rate” is the same. What you defined with Hit rate is the so-called “Hit score” e.g. following https://iri.columbia.edu/~jhansen/mason11july.pdf

AR: Thank you for noting this point. We used the definition of the Wilks book (Chapter 7). However, in the revised version of the paper only the POD is considered. Following the remarks of the reviewer#1 we deleted the equations for the scores. This helped to have a shorter paper. Also the scores were put in tables (not graphs), following a comment of reviewer #2. Graphs of the scores are presented in the supplemental material (Section S2).

RC: Translate the acronym “GPROF”

AR: It stands for Goddard Profiling Algorithm (added into the paper).

RC: Before you start to discuss the result, mention once how you name your different experiments. It gets clear during the reading, but if you mention it once, you do not need to repeat it later during the manuscript.

AR: Thanks for noting this point (also requested by reviewer#2). We did it at the start of Section 4 (results). We also added a table (Table 3) to better clarify the point. Also the supplemental material of the paper has a table (Table S1) specifying the types of simulations considered.

RC: Page 19, line 570: you mean LIGHT instead of FLASH?
AR: Yes. It was an error. Corrected.

RC: Page 22, lines 673 to 677: You mention that reflectivity data assimilation helps to better

represent light precipitation events and lightning data helps to represent strong events. One abstract later (lines 684 to 686) you argue the other way round. So, the influence of the different observation types also depend on the situation.
AR: Thanks for noting the point. We added the following sentence: “These results show also that the influence of different observations depends on the meteorological situation.”

RC: Page 23, line 702: Start a new paragraph and sentence after the promising results and the drawbacks.
AR: Done.

RC: What do you think is the reason for the increased false alarm rate in the RADLI forecasts? How do you think you can improve the situation in future versions of the system?
AR: The reason for having more false alarms in RADLI forecasts compared to other configurations is the larger amount of water vapour added to this kind of simulation, a direct consequence of the addition of water vapour given by both radar and lightning. In the supplemental material of this paper the evolution of the water vapour mass is presented, including the assimilation stage. Results, as expected, show the largest amount of water (not only in the vapour form) added to RADLI by data assimilation. Possible ways to decrease false alarms in future versions of the software are shortly introduced in Section 5 (Conclusion and discussion). We wrote: “To reduce the moisture added by radar and lightning data assimilation further research is needed and different approaches are possible (Fierro et al., 2016). In particular: a) assimilating for a shorter time (0-6h in this paper); b) reducing the length-scales of the 3D-Var in the horizontal directions to limit the spreading of the innovations or assuming an innovation equal to zero for grid points without lightning and with zero reflectivity factor; c) reducing the amount of water vapour added to the model (for example reducing the values of A and B constants for lightning data assimilation or relaxing the request of saturation when radar reflectivity is observed in areas where the model has zero reflectivity); d) adding moisture to a shallower vertical layer.
It is also noted that a combination of heating and moistening could provide the same buoyancy with less water vapour addition (Marchand and Fulberg, 2014) and this approach could be used in future studies.”

RC: Figures: Increase the sizes of the figures. You have space on the page to do this. If not put only two instead of three Figures on one page as done for Figures 10 to 12 on page 37.

AR: We enlarged the figures in the revised version of the paper. We will consider this point when revising the proofs of the paper, if accepted for publication.

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Marchand, M., and H. Fuelberg, 2014: Assimilation of lightning data using a nudging method involving low-level warming. Mon. Wea. Rev., 142, 4850–4871, doi:10.1175/MWR-D-14-00076.1

D. S. Wilks, Statistical Methods in the Atmospheric Sciences, Academic Press, New York, NY, USA, 2006

LIST OF THE MAJOR CHANGES MADE IN THE PAPER

-The Title was changed.

-The introduction was partially rewritten, especially in the part considering lightning data assimilation.

-Section 3.1 had major revisions to specify the vertical grid of RAMS@ISAC model and to clarify the role of domain D3 in the simulations of the Livorno case study.

-Section 3.2 underwent a substantial rewriting to clarify better how the radar reflectivity factor data assimilation is performed. An example of analysis is introduced and all the details of the 3D-Var setting have been hopefully clarified.

-Section 3.3 underwent a substantial rewriting to clarify better how lightning data assimilation works. A sensitivity experiment to the formulation of lightning data assimilation was added in the supplemental material.

-Section 4 underwent major revision. Three VSF are considered (revised version) instead of five (first submission) to reduce the length of the paper and to avoid repetitive comments. Scores were computed for three neighborhood radii and were put in tables (Table 4-6) according to reviewers' comments.

-We added supplemental material to the paper. Specifically, in this supplement we study: a) the relative contribution to the total water mass given by lightning and radar reflectivity factor data assimilation (Section S.1); b) the sensitivity of the precipitation VSF to the nudging formulation (Section S2). Also, the supplemental material gives different plots of Figures 15-17 (Section S3) and the forward radar operator used in RAMS-3DVar (Section S4).

-Discussion and conclusions were changed according to the major revision.

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Preliminary results of the impact of lightning and radar reflectivity factor data assimilation on the very short term rainfall forecasts of RAMS@ISAC: application to two case studies in Italy

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Abstract

In this paper, we study the impact of lightning and radar reflectivity factor data assimilation on the precipitation VSF (Very Short-term Forecast, 3 hours in this study) for two relevant case studies occurred in Italy. The first case refers to a moderate and localised rainfall over central Italy occurred on 16 September 2017. The second case, occurred on 9 and 10 September 2017, was very intense and caused damages in several geographical areas, especially in Livorno (Tuscany) where nine people died.
The first case study was missed by several operational forecasts (from both public and private sectors), including that performed by the model used in this paper, while the Livorno case was partially predicted by operational models.
We use the RAMS@ISAC model (Regional Atmospheric Modelling System at Institute for Atmospheric Sciences and Climate of the Italian National Research Council), whose 3D-Var extension to the assimilation of RADAR reflectivity factor is shown in this paper for the first time.
Results for the two cases show that the assimilation of lightning and radar reflectivity factor, especially when used together, have a significant and positive impact on the precipitation forecast. For specific time intervals, the data assimilation is of practical importance for civil protection purposes because changes a missed forecast of intense precipitation (≥ 40 mm/3h) in a correct one.
While there is an improvement of the rainfall VSF thanks to lightning and radar reflectivity factor data assimilation, its usefulness is partially reduced by the increase of the false alarms, especially when both data area assimilated.

Keywords: data assimilation, lightning, radar reflectivity factor, RAMS@ISAC.

1. Introduction

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Initial conditions of numerical weather prediction (NWP) models are a key point for a good forecast (Stensrud and Fritsch, 1994; Alexander et al., 1999). Nowadays limited area models are operational at the resolution of few kilometres (< 5 km) and data assimilation of non-conventional observations, as lightning or radar data, is crucial to correctly represent the state of the atmosphere at local scale (Weisman et al., 1997; Weygandt et al., 2008). This is especially important over the sea, where the absence of local observations and model deficiencies can misrepresent convection.

The assimilation of radar reflectivity factor[1] is useful to improve the weather forecast considering the high repetition rate (asynoptic data) and the high spatial resolution (local scale) of the radar data.

First attempts to assimilate radar reflectivity factor are reported in Sun and Crook (1997, 1998), who expanded VDRAS (Variational Doppler Radar Analysis System) to include microphysical retrieval. Following these studies, several systems to assimilate radar observations, both Doppler velocity and reflectivity factor, were developed (Xue et al., 2003, Zhao et al., 2006; Xu et al., 2010). All these studies showed the stability and robustness of assimilating radar observations as well as the improvement of weather forecast.

Radar data are also assimilated in WRF (Weather Research and Forecasting model, Skamarock et al., 2008; Barker et al., 2012) both using 3DVar (Xiao et al., 2005, 2007; Barker et al., 2004) and 4DVar (Wang et al., 2013; Sun and Wang, 2012). The capability to assimilate radar data into WRF was recently applied to a heavy rainfall event over Central Italy by Maiello et al. (2014). They showed a notable and positive impact of the radar data assimilation on the precipitation forecast, also when radar data were assimilated together with conventional data (SYNOP and RAOB).

In addition to direct methods, which assimilate the radar reflectivity factor adjusting the hydrometeor contents, there are indirect methods adjusting other variables. In particular, the method of Caumont et al. (2010) acts on the relative humidity field. It consists of two different steps: a 1D retrieval of relative humidity (pseudo-profile), which depends on the radar reflectivity factor observations, followed by 3D-Var assimilation of the pseudo-profile. This method has the advantage to reduce the computational cost at the kilometric scale.

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[1] Throughout the paper we use the expression radar reflectivity factor, which is the quantity provided by the radar (and expressed in mm^6m^{-3} or dBz) after conversion from the received power. The radar reflectivity factor is different from reflectivity and is obtained in the special case of Rayleigh scattering. Reflectivity is not the quantity that radars usually provide and display on their screens although most of people refer to it.

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The choice of updating the moisture field directly is motivated by its greater impact on analyses and forecasts in comparison to that of hydrometeor-related quantities (e.g., Fabry and Sun, 2010). Caumont et al. (2010) showed that the method improved the weather prediction of a heavy precipitation event in southern France and of a eight-day long assimilation cycle experiment. The method was applied in other studies (Wattrelot et al., 2014, using AEROME model; Ridal and Dalbom, 2017; using HARMONIE model), or modified using 4D-Var in place of 3D-Var (Ikuta and Honda, 2011; using JNoVa model) showing its capability to improve the weather forecast. The method is also used in the operational context (Wattrelot et al., 2014).

Flashes are another important source of asynoptic data due to their ability to locate precisely the convection with few temporal gaps (Mansell et al., 2007). In the last two decades, there have been attempts to assimilate lightning into meteorological models both at low horizontal resolution, which need a cumulus parameterization scheme to simulate convection, and at convection permitting scales.

The first attempts to assimilate lightning in NWP models were based on relationships between lightning and rainfall rate estimated by microwave sensors on board polar satellites (Alexander et al., 1999; Chang et al., 2001; Jones and Macpherson, 1997; Pessi and Businger, 2009). In this approach, the rainfall rate was computed as a function of lightning observations and then transformed into latent heat, which was assimilated. The results of these studies showed a positive impact of lightning data assimilation on the forecast up to 24h also for fields at the large scale, as sea-level pressure.

The study of Papadopulos et al. (2005) used lightning to locate convection and the model water vapour profile was nudged towards vertical profiles recorded during convective events.

Mansell et al. (2007) modified the Kain-Fritsch (Kain and Fritsch, 1993) cumulus convective scheme to force convection when/where flashes are observed while the convective scheme was not activated in the model simulation, demonstrating the potential of lightning to improve the convection forecast. A similar approach was introduced by Giannaros et al. (2016) into WRF showing the positive impact of lightning data assimilation on the precipitation forecast up to 24h for eight convective events occurred over Greece.

Fierro et al. (2012) introduced a methodology to assimilate lightning at convection permitting scales by modifying the water vapour mixing ratio simulated by the WRF according to a function depending on the flash-rate and on the simulated graupel mixing ratio. The water vapour could be assimilated by nudging (Fierro et al., 2012) or 3D-Var (Fierro e al., 2016).

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Qie et al. (2014), using WRF, extended the methodology of Fierro et al. (2012) to assimilate ice crystals, graupel and snow, showing promising results for deep convective events in China.

Fierro et al. (2015) studied the performance of the Fierro et al. (2012) method for 67 days spanning the 2013 warm season over the CONUS giving a statistically robust estimation of the performance of the method. The computationally inexpensive lightning data assimilation method improved considerably the short-term (≤ 6h) precipitation forecast of high impact weather.

Lynn et al. (2015) and Lynn (2017) also applied the method of Fierro et al. (2012) to boost the local thermal buoyancy where/when lightning is observed. Results show that lightning data assimilation improved lightning forecast. Importantly, Lynn et al. (2015) offer an approach to address spurious convection (i.e., convection removal), which is a far more challenging problem to tackle.

Federico et al. (2017a) implemented the methodology of Fierro et al. (2012) in RAMS@ISAC model, showing the systematic and significant improvement of the precipitation forecast at the very short range (3h) for twenty case studies occurred over Italy; the impact of lightning data assimilation for longer time ranges (6h-24h; Federico et al., 2017b) showed considerable impact on the 6h precipitation forecast, with smaller (negligible) effects at 12 h (24 h).

In this paper, we study the impact of radar reflectivity factor and lightning data assimilation on the very short term (3h) rainfall prediction for two case studies over Italy. We use the method of Fierro et al. (2012) to assimilate lightning and the method of Caumont et al. (2010) to assimilate the radar reflectivity factor. The case studies occurred in September 2017. The first case, hereafter also referred to as Serano, occurred on 16 September, was characterized by moderate-intense and localized rainfall. The second case, hereafter also referred to as Livorno, occurred on 09-10 September, was characterized by deep convection and very intense precipitation in several parts of Italy. Even if the Livorno case occurred before the Serano case, we reverse the chronological order in the discussion, ordering the event from the less intense to the most intense.

The forecast of severe events at the local scale still remains a challenge because of the multitude of physical processes involved over a wide range of scales (Stensrud et al., 2009). The Serano case study, being localized in space, poses challenges in forecasting the exact position and timing of convection initiation; the Livorno event involves the interaction between a high impact storm and the complex orography of Italy, which is difficult to simulate at the local scale. For the above reasons the forecast of both events was challenging, as confirmed by the poor forecast of RAMS@ISAC. The difficulty to forecast timely and accurately the precipitation field is the reason for choosing them as test cases.

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This paper presents for the first time the assimilation of the total lightning (intra cloud + cloud to ground) and radar reflectivity factor in RAMS@ISAC model and shows how the assimilation of the radar reflectivity factor works together with total lighting data assimilation. Also, this paper shows how accurate in space and time can be the forecast of the precipitation field using cloud scale observations over complex terrain, contributing in this way to a number of works on the same subject.

The paper is organized as follows: Section 2 gives details on the synoptic environment of the case studies showing daily precipitation, lightning and radar observations; Section 3 gives details on the meteorological model, lightning and radar data assimilation; Section 4 shows the results for three very short-term forecast (VSF), one for Serano and two for Livorno; Discussion and conclusions are given in Section 5. This paper has additional material where we discuss: a) how lightning and radar reflectivity factors data assimilation adjust the total water field; b) the sensitivity of the results to the choice of key parameters of lightning data assimilation.

2. The case studies

2.1 The 16 September 2017 (Serano) case study

During the 16 September 2017 Italy was under the influence of a cyclone that developed to the lee of the Alps. The storm crossed Italy from NW to SE leaving light precipitation over most of the peninsula with moderate rainfall over Central Italy. Figure 1 shows the precipitation recorded by the Italian raingauge network on 16 September 2017. Light precipitation (< 5 mm/day) is reported by 1018 raingauges out of the 1666 stations measuring precipitation (≥ 0.2 mm/day) on this day. Fourteen stations over Central Italy recorded more than 50 mm/day. The maximum precipitation was 90 mm/day in Città di Castello (Umbria Region, Figure 1). Because the meteorological radar closest to the maximum precipitation is over mount Serano (Figure 1), hereafter this event will be referred to as Serano.

The synoptic condition during the event is shown in Figure 2. At 500 hPa (Figure 2a) a trough, elongated in the SW-NE direction, extends over Western Europe and air masses are advected from SW towards western Alps. The interaction between the airflow and the Alps generates a low pressure to the lee of the Alps over Northern Italy.

The analysis at the surface (Figure 2b) shows the meteorological front represented by the equivalent potential temperature gradient between air masses advected over the Mediterranean

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Sea from NW and air masses advected from the South over the Tyrrhenian Sea. Notable is the feeding of warm unstable air masses towards Central Italy.

Infrared satellite images (Figure 3), from 00 UTC on 16 September to 00 UTC on 17 September, show the cold front structure moving slowly from NW to SE. Interestingly, at 00 UTC on 16 September, it is apparent the well-defined cloud system over Central Italy (red circle of Figure 3a), which caused most of the daily precipitation observed between 43.50 N and 45.0 N in the six-hours 00 UTC-06 UTC on 16 September.

The well-defined cloud system over Central Italy is also evident in the radar Constant Altitude Plan Position Indicator (CAPPI) at 3 km above sea level at 02 UTC on 16 September (Figure 4). This CAPPI is formed by interpolating all the available data from the federated Italian radar network coordinated by the Department of Civil Protection (twenty-two radars, see Section 3.3 for their positions) and it is also referred to as the national radar composite (hereafter also mosaic). Several convective cells exceeding 35 dBz can be noted over central-northern Italy. Importantly, the cloud system over Central Italy shown by the satellite infrared channel at 00 UTC (Figure 3a) and that of the radar at 02 UTC have similar positions, showing that the cloud system was active for several hours over Central Italy.

Figure 5 shows lightning recorded by the LINET network (Betz et al., 2009) on 16 September 2017. More than 105.000 flashes were recorded during the day; most of them occurred during the afternoon and evening, but a secondary maximum occurred in the night, from 00 UTC to 06 UTC. In this phase, more than 3000 flashes were observed over Central Italy.

2.2 The 09-10 September 2017 (Livorno) case study

During the days 09 and 10 September 2017, Italy was hit by a severe storm characterised by intense and widespread rainfall over the country. Figure 6a shows the precipitation on 09 September recorded by the Italian raingauge network. Rainfall was intense over the Alps, where the maximum daily precipitation was observed (193 mm/day) and over Liguria, with precipitation of the order of 30-50 mm/day. One station over Tuscany reported 90 mm/day, showing that intense precipitation already started over the Region. The intensity of the storm on 09 September was high because 20 raingauges reported more than 100 mm/day and 70 raingauges more than 60 mm/day, and, in most cases, this precipitation occurred within few hours.

The following day (see Figure 6b) had higher rainfall. Precipitation occurred mainly over Central Italy, especially over Lazio, and over Northern Italy, in particular the North-East. In Tuscany, the

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two stations close to the sea, in the Livorno area, recorded about 150 mm/day mostly fallen in the hours between 00 and 06 UTC. The rainfall on 10 September was abundant: and 60 raingauges recorded more than 100 mm/day.

Synoptic conditions leading to this storm are shown in Figure 7. At 500 hPa (Figure 7a) a trough extends from Northern Europe towards the Mediterranean. The interaction between the air-masses and Western Alps generated a depression to the lee of the Alps, which crossed the whole peninsula from NW to SE. It is noted the divergent flow over Central and Northern Italy favouring upward motions.

At the surface, Figure 7b, it is evident the equivalent temperature gradient over the western Mediterranean caused by the contrast between air masses pre-existing over the sea and air masses advected from France towards the Mediterranean. The pressure field at the surface advects air masses from the South over the Tyrrhenian Sea. These warm and humid air masses feed the cyclone during its development.

From a synoptic point of view, Livorno and Serano cases are similar and represent two cyclones developing to the lee of the Alps (Buzzi and Tibaldi, 1978). However, the Livorno case is more intense than Serano as shown by the larger rainfall occurred in the former case.

The notable intensity of the Livorno case is confirmed by lightning observations (Figure 8). During the evening on 9 September (after 18 UTC) about 38.000 flashes were recorded by LINET. On 10 September about 290.000 flashes were recorded over Italy, following the movement of the storm propagating from NW to SE. So, more than 300.000 flashes were recorded from 18 UTC on 09 September to 00 UTC on 11 September, which are more than three times those recorded for Serano.

Thermal infrared satellite images (channel, 10.8 micron; Figure 9) show the extension of the cloud coverage every 12 hours. It is well evident the cloud system associated with the cold front over Europe. More specifically, the satellite image at 00 UTC shows the cloud system over Livorno area (red circle in Figure 9b), before the main precipitation event over Tuscany (00-06 UTC), while Figure 9c shows the cloud system over Central Italy (orange circle), at the end of the period of intense precipitation over Lazio (06-12 UTC).

We conclude the synoptic analysis of the case study with two CAPPI at 3 km observed by the radar network of the Department of Civil Protection. The CAPPI in Figure 10a, at 00 UTC on 10 September, shows the cloud system over Tuscany with reflectivity factor up to 40 dBz. Other

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clouds cause rainfall over northern Italy. The CAPPI of Figure 10a is the last assimilated by the 00-03 UTC VSF on 10 September shown in Section 4.2.1.

Figure 10b shows the CAPPI of the national radar mosaic at 3 km above the sea level and at 06 UTC. The cloud system is moving towards Central Italy with reflectivity up to 45 dBz. Other cloud systems are apparent over northern Italy. Figures 10a-10b well represent the movement of the storm towards SE and Figure 10b shows the last CAPPI assimilated by the 06-09 UTC VSF shown in Section 4.2.2.

3.Data and Methods

3.1 RAMS@ISAC and simulations set-up

The RAMS@ISAC is used as NWP driver in this work. The model is based on the RAMS 6.0 model (Cotton et al., 2003) with the addition of four main features, as well as a number of minor improvements. First, it implements additional single moment microphysical schemes, whose performance is shown in Federico (2016): among them, the WSM6 (Hong and Lim, 2006) is used in this paper. Second, it predicts the occurrence of lightning following the diagnostic method of Dahl et al. (2011), the implementation being discussed in Federico et al. (2014). Third, the model assimilates lightning through nudging (Fierro et al., 2012, 2015; Federico et al., 2017a). Fourth, the model implements a 3D-Var data assimilation system (Federico, 2013, hereafter also RAMS-3DVar), whose extension to the radar reflectivity factor is presented in this paper (Section 3.3). The list of the main physical parameterisation schemes used in the simulations of RAMS@ISAC is shown in Table 1.

Considering the domains and the configuration of the grids (Figure 11 and Table 2), two different set-ups are used for Serano and Livorno. For the first case, we use the domains D1 and D2, while for Livorno we use also the domain D3. The first domain covers a large part of Europe and extends over the North Africa. For this domain, the horizontal resolution of the grid is 10 km (R10). The second domain extends over the whole Italy and part of Europe and the grid has 4 km horizontal resolution (R4). The third domain covers the Tuscany Region, has 4/3 km horizontal resolution (R1), and it is used for Livorno to represent with higher spatial detail the precipitation field over Tuscany. The fine structures of the precipitation field are smeared out over Tuscany using only domains D1 and D2. The operational implementation of the RAMS@ISAC model uses the domains D1 and D2 and no refinements for specific areas of Italy are used because Italy is a complex

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The resolution and the extension of the grids in the vertical direction is the same for the three domains. The vertical grid covers the troposphere and the lower stratosphere. Vertical levels have different spacings and are more packed close to the ground. Among the 36 levels used in this paper 10 are below 1 km, 15 below 2 km and 18 below 3 km. The first vertical level is at 24 m above the surface in the terrain following coordinates used by RAMS@ISAC, the level 21 is at 5200 m. Above 6 km the model levels are about 1000 m apart, with a maximum of 1200 m for the vertical layer at the model top.

The vertical grid is the same as the operational setting of RAMS@ISAC and is a compromise between vertical resolution and computing time. In the future, the number of vertical levels will be increased to better resolve the phenomena in this direction (Planetary Boundary Layer processes, vertical motions, interaction between air masses and orography etc.), nevertheless the current setting was used successfully in the forecast of several heavy precipitation events over Italy. The nesting between the first and second domains is one-way, while the nesting between the second and the third domains is two-way.

VSF is implemented as shown in Figure 12. First a run with R10 configuration is performed using the 0.25° horizontal resolution GFS analysis/forecast cycle issued at 12 UTC as initial and boundary conditions. R10 run, which starts at 12 UTC on 16 September for Serano and at 12 UTC on 09 September for Livorno, lasts 36 h and doesn't assimilate neither radar reflectivity factor nor lightning. The R10 run is not updated after the acquisition of new data by the analysis system and this is a limitation of the results shown in this paper.

Starting from 12 UTC, ten VSF are performed using R4 for Serano and both R4 and R1 for Livorno. The VSF lasts 9h and uses R10 simulation as initial and boundary conditions (one-way nesting). The 9h forecast is divided into two parts: the first six hours are the assimilation stage when RAMS@ISAC simulation is adjusted by data assimilation, whereas the last three hours are the forecast stage, without data assimilation. During the assimilation stage, flashes are assimilated by nudging (Section 3.2), while radar reflectivity factor is assimilated every one-hour by RAMS-3DVar (Caumont et al. (2010), Section 3.3).

It is noted that data assimilation is performed over the domain D2 (R4) only, and the innovations are transferred to the domain D3 (R1), for the Livorno case, by the two way-nesting. The domain D3 is used for the Livorno case to refine the resolution of the precipitation field over Tuscany and

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to show the spatial and temporal precision of the precipitation forecast over Tuscany using data assimilation. However, its usage is exceptional because, as stated above, Italy is a complex orography country and grid refinements for specific areas are used only after the occurrence of the event. For this reason the domain D3 is usually not used in RAMS@ISAC and no statistics about the background error are available for this grid.

Because lightning and radar reflectivity factor are cloud scale observations, their assimilation at higher horizontal resolution by 3D-Var is foreseeable in future works.

The verification of the VSF for precipitation is done by visual comparison of the model output with the raingauge network of the Department of Civil Protection, which has more than 3000 raingauges all over Italy.

In addition we consider the FBIAS (Frequency Bias; range [0, + ∞)), where 1 is the perfect score, i.e. when no misses and false alarms occur), POD (Probability of Detection; range [0, 1], where 1 is the perfect score and 0 the worst value) and ETS (Equitable Threat Score; range [-1/3,1], where 1 is the perfect score and 0 is a useless forecast). Scores are computed from 2x2 dichotomous contingency tables (Wilks, 2006) for different rainfall thresholds.

3.2 Lightning data assimilation

Lightning data are provided by LINET (LIghtning detection NETwork; Betz et al., 2009; www.nowcast.de) which has more than 500 sensors worldwide with the greatest density over Europe (more than 200 sensors). The network has a good coverage over Central Europe and Western Mediterranean (from 10 W to 35 E and from 30 N to 60 N). The area of good coverage includes the region considered in this paper.

LINET exploits the VLF/LF electromagnetic bands and provides measurements of both intra-cloud (IC) and cloud to ground (CG) discharges. IC strokes are detected as long as lightning occurs within 120 km from the nearest sensor thanks to an optimised hardware and advanced techniques of data processing (TOA-3D, Betz et al., 2004). According to Betz et al. (2009), LINET has a location accuracy of 125 m for an average distance of 200 km among the sensors verified by strikes into towers of known positions.

The good performance of the LINET network and its ability to detect IC strokes is shown in Lagouvardos et al. (2009) for a storm in southern Germany, while the good performance over Italy, including both CG and IC strokes, is discussed in Petracca et al. (2014).

Lightning data assimilation scheme is that of Fierro et al. (2012; 2015) and uses the total lightning, i.e. intra-cloud plus cloud to ground flashes.

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$$FBIAS = \frac{a+b}{a+c}$$

$$POD = \frac{a}{a+c}$$

$$ETS = \frac{a-a_r}{a+b+c-a_r}; \quad a_r = \frac{(a+b)(a+c)}{a+b+c+d} \qquad (1)$$

$$HR = \frac{a+d}{a+b+c+d}$$

where a_r is the probability to have a correct forecast by chance (Wilks, 2006) .The hits, false alarms, misses and correct no forecast are computed comparing the precipitation forecast at four RAMS@ISAC grid points surrounding a raingauge and taking among them the closest value to the raingauge measurement (nearest-neighbour). In this way, we tolerate a spatial error of $D*(2)^{1/2}$ for the rainfall forecast, where *D* is the model grid spacing (4 km or 4/3 km depending by the case considered). Because the scores are computed for the second and third RAMS@ISAC domains, we tolerate spatial errors of 5.7 km and 1.9 km, respectively.

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The method starts by computing the water vapour mixing ratio q_v:

$$q_v = Aq_s + Bq_s \tanh(CX)(1 - \tanh(Dq_g^{\alpha})) \qquad (1)$$

Where coefficients are set to A=0.86, B=0.15, C=0.30, D=0.25, α=2.2, q_s is the saturation mixing ratio at the model atmospheric temperature, and q_g is the graupel mixing ratio (g kg^{-1}). X is the number of total flashes (IC+CG) falling in a grid box of domain D2 (R4) in the past five minutes. The mixing ratio q_v of Eq. (1) is computed only for grid points where flashes are recorded. More specifically, for each grid point we consider the number of flashes falling in a grid box centred at the grid point in the last five minutes. The mixing ratio of Eqn. (1) is compared with that predicted by the model. If the mixing ratio of Eqn. (1) is larger than the simulated one, the latter is nudged towards the value of Eqn. (1), otherwise the modelled mixing ratio is left unchanged. This method can only add water vapour to the forecast.

The check and eventual substitution of the water vapour is performed every five minutes and it is made within the mixed phase layer zone (0 °C, -25°C), wherein electrification processes caused by the collision of ice and graupel are the most active (Takahashi 1978, Emersic and Sounders, 2010; Fierro et al., 2015).

The scheme of Fierro et al. (2012; 2014; 2015) was adapted to RAMS@ISAC in Federico et al. (2017a). In particular, the coefficient C of Eqn. (1) was rescaled from that of Fierro et al. (2012) considering the different spatial and temporal resolution of the gridded lightning data; then the coefficient C was tuned (increased) by trials and errors considering two case studies of HyMeX-SOP1 (15 and 27 October 2012). The C constant was adapted subjectively considering two opposite requests: increasing the hits and minimising false alarms. POD and ETS scores were considered as metrics for this purpose. Then, Eqn. (1) was applied to twenty case studies of HyMeX-SOP1 giving a statistically significant (90, or 95% depending on the rainfall threshold) improvement of the RAMS@ISAC precipitation VSF (3h).

Nevertheless, an exhaustive statistic on the performance of rainfall VSF to nudging formulation in RAMS@ISAC is missing and further studies are needed in this direction. Also, the optimal choice of the coefficients A, B, C, D and α is case dependent.

Fierro et al (2012) applied the method using the ENTLN network, which has a detection efficiency (DE) greater than 50% for IC over Oklahoma, where the ENTLN data were used. The emphasis on IC flashes in the set-up of Fierro et al. (2012) is given because observational and model studies have provided evidence that IC flashes correlate better than CG flashes with various measures of intensifying convection (updraft strength, volume, graupel mass flux etc.; MacGorman et al. 1989;

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Carey and Rutledge 1998; MacGorman et al. 2005; Wiens et al. 2005; Kuhlman et al. 2006; Fierro et al. 2006; Deierling and Petersen 2008; MacGorman et al. 2011). For this reason methods that use both IC and CG flashes performs better than those using CG only, being CG flashes correlated with the descent of reflectivity cores and the onset of the demise of the storm' s updraft core (MacGorman and Nielsen, 1991).

The analysis of the case studies shows that IC strokes are about 30% of the total number of strokes reported. Also, the fraction of IC strokes to the total strokes depends on the position. For example, for the Serano case, the fraction of IC strokes detected by LINET over the area hit by the largest precipitation is more than 50% while over the Adriatic Sea it decreases to 10%.

It is also noted that DE for IC strokes cannot be reliably compared between LINET and ENTLN, because the area is different and the technical details about IC detection remain unclear (type of signals, VLF/LF or VHF, discrimination IC-CG).

For all the above reasons the application of the Fierro method to RAMS@ISAC is not straightforward and it is appropriate to study the dependence of the rainfall VSF to the nudging formulation. This subject is studied in the supplemental material of this paper (Section S.2) and the results show that the choice of the coefficient of Eqn. (1) used in this paper is reasonable.

It is finally noted that despite the limitations noted above, lightning data assimilation, as used in this paper, has a significant and positive impact on RAMS@ISAC rainfall VSF (Federico et al., 2017a; 2017b).

3.3 Radar data assimilation

The method assimilates CAPPI of radar reflectivity factor operationally provided by the Italian Department of Civil Protection (DPC). Radar data are provided over a regular Cartesian grid with 1 km horizontal resolution and for three vertical levels (2, 3, 5 km above the sea level). The CAPPIs at 2, 3, and 5km can be considered as under-sampled vertical profiles. CAPPIs are composed starting from the 22 radars of the Italian Radar Network (Figure 13) 19 operating at the C-band (i.e., 5.6 GHz) and 3 at X-band (i.e., 9.37 GHz). Data quality control and CAPPI composition is performed by DPC. Data quality processing chain aims at identifying most of the uncertainty sources as clutter, partial beam blocking and beam broadening. The radar observations are processed according to nine steps detailed in Vulpiani et al. (2014), Petracca et al. (2018) and references therein.

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Radial velocity is not assimilated into RAMS@ISAC because it is not operationally processed, the scan strategy being optimized for QPE purposes. Furthermore, the implementation of a radial velocity data assimilation scheme is under development in RAMS-3DVAR and it is not currently available for testing. For these reasons, we didn't consider the assimilation of this parameter.

Before entering data assimilation, the Cartesian grid is reduced to 5 km by 5 km by choosing one point every five of the Cartesian grid provided by DPC in order to reduce the numerical cost of the data assimilation and to reduce the effect of correlated observation errors (Rohn et al., 2001). The radar grid (Figure 4, for example) is then a Cartesian grid with 5 km grid-spacing and three vertical levels.

It is important to note the pure sampling of the data could result in implementation of errors (for example reflectivity given by insects or birds) or extremes. Creating superobservations would reduce this problem, the main drawback being the missing of very localised phenomena. While the aim of this paper is to present the update of the data assimilation system of RAMS@ISAC and its application to two challenging cases, the problem of using superobservations will be considered in future studies because it impacts the results.

The methodology to assimilate radar reflectivity factor is that of Caumont et al. (2010), named 1D+3DVar, which is a two-step process: first, using a Bayesian approach inspired to GPROF (Goddard Profiling Algorithm; Olson et al., 1996; Kummerow et al., 2001), 1D pseudo-profiles of model variables are computed, then those pseudo-profiles are assimilated by 3DVar. Both steps are discussed below.

The first step computes a pseudo-profile of relative humidity weighting the model profiles of relative humidity around the radar profile (Bayesian approach). The pseudo-profile is computed by:

$$\mathbf{z}_\mathbf{o}^\mathbf{p} = \frac{\sum_i \mathbf{RH}_\mathbf{i} W_i}{\sum_j W_j} \qquad (2)$$

Where RH_i is the RAMS@ISAC vertical profile of relative humidity at a grid point inside a square of 50*50 km^2 centred at the radar vertical profile, W_i is the weight of each profile and $\mathbf{z_o^p}$ is the relative humidity pseudo-profile. The summation is taken over all the grid points inside a square of 50*50 km^2 around the observed profile and the denominator is a normalisation factor. The weights are determined by the agreement between the simulated and observed reflectivity factor:

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$$W_i = \exp\left\{-\frac{1}{2}\left[\mathbf{z}_o - h_z(x_i)\right]^T \mathbf{R}_z^{-1}\left[\mathbf{z}_o - h_z(x_i)\right]\right\} \qquad (3)$$

Where h_z is the forward observation operator, transforming the background column $\mathbf{x}_i$ into the observed reflectivity factor. The forward radar observation operator is taken from the RIP (Read/Interpolate/Plot) software (https://dtcenter.org/wrf-nmm/users/OnLineTutorial/NMM/RIP/index.php, last access 03 March 2019) and is given in the supplemental material of this paper (Section S4). It assumes a Marshall-Palmer hydrometeors size-distribution, Rayleigh scattering, and depends on the mixing ratios of rain, graupel and snow.

The matrix $\mathbf{R}_z$ in Eqn. (3) is diagonal and its value is $n\sigma^2$, where σ is 1 dBz and n is the number of available observations in the vertical profile (from 1 to 3). In this way, we give more weight to vertical profiles containing more data.

The error of radar data is assumed small (1dBz) for two reasons: a) reflectivity data are carefully checked by the Civil Protection Department; b) the performance of control simulation, not assimilating any data, is rather poor for the case studies. This setting, however, could not be optimal for cases when the control forecast performs better.

It is important to point out that the 50 km length-scale of the above step doesn't represent the horizontal correlation length-scale of the background error, which determines the horizontal spread of the innovations in the 3D-Var data assimilation (the latter length-scale is between 14 and 25 km depending on the level). The 50 km length-scale is used to set a square for computing the pseudo-profile of relative humidity (Eqn. (2)). This profile is given by a weighted average whose weights are determined by the agreement between the simulated and observed reflectivity factor. The larger the agreement the larger the weight. This distance is appropriate because the spatial error of meteorological models in simulating meteorological features, for example fronts, can be of this order. The control simulation of the two events considered in this paper confirms this choice.

The method is not able to force convection when the model has no rain, snow or graupel in a square around (50*50 km^2) a radar profile with reflectivity factor greater than zero. In this case, the pseudo-profile of relative humidity is assumed saturated above the lifting condensation level and with no data below (Caumont et al., 2010).

It is also noted that the method is able to reduce spurious convection when the reflectivity factor is simulated but not observed, because the pseudo-profile of relative humidity gives more weight to the drier relative humidity profiles simulated by RAMS@ISAC inside the 50*50 km^2 square

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centred at the radar profile. Of course, the ability to reduce spurious convection depends on the availability of dry model profiles around the specific radar profile (see the example below). Finally, if the observed profile is dry and the profile simulated by RAMS@ISAC is dry too, the pseudo-profile is not computed.

In summary, pseudo-profiles are computed for each profile of the radar grid whenever reflectivity is observed or simulated.

The pseudo-profiles computed with the procedure introduced above, are then used as observations in the RAMS-3DVar data assimilation (Federico, 2013), minimising the cost-function:

$$J(\mathbf{x}) = \frac{1}{2}(\mathbf{x}-\mathbf{x}_b)^T\mathbf{B}^{-1}(\mathbf{x}-\mathbf{x}_b) + \frac{1}{2}(\mathbf{z}_o^p - h(\mathbf{x}))^T\mathbf{R}^{-1}(\mathbf{z}_o^p - h(\mathbf{x})) \quad (4)$$

Where **x** is the state vector giving the analysis when *J* is minimized, $\mathbf{x}_b$ is the background, **B** and **R** are the background and observations error covariance matrices, $\mathbf{z}_o^p$ is the pseudo vertical profile computed by Eqn. (2) and *h* is the forward observation operator transforming the state vector (RAMS@ISAC water vapour mixing ratio) into observations. The cost function in RAMS-3DVar is implemented in incremental form (Courtier et al., 1994) and its minimization is performed by the conjugate-gradient method (Press et al., 1992). No multi-scale approach is used.

The background error matrix is divided into three components along the three spatial directions (*x, y, z*). The $\mathbf{B}_x$ and $\mathbf{B}_y$ matrices account for the spatial correlation of the background error. The correlations are Gaussian with length-scales between 14 and 25 km, depending on the vertical level. These distances are computed using the NMC method (Barker et al., 2012) applied to the HyMeX-SOP1 (Hydrological cycle in the Mediterranean Experiment – First Special Observing Period occurred in the period 6 September-6 November 2012; Ducroq et al., 2014) period. It is again stressed that the spread of the innovations along the horizontal spatial directions in the 3D-Var analysis is determined by the length scales of $\mathbf{B}_x$ and $\mathbf{B}_y$ matrices and varies between 14 and 25 km, depending on the level.

The $\mathbf{B}_z$ matrix contains the error for the water vapour mixing ratio, which is the control variable used in RAMS-3DVar. This error is about 2 g/kg at the surface and decreases with height. In particular, it is larger than 0.5 g/kg below 4 km, and less than 0.2 g/kg above 5 km. The vertical decorrelation of the background error depends on the level and can be roughly estimated in 500-2000 m. The observation error matrix **R** in Eqn. (4) is diagonal and observations' errors are uncorrelated. This choice is partially justified by under sampling the radar reflectivity factor observation by choosing one point every five grid points in both horizontal directions of the radar

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Cartesian grid. However, correlation observations errors have significant impact on the final analysis, as shown for example in Stewart et al. (2013), and different choices of the matrix **R** will be considered in future studies.

The value of the elements on the diagonal of **R** depends on the vertical level and are 1/4 of the diagonal element of the $\mathbf{B}_z$ matrix at the corresponding height. By this choice, we give more credit to the observations than to the background and analyses strongly adjust the background towards observations. The background error matrix is computed using the NMC method (Parrish and Derber, 1992; Barker et al. 2004) applied to the HyMeX-SOP1 (Hydrological cycle in the Mediterranean Experiment – First Special Observing Period occurred from 6 September to 6 November 2012; Ducroq et al., 2014). This choice is motivated by the fact that HyMeX-SOP1 contains several heavy precipitation events over Italy and the background error matrix is representative of the convective environment of the cases considered in this paper. In particular, 10 out of 20 declared IOP (Intense Observing Period) of HyMeX-SOP1 occurred in Italy (Ferretti et al., 2014). On the contrary, the period of September 2017, especially before the events selected in this study was characterized by fair and stable weather conditions over Italy and the background error matrix for September 2017 is less representative of the convective environment that characterise the events of this paper.

Because it is the first time that we show the assimilation of radar reflectivity factor in RAMS@ISAC, it is useful to discuss an example of analysis. We select the analysis of Livorno case study at 06 UTC. The observed CAPPI at 3km above sea level is shown in Figure 10b. The corresponding CAPPI simulated by the background is shown in Figure 14a. In general, the comparison between simulated and observed reflectivity factor shows the difficulty of the model to represent convection properly. In particular, the model is able to represent the convection over Northern Italy but it has poor performance over Sardinia, south of Sicily and over Central Italy. The difference between the analysis and background relative humidity after and before the analysis is shown in Figure 14b (absolute values less than 1% are suppressed in the figure for clarity). Both positive (convection enhancing) and negative (convection suppressing) adjustments are found. Over Central Italy, Sardinia and South of Sicily relative humidity is increased because the model doesn't simulate the observed reflectivity (Figure 10b). Over northern Italy the model is partially dried for two different reasons: over northwest of Italy because RAMS@ISAC simulates unobserved reflectivity, over north and northeast of Italy because the model simulates larger values of reflectivity factor compared to the observations. The RAMS-3DVar is able to dry the

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relative humidity field north of Corsica island, where the RAMS@ISAC predicts unobserved reflectivity, while RAMS-3DVar didn't suppress the unobserved convection west of Sardinia because the pseudo profiles computed over this area weren't appreciably drier than the background.

Cross correlations among different variables of the data assimilation system are neglected in this study and the application of the RAMS-3DVar affects the water vapour mixing ratio only. Cross correlations among different variables can improve the performance of data assimilation system, and an example of their impact in the RAMS-3DVar is shown in Federico (2013). Nevertheless, the impact of cross correlations among different variables in the precipitation VSF will be explored in future works.

Because also lightning data assimilation adjusts the water vapour mixing ratio, it follows that the data assimilation presented in this study adjusts only this parameter.

Lightning and radar data assimilation may produce sharp gradients in vertical direction caused by the addition of water vapour to specific layers. In the case of lightning, the water vapour is added by nudging to reduce sharp gradients. However, radar data assimilation, which accounts for the largest mass of water added to RAMS@ISAC (see Section S.1 of the supplemental material), directly adjusts the water vapour into the model. Our experience with RAMS@ISAC, however, shows that results are reliable and the sudden addition of water vapour doesn't cause shocks to the model simulation, despite the notable gradients of specific humidity.

It is finally noted that the data assimilation increase/decrease the water vapour into the model depending on the cases. The eventual increase/decrease of the forecasted rainfall depends on the physical and dynamical processes occurring into the meteorological model, without any specific tuning.

4. Results

In this section, we discuss the most intense phase of the Serano case, 03-06 UTC on 16 September, and two VSF forecasts, 00-03 UTC and 06-09 UTC on 10 September, for the Livorno case. The two VSF for Livorno correspond to the most intense phase of the storm in Livorno and to a very intense phase over Lazio region, Central Italy. The aim of the section is to show the notable improvement given by lightning and radar reflectivity factor data assimilation to the VSF.

We consider four types of VSF (Table 3): a) CTRL, without radar reflectivity factor and lightning data assimilation; b) LIGHT, assimilating lightning but not radar reflectivity factor; c) RAD,

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4.1 Serano¶
In this section we analyse two VSF forecasts of the Serano case. The first period (03-06 UTC) is the most intense, while the second period (18-21 UTC) corresponds to a rejuvenating phase of the storm. ¶

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assimilating radar reflectivity factor but not lightning; d) RADLI, assimilating both lightning and radar reflectivity factor.

In order to avoid excessive length two specific topics are considered in the supplemental material of this paper; specifically, we study: a) the relative contribution to the total water mass given by lightning and radar reflectivity factor data assimilation (Section S.1); b) the sensitivity of the precipitation VSF to the nudging formulation (Section S2). Also, the supplemental material gives different plots of Figures 15-17 (Section S3) and the forward radar operator used in RAMS-3DVar (Section S4).

4.1 Serano: 03-06 UTC on 16 September 2017

In this period, an intense and localised storm hit central Italy, while light precipitation occurred over northern Italy (Figure 15a). Considering the storm over central Italy, 10 raingauges observed more than 30 mm/3h, 6 more than 40 mm/3h, 3 more than 50 mm/3h and 1 more than 60 mm/3h, the maximum observed value being 63 mm/3h.

The CTRL forecast, Figure 15b, misses the storm over central Italy and considerably underestimates the precipitation area over Northern Italy, giving unsatisfactory results.

The assimilation of the radar reflectivity factor improves the forecast, as shown in Figure 15c. In particular, RAD forecast shows localized precipitation (30-35 mm/3h) close to the area were the most abundant precipitation was observed. However, the maximum precipitation is underestimated. Also, the RAD forecast better represents the precipitation over Northern Italy compared to CTRL.

The rainfall forecast of LIGHT, Figure 15d, shows some improvements compared to CTRL because the precipitation over central Italy has a maximum of 25-30 mm/3h, close to the area where the maximum precipitation was observed. LIGHT, however, has a worse performance compared to RAD because it underestimates the area of light precipitation over northern Italy. Also, similarly to RAD, LIGHT underestimates the maximum precipitation in central Italy.

RADLI forecast, Figure 15e, has the best performance. The precipitation over central Italy is well represented because the maximum rainfall (40-45 mm/3h) is in reasonable agreement with observations, and also because the area of intense precipitation (> 25 mm/3h) is elongated in the SW-NE direction in agreement with raingauge observations, giving a much better idea of the real storm intensity compared to RAD and LIGHT, as well as CTRL. The precipitation over northern Italy is well represented by RADLI.

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Table 4 shows the ETS and POD scores for selected rainfall thresholds for different neighbourhood radii. Different radii are considered to account for the well-known double penalty error (Mass et al., 2002; Mittermaier et al., 2013) caused by displacement errors of the detailed precipitation forecast in convection allowing grids. CTRL was unable to predict rainfall larger than 6 mm/3h. The comparison between RAD and LIGHT shows that assimilating radar reflectivity factor performs better than assimilating lightning. This behaviour, however, is not general and sometimes the assimilation of lightning has a better performance than assimilating radar reflectivity factor (see section 4.2.1).

RADLI forecast has the best performance among all model configurations. In particular, it is the only forecast having positive scores for thresholds larger than 30 mm/3h.

In conclusion, for this VSF, the assimilation of lightning and radar reflectivity factor acted synergistically to improve the precipitation VSF and the simulation assimilating both data performs considerably better than simulations assimilating either lightning or radar reflectivity factor.

4.2 Livorno

The Livorno case study lasted for several hours starting at 18 UTC on 9 September 2017 and ending more than a day later. The most intense phase in Livorno and its surroundings was observed during the night between 9 and 10 September. In the following, we will show two representative VSF (3h), including the most intense phase in Livorno.

4.2.1 Livorno: 00-03 UTC on 10 September 2017

This period represents the most intense phase of the storm in Livorno. In particular, the raingauge close to the label A (Figure 16a) reported 151 mm/3h (Collesalvetti), while the one close to the label B measured 82 mm/3h. Among the 518 raingauges reporting valid data, 75 observed more than 10 mm/3h, 31 more than 20 mm/3h, 17 more than 30 mm/3h, 9 more than 40 mm/3h, and 6 more than 50 mm/3h.

The CTRL precipitation forecast is shown in Figure 16b. The forecast is poor because it misses the precipitation swath from the coast towards NE. A precipitation swath is forecasted about 50 km to the North of the real occurrence, but it is less wide compared to the observations.

The RAD forecast, Figure 16c, shows that the assimilation of radar reflectivity factor gives a clear improvement to the forecast. The largest precipitation in the coastal part of the swath (we searched for the maximum in the area with longitudes between 10.20E and 10.70E and latitudes

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Figure 14f also shows the significant improvement of RAD and RADLI for the light rainfall forecast because the POD for the 0.2 mm/3h threshold increases from 0.5 of CTRL (0.55 for LIGHT) to about 0.85 for both RAD and RADLI.¶
The ETS score shows again the positive impact of the data assimilation, especially radar reflectivity factor, on the rainfall forecast for this phase of the storm, the best performance given by RADLI.¶
The proportion of correct forecast, Figure 14h, is larger than 84% for all configurations. HR, however, is lower for RAD and RADLI compared to other configurations because of the larger number of false alarms given by the assimilation of radar reflectivity factor.¶
It is finally remarked that lightning and reflectivity factor data assimilation acted synergistically because the simulation assimilating both data performs much better than the simulations assimilating only one kind of observation, either radar reflectivity factor or lightning.¶
¶
4.1.2 Serano: 18-21 UTC 16 September 2017 ¶
In this phase, rainfall occurred mainly over central Italy with moderate-heavy amounts. In particular, 51 raingauges measured more than 10 mm/3h, 13 more than 20 mm/3h, 3 more than 30 mm/3h and 2 between 40 mm/3h and 50 mm/3h (Figure 15a). Rainfall was also observed over north-western Italy with 12 raingauges observing more than 10 mm/3h, 7 more than 20 mm/3h, 4 more than 30 mm/3h, and 3 between 40 mm/3h and 50 mm/3h.¶
The CTRL forecast, Figure 15b, shows little precipitation over central Italy, giving an unsatisfactory forecast, while the forecast over north-western Italy is well represented even if displaced few tens of kilometres to the North of the real occurrence.¶ ... [1]

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4.2.1 Livorno: 18-21 UTC 9 September 2017¶
During this period, the precipitation started to hit intensely Livorno and its surroundings (point A in the Figure 16a). ... [2]

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between 43.10N and 43.60N) is 94 mm/3h. Another local maximum is in the southern part of the domain (label B of Figure 16a). The maximum location is well represented, but the forecast value (55 mm/3h) underestimates the observed maximum (82 mm/3h).

An improvement, compared to both CTRL and RAD, is given by the assimilation of lightning (Figure 16d). Also for this simulation there is a precipitation swath from coastal Tuscany to the Apennines, but the shape of the swath better resembles that observed. The maximum value close to Livorno, i.e. in the coastal part of the swath, is 158 mm/3h. LIGHT simulation shows the local maximum in the southern part of the domain (about 50 mm/3h), but the amount is underestimated.

Figure 16e shows the RADLI rainfall forecast. The precipitation swath from coastal Tuscany towards NE is more apparent compared to LIGHT and RAD. The maximum rainfall accumulated close to Livorno is 186 mm/3h. Also, the second precipitation maximum in the southern part of the domain reaches 70 mm/3h in good agreement with observations (82 mm/3h). RADLI is the only run giving a satisfactory precipitation VSF over the south-eastern Emilia Romagna (north-eastern part of the domain), to the lee of the Apennines. It is also noted that the main precipitation swath forecasted by RADLI is too broad in the direction crossing the swath compared to the observations. This is confirmed by the FBIAS of RADLI (not shown), which is more than 3 for thresholds larger than 42 mm/3h.

The analysis of the scores (Table 5) confirms the results outlined above. CTRL has the lowest performance and the improvement given by the data assimilation to the VSF is apparent for POD and ETS for all thresholds and neighbourhood radii considered. For this specific VSF, lightning data assimilation gives a better improvement to rainfall forecast compared to RAD. RADLI has the best performance, especially for 25 km and 50 km neighbourhood radii, nevertheless it over forecast the precipitation field. Because ETS penalises false alarms, the value of this score for RADLI is sometimes lower than that of LIGHT.

4.2.3 Livorno: 06-09 UTC on 10 September 2017

In this period, the most intense precipitation occurred over the coastal part of Lazio (Figure 17a). More in detail, among the 2695 raingauges reporting valid data over the domain of Figure 17a, 307 reported more than 10 mm/3h, 132 more than 20 mm/3h, 86 more than 30 mm/3h, 66 more than 40 mm/3h, 49 more than 50 mm/3h and 35 more than 60 mm/3h. Among the 35 raingauges

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Eliminato: Considering the POD, Figure 17f, we note the considerable improvement given to the score by data assimilation (lightning and/or radar reflectivity factor). POD is larger than 0.5 for RADLI and LIGHT up to the 52 mm/3h thresholds, clearly showing that those two configurations are able to catch the position and timing of the very intense precipitation, especially considering that the maximum displacement error for the precipitation field is 1.9 km.¶
RAD has a lower capability to correctly forecast the precipitation inland compared to FLASH and RADLI, however: a) it qualitatively reveals the heavy precipitation occurring in the Livorno area; b) the POD score is considerably improved compared to CTRL.¶
The ETS score, Figure 17g, underlines the good performance of RAD, LIGHT and RADLI compared to CTRL. RAD has a useful forecast (ETS > 0) up to 42 mm/3h, while LIGHT and RADLI show useful forecast up to 60 mm/3h. The lower ETS of RADLI compared to LIGHT for thresholds larger than 42 mm/3h is caused by the greater number of false alarms occurring in RADLI. The large variations of the scores for thresholds above 40 mm/3h is caused by the low number of raingauges observing those rainfall amounts.¶
CTRL ha the lowest HR, Figure 17h, up to 16 mm/3h because of the lower number of hits compared to other configurations. For thresholds larger than 32 mm/3h RADLI has the lowest HR due to the comparatively higher number of false alarms. ¶
In summary, for the most intense precipitation period over Livorno, the data assimilation of lightning and radar reflectivity factor plays a key role for the correct representation of the storm intensity, timing and position, giving an improvement of paramount practical importance.¶
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measuring more than 60 mm/3h, 33 were over Lazio, showing the heavy rainfall occurred over the Region.

Some precipitation persisted over Tuscany but the rainfall is much lower compared to previous 6h (the rainfall over Tuscany between 03 and 06 UTC was very intense, not shown). Other notable precipitation areas are over the NE of Italy (moderate to low amounts), over central Alps (moderate values) and over the whole Sardinia (small amounts).

Figure 17b shows the rainfall simulated by CTRL. The forecast is unsatisfactory, mainly for the following two reasons: a) heavy precipitation is simulated over Tuscany (> 75 mm/3h), also close to the Livorno area; b) few millimetres of precipitation are forecasted over central Italy. The rainfall over NE Italy is well represented in space, but overestimated.

Considering the evolution of CTRL forecast for the two VSF of Livorno, we conclude that it was able to predict abundant rain over Livorno, but the rainfall forecast was delayed compared to the real occurrence. A similar behaviour was found in Ricciardelli et al. (2018) using the WRF model, showing that the results of this paper for Livorno are likely not tied to the specific model used.

The rainfall simulated by RAD (Figure 17c) clearly improves the forecast compared to CTRL. First, the precipitation over Lazio is very well predicted and the rainfall values are up to 65 mm/3h, so RAD forecast well represents the main precipitation spot over Italy for this VSF. Second, the precipitation over Tuscany is less than for CTRL, showing the ability of radar reflectivity factor data assimilation to dry the model when it predicts reflectivity that is not observed. This is confirmed by the inspection of the analysis of Figure 14b, the last analysis used before this VSF, which gives a decrease of the relative humidity over most of Tuscany and over the sea in front of Livorno. Third, the precipitation over central Alps is represented, even if located about 30 km to the East. It is noted, however, that the area of intense rainfall (>60 mm/3h) is overestimated by RAD, showing a wet forecast. This is confirmed by the wet frequency bias of the RAD simulation, which is greater than 3 between 14 and 44 mm/3h. The wet bias of the RAD forecast is apparent in the representation of the rainfall VSF shown in the supplemental material of this paper (Figure S5).

LIGHT forecast, Figure 17d, shows a worse performance compared to RAD for this time period. The precipitation forecast is mainly over Tuscany, where it is overestimated, with a small precipitation spot over Lazio.

The precipitation forecast of RADLI, Figure 17e, represents very well the precipitation over Lazio, and the rainfall amount is better predicted compared to RAD. The precipitation over Sardinia is

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Eliminato: There are, however, three improvements compared to CTRL and RAD: a) the small precipitation over Sardinia is well represented in LIGHT; b) the precipitation over Central Alps is well predicted; c) the rainfall forecast over NE Italy is overestimated by LIGHT but to a less extent compared to RAD.
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well represented by RADLI as well as the precipitation over Central Alps, giving the best results among all VSF.

The analysis of the scores confirms the above results (Table 6). CTRL has a poor performance as shown by the POD and ETS values, close to zero, for all thresholds above 30 mm/3h and for all neighbourhood radii. The simulations assimilating radar reflectivity factor performs better than LIGHT, the difference being larger for higher rainfall thresholds and for smaller neighbourhood radii.

It is also notable the good performance of RADLI forecast for the nearest neighbourhood radii (ETS=0.43, POD=0.92) for the 50 mm/3h threshold.

5. Discussion and Conclusions

In this paper, we showed the impact of lightning and radar reflectivity factor data assimilation on the very short term precipitation forecast (3h) for two case studies occurred in Italy. We used RAMS@ISAC model, whose 3DVar extension to the assimilation of radar reflectivity factor is shown in this paper for the first time.

The first case study occurred on 16 September 2017 and it is a moderate case with localised rainfall over central Italy. It was chosen because the control forecast, i.e. without radar reflectivity factor or lightning data assimilation, missed the event. The second event, occurred on 9-10 September 2017, was characterised by exceptional rainfall over several parts of Italy. This event was partially represented by the control forecast. In particular, the forecast of the event was incorrect because: a) the control forecast was delayed compared to the observations; b) the control forecast missed the rainfall over central Italy (Lazio Region).

It is important to recall that the impact of lightning data assimilation on the precipitation forecast of RAMS@ISAC was already studied for the HyMeX-SOP1 period (Federico et al., 2017a, 2017b), and a robust statistic is already available. The results of this study confirm the important role of lightning data assimilation on the rainfall forecast for other two case studies. However, considering the assimilation of radar reflectivity factor, and its combination with lightning data assimilation in RAMS@ISAC, the results of this paper are new.

Because we analysed only two case studies, no definitive conclusions can be derived on the performance of RAMS@ISAC for radar reflectivity factor data assimilation. There are, however, few points worth of mention.

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Eliminato: The POD score (Figure 18f) confirms the above analysis. All the experiments with data assimilation outperform the CTRL forecast, and, for this time period, RAD performs better than LIGHT. RADLI shows the best POD among all configurations because it represents better the amount of rainfall over Lazio. ¶
Similar considerations apply to ETS (Figure 18g); it is worth of note the high value of ETS for thresholds larger than 50 mm/3h, which represent heavy rainfall. Again, a forecast that was missed by CTRL is correctly represented by the assimilation of both radar reflectivity factor and lightning.¶
The HR score (Figure 18h) shows that CTRL has the lowest score for thresholds below 14 mm/3h because it has a lower number of hits. For higher thresholds (> 32 mm/3h), the impact of the false alarms become important and RADLI has the lowest HR.¶

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The VSF performance of RAMS@ISAC is systematically improved by the assimilation of radar reflectivity factor. This improvement is of paramount importance for some specific VSF (for example for the 00-03 UTC of Livorno), when the control forecast missed the event while it was correctly predicted by radar reflectivity factor data assimilation. Sometimes the improvement of reflectivity factor data assimilation has a lower impact on the precipitation forecast, as for the period 18-21 UTC on 9 September 2017 (Livorno, not shown, see the discussion paper Federico et al. (2018) for a description of this VSF). This suggests that there is space for improvement for all components of the VSF: observations, data assimilation, meteorological model.

Lightning and radar observations are different and both add value to the VSF. In particular, flashes are recorded when deep convection develops, while radar reflectivity factor is observed also for light stratiform rain. Flashes of ground based network, as LINET, are available over the open sea, even if with a reduced detection efficiency, while radar reflectivity factor is confined to the range of coastal radars in the network. Lightning has a seasonal dependence over Italy, with the maximum in summer and fall, while radar reflectivity factor is available in all seasons.

For the above reasons, the impact of the two kinds of data on the rainfall VSF is expected different. Some examples have been shown: the light precipitation over Northern Italy for Serano is well forecasted assimilating radar reflectivity factor, while it is not simulated assimilating flashes because they are too few in this area to force convection; lightning data assimilation is able to better represent the deep convection occurring during the intense phase of the Livorno case (00-03 UTC), especially because it is able to force convection where it occurs, reducing false alarms. The ability of lightning data assimilation to reduce false alarms compared to RAD and RADLI it is shown by the fact that the ETS score for LIGHT is sometimes the best among all simulations (see also the section S2 of the supplemental material of this paper). These results show also that the influence of different observations depends on the meteorological situation.

The model configuration assimilating both radar reflectivity factor and lightning (RADLI) is able to retain important features of both data assimilation. For example, the simulation of the Livorno case in the phase 06-09 UTC was able to simulate the heavy precipitation over Lazio thanks to the radar reflectivity factor data assimilation and the precipitation over Sardinia, as well as the moderate precipitation over central Alps, thanks to lightning data assimilation.

The property of RADLI to retain the precipitation features of both RAD and LIGHT it is shown by the POD score, which is the best, for most cases and thresholds, for RADLI.

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Eliminato: Another example of synergistic interaction between the two types of data assimilation was found for the most intense phase of the Serano case (03-06 UTC on 16 September 2017). In this period, the light precipitation over the Alps was forecast by RADLI because of the assimilation of radar reflectivity factor, while the localised precipitation maximum over Central Italy was better forecast thanks to the synergistic action of lightning and reflectivity factor data assimilation.¶

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Another interesting feature is the considerable improvement of the POD of RADLI compared to CTRL for the lowest thresholds.

It is also underlined that the data assimilated, both lightning and radar reflectivity factor, are available in real time and could be used for an operational implementation of the VSF.

All the above features are promising and deserve future studies to better understand the role of radar reflectivity factor and its interaction with lightning data assimilation to improve the precipitation forecast.

There are, however, less satisfactory aspects of assimilating both radar reflectivity factor and lightning data. In particular, the wet bias of RAD and RADLI forecast is the main drawback of the results of this paper. To reduce the moisture added by radar and lightning data assimilation further research is needed and different approaches are possible (Fierro et al., 2016). In particular: a) assimilating for a shorter time (0-6h in this paper); b) reducing the length-scales of the 3D-Var in the horizontal directions to limit the spreading of the innovations, or assuming an innovation equal to zero for grid points without lightning and with zero reflectivity factor; c) reducing the amount of water vapour added to the model (for example reducing the values of A and B constants for lightning data assimilation or relaxing the request of saturation when radar reflectivity is observed in areas where the model has zero reflectivity); d) adding moisture to a shallower vertical layer.

It is also noted that a combination of heating and moistening could provide the same buoyancy with less water vapour addition (Marchand and Fulberg, 2014) and this approach could be used in future studies.

In addition to the acquisition of more case studies, there are two directions of future development of this work. Lightning data assimilation can be formulated by 3DVar, using a strategy similar to the radar reflectivity factor in which pseudo-profiles of relative humidity are first generated where flashes are recorded, and then those profiles are assimilated by 3DVar. This methodology was already reported in Fierro et al. (2016). The assimilation of both radar reflectivity factor and lightning using RAMS-3DVar will be explored in future studies.

Another important point to study is how long the innovations introduced by data assimilation lasts in the forecast. While in this study we consider the VSF at 3h, future studies must explore longer time ranges. This kind of study was performed for lightning data assimilation (Fierro et al., (2015); Federico et al., 2017b; Lynn et al. (2015) among others) and for radar data assimilation (Hu et al. (2006); Jones et al. (2014), among others), using a rationale similar to that used in this paper.

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Eliminato: The RADLI forecast has more false alarms compared to RAD and LIGHT and this penalises the usefulness of RADLI forecast. This is shown by the lower ETS and HR score of RADLI, especially compared to LIGHT, for some thresholds and VSF, despite the larger values of the POD of RADLI.

Eliminato: The RADLI forecast can miss intense precipitation: this is shown, for example, by the VSF of 18-21 UTC on 9 September 2017 (Livorno), when RADLI underestimated the most intense phase of the storm in Livorno. ¶

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In general, the performance of the forecast and the impact of lightning and radar data assimilation decrease with forecasting time because of the propagation of boundary conditions inside the domain and because of model errors growth. Improving the data assimilation system also contributes to a longer resilience of model performance. The studies cited above showed that lightning and radar data assimilation can have an impact up to 24h depending on several factors (meteorological model, data assimilation, quality of the data, meteorological conditions, initial and boundary conditions).

A study considering both radar reflectivity factor and lightning should be performed to understand the resilience of the innovations introduced by data assimilation.

Eliminato: Results showed that the lightning data assimilation gave a small and positive contribution to the precipitation forecast up to 24 h. However, the impact of data assimilation decreased rapidly, and the improvement of the rainfall forecast was significant after 6h, small after 12h and negligible after 24 h.

ACKNOWLEDGMENTS

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TABLES

Table 1: List of physical parameterisations used for RAMS@ISAC in this paper.

Physical parameterization	Selected scheme
Parametrized cumulus convection	Modified Kuo scheme to account for updraft and downdraft (Molinari and Corsetti, 1985). The scheme is applied to R10 only.
Explicit precipitation parameterization	Bulk microphysics with six hydrometeors (cloud, rain, graupel, snow, ice, water vapour). Described in Hong and Lim (2006).
Exchange between the surface, the biosphere and atmosphere.	LEAF3 (Walko et al., 2000). LEAF includes prognostic equations for soil temperature and moisture for multiple layers, vegetation temperature and surface water, and temperature and water vapour mixing ratio of canopy air.
Sub-grid mixing	The turbulent mixing in the horizontal directions is parameterised following Smagorinsky (1963), vertical diffusion is parameterised according to the Mellor and Yamada (1982) scheme, which employs a prognostic turbulent kinetic energy.
Radiation scheme	Chen-Cotton (Chen and Cotton, 1983). The scheme accounts for condensate in the atmosphere.

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Table 2: Basic parameters of the RAMS@ISAC grids (R10, R4 and R1, corresponding, respectively, to the domains D1, D2 and D3). NNXP is the number of grid points in the WE direction, NNYP is the number of grid-points in the NS direction, NNZP is the number of vertical levels, DX is the size of the grid spacing in the WE direction, DY is the grid spacing in the SN direction. Lx, Ly, and Lz are the domain extensions in the NS, WE, and vertical directions. CENTLON and CENTLAT are the coordinates of the grid centres.

	R10, D1	R4, D2	R1, D3
NNXP	301	401	203
NNYP	301	401	203
NNZP	36	36	36
Lx	3000 km	1600 km	~270 km
Ly	3000 km	1600 km	~270 km
Lz	~22400 m	~22400 m	~22400 m
DX	10 km	4 km	4/3 km
DY	10 km	4 km	4/3 km
CENTLAT (°)	43.0 N	43.0 N	43.7 N

CENTLON (°)	12.5 E	12.5 E	11.0 E

Table 3: Types of simulations performed.

Experiment	Description	Data assimilated	Model variable impacted
CTRL	Control run	None	None
RAD	RADAR data assimilation	Reflectivity factor CAPPI (RAMS-3DVar)	Water vapour mixing ratio
LIGHT	Lightning data assimilation (A=0.85; B=0.16 in Eqn (1))	Lightning density (nudging)	Water vapour mixing ratio
RADLI	RADAR + lightning data assimilation (A=0.86; B=0.15 in Eqn (1))	Reflectivity factor CAPPI (RAMS-3DVar) + Lightning density (nudging)	Water vapour mixing ratio

Table 4: ETS and POD scores for three different neighbourhood radii. Scores are computed over the domain D2.

Threshold (mm/3 h)	ETS nearest neighboorhood (CTRL, RAD, LIGHT, RADLI)	POD nearest neighbourhood (CTRL, RAD, LIGHT, RADLI)	ETS 25 km (CTRL, RAD, LIGHT, RADLI)	POD 25 km (CTRL, RAD, LIGHT, RADLI)	ETS 50 km (CTRL, RAD, LIGHT, RADLI)	POD 50 km (CTRL, RAD, LIGHT, RADLI)
1	(0.42,0.36,0.44,0.33)	(0.57,0.87,0.60,0.81)	(0.68,0.73,0.68,0.73)	(0.77,0.93,0.75,0.89)	(0.79,0.89,0.82,0.87)	(0.84,0.92,0.84,0.90)
6	(0.06,0.10,0.14,0.13)	(0.0,0.5,0.20,0.72)	(0.11,0.44,0.72,0.41)	(0.11,0.86,0.72,0.83)	(0.19,0.86,0.86,0.92)	(0.19,0.86,0.86,0.92)
10	(0.,0.05,0.,0.15)	(0.,0.26,0.,0.79)	(0.,0.66,0.58,0.74)	(0.0,0.84,0.58,0.89)	(0.,0.95,0.74,0.90)	(0.,0.95,0.74,0.90)
20	(0.,0.,0.,0.41)	(0.,0.,0.,0.8)	(0.0,0.41,0.33,0.87)	(0.,0.47,0.3,0.9)	(0.,0.73,0.80,1.0)	(0.,0.73,0.80,1.0)
30	(0.,0.,0.,0.31)	(0.,0.,0.,0.5)	(0.,0.,0.,0.90)	(0.,0.,0.,0.9)	(0.,0.,0.,1.0)	(0.,0.,0.,1.0)
40	(0.,0.,0.,0.)	(0.,0.,0.,0.)	(0.,0.,0.,0.33)	(0.,0.,0.,0.33)	(0.,0.,0.,0.50)	(0.,0.,0.,0.50)

Table 5: ETS and POD scores for three different neighbourhood radii. Scores are computed over the domain D3.

Threshold (mm/3 h)	ETS nearest neighbourhood (CTRL, RAD, LIGHT, RADLI)	POD nearest neighbourhood (CTRL, RAD, LIGHT, RADLI)	ETS 25 km (CTRL, RAD, LIGHT, RADLI)	POD 25 km (CTRL, RAD, LIGHT, RADLI)	ETS 50 km (CTRL, RAD, LIGHT, RADLI)	POD 50 km (CTRL, RAD, LIGHT, RADLI)
1	(0.43,0.64,0.70,0.56)	(0.67,0.86,0.98,0.99)	(0.68,0.80,0.82,0.71)	(0.83,0.92,0.98,0.99)	(0.68,0.80,0.82,0.71)	(0.83,0.92,0.98,0.99)
6	(0.1,0.31,0.60,0.49)	(0.24,0.58,0.89,0.95)	(0.49,0.70,0.91,0.96)	(0.55,0.76,0.96,0.97)	(0.49,0.70,0.91,0.96)	(0.55,0.76,0.96,0.97)
10	(0.11,0.33,0.56,0.54)	(0.19,0.56,0.75,0.80)	(0.48,0.76,0.91,0.97)	(0.52,0.79,0.92,0.97)	(0.48,0.76,0.91,0.97)	(0.52,0.79,0.92,0.97)
20	(0.02,0.30,0.52,0.59)	(0.03,0.39,0.74,0.81)	(0.18,0.73,0.97,0.93)	(0.19,0.74,0.97,0.97)	(0.18,0.73,0.96,0.93)	(0.19,0.74,0.97,0.97)
30	(0.,0.27,0.51,0.47)	(0.,0.29,0.76,0.76)	(0.,0.64,0.94,1.)	(0.,0.65,1.,1.)	(0.,0.64,0.94,1.)	(0.,0.65,1.,1.)
40	(0.,0.44,0.27,0.27)	(0.,0.44,0.56,0.67)	(0.,0.89,1.,1.)	(0.,0.89,1.,1.)	(0.,0.89,1.,1.)	(0.,0.89,1.,1.)
50	(0.,0.33,0.66,0.50)	(0.,0.33,0.67,0.67)	(0.,0.67,1.,1.)	(0.,0.67,1.,1.)	(0.,0.66,1.,1.)	(0.,0.67,1.,1.)

Table 6 ETS and POD scores for three different neighbourhood radii. Scores are computed over the domain D2.

Threshold (mm/3h)	ETS nearest neighboorhood (CTRL, RAD, LIGHT, RADLI)	POD nearest neighbourhood (CTRL, RAD, LIGHT, RADLI)	ETS 25 km (CTRL, RAD, LIGHT, RADLI)	POD 25 km (CTRL, RAD, LIGHT, RADLI)	ETS 50 km (CTRL, RAD, LIGHT, RADLI)	POD 50 km (CTRL, RAD, LIGHT, RADLI)
1	(0.41,0.63,0.61,0.65)	(0.66,0.89,0.89,0.93)	(0.79,0.83,0.82,0.83)	(0.89,0.95,0.95,0.96)	(0.88,0.92,0.93,0.94)	(0.93,0.97,0.98,0.98)
6	(0.2,0.4,0.39,0.47)	(0.43,0.82,0.77,0.88)	(0.45,0.63,0.71,0.76)	(0.63,0.90,0.95,0.96)	(0.72,0.86,0.88,0.92)	(0.82,0.96,0.97,0.96)
10	(0.,0.24,0.18,0.28)	(0.14,0.78,0.55,0.80)	(0.14,0.47,0.58,0.62)	(0.24,0.86,0.82,0.93)	(0.32,0.91,0.96,0.95)	(0.35,0.95,0.97,0.97)
20	(-0.03,0.18,0.13,0.22)	(0.01,0.81,0.30,0.80)	(0.09,0.46,0.57,0.61)	(0.11,0.86,0.59,0.90)	(0.15,0.84,0.91,0.96)	(0.15,0.90,0.92,0.97)
30	(-0.02,0.22,0.13,0.28)	(0.,0.90,0.23,0.88)	(0.01,0.79,0.46,0.80)	(0.01,0.93,0.47,0.94)	(0.02,0.95,0.93,0.99)	(0.02,0.95,0.93,0.99)
40	(-0.1,0.24,0.08,0.36)	(0.,0.83,0.12,0.89)	(0.01,0.83,0.37,0.83)	(0.02,0.97,0.38,0.97)	(0.1,0.97,0.95,0.98)	(0.02,0.98,0.95,0.98)
50	(-0.01,0.27,0.,0.43)	(0.,0.67,0.,0.92)	(0.,0.90,0.,0.90)	(0.,0.94,0.,0.96)	(0.,0.96,0.,0.96)	(0.,0.96,0.,0.96)

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Formattato ... [152]

FIGURES

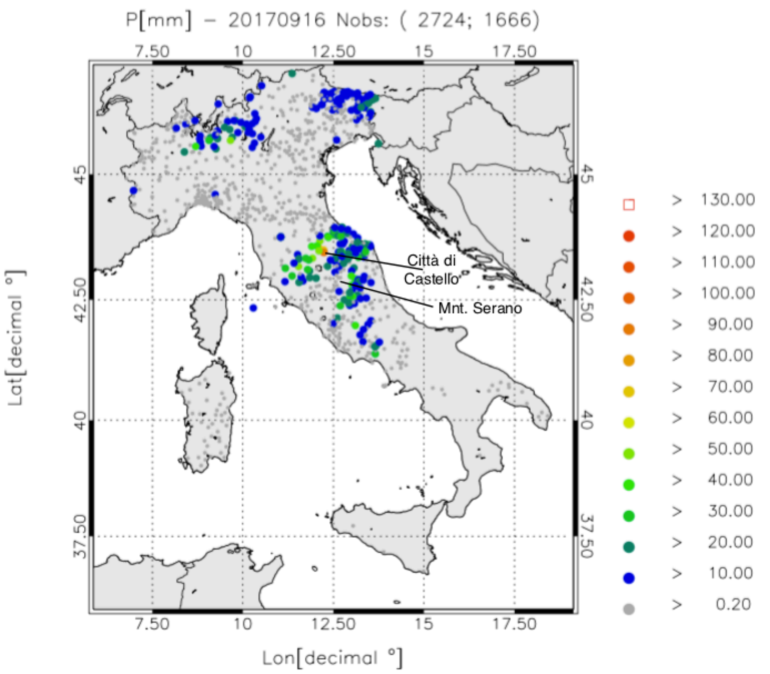

Figure 1: Daily precipitation (P) [mm] over Italy on 16 September 2017. Only raingauges observing at least 0.2 mm/day are shown. The first number in the figure title within brackets represents the available raingauges, while the second number represents raingauges observing at least 0.2 mm/3h. The lowest precipitation class is represented by smaller dots, the largest by a red square. The locations of Città di Castello and Mount Serano are indicated.

a)

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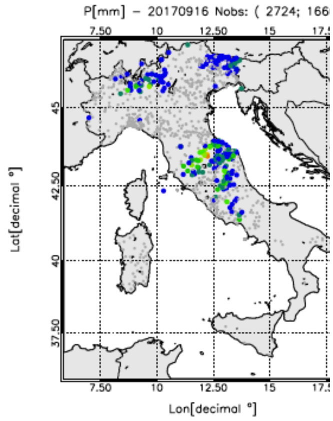

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Eliminato: from the network of the Department of Civil Protection

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Eliminato: ¶

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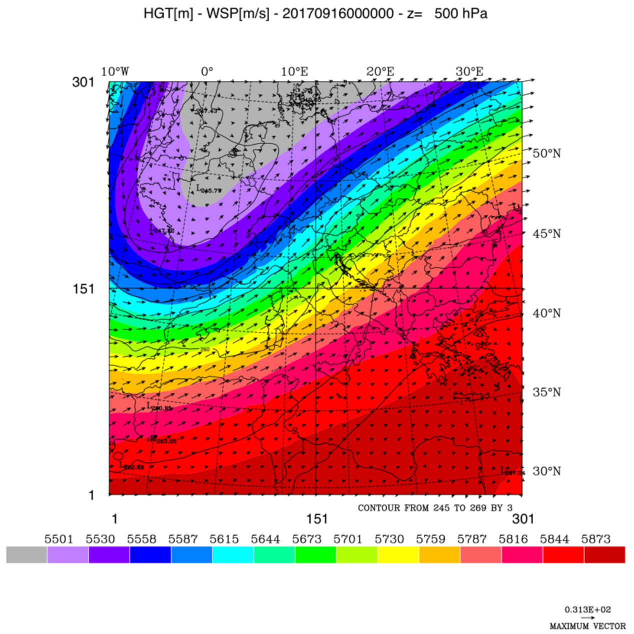
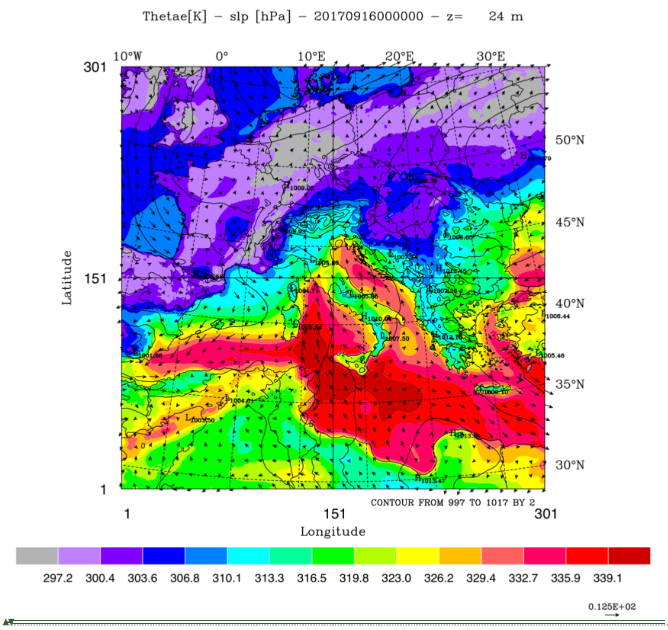


b)



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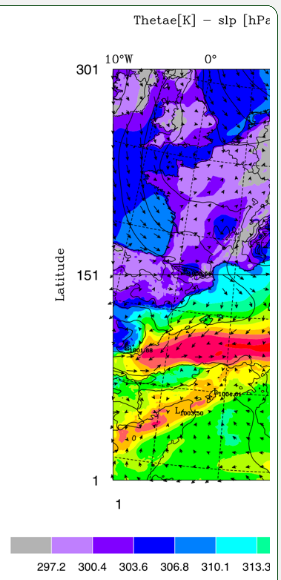

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Spostato (inserimento) [1]

Figure 2: a) Geopotential height (filled contours), temperature (contours) and wind vectors at 500 hPa on 16 September 2017 at 00 UTC. Maximum velocity is 31 m/s; b) equivalent potential temperature (filled contours), sea-level pressure (contours) and wind vectors at 24 m above the surface (first vertical level of RAMS@ISAC, maximum value 13 m/s). A low-pressure patter is forming over northern Italy, with a front in the western Mediterranean.

Eliminato: at 00 UTC

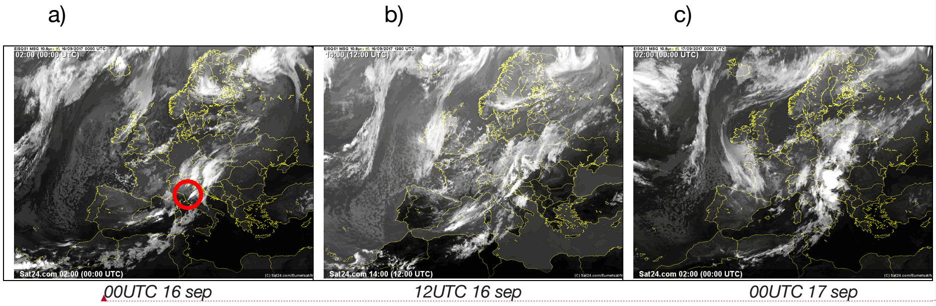

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Figure 3: a) Satellite images (METEOSAT second generation) of the infrared channel, 10.8 micron, at 00 UTC and 12 UTC on 16 September, and at 00 UTC on 17 September 2017. A well-defined cloud system is apparent inside the red circle of the image at 00 UTC on 16 September 2017.

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Eliminato: for

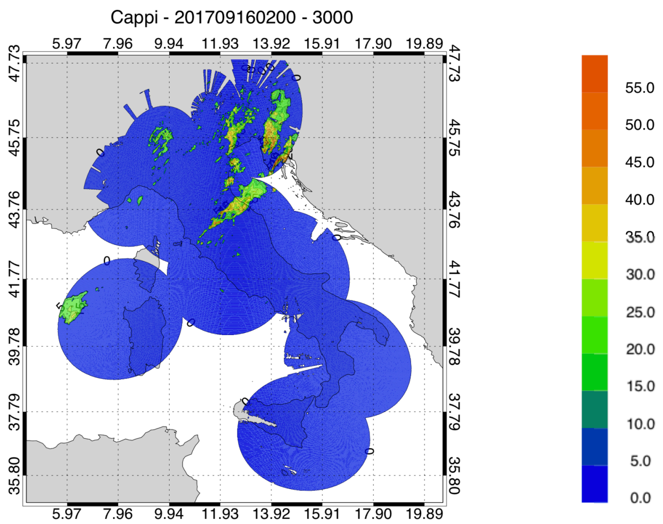

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Figure 4: National radar mosaic at 3 km above the sea level observed at 02 UTC on 16 September 2017.

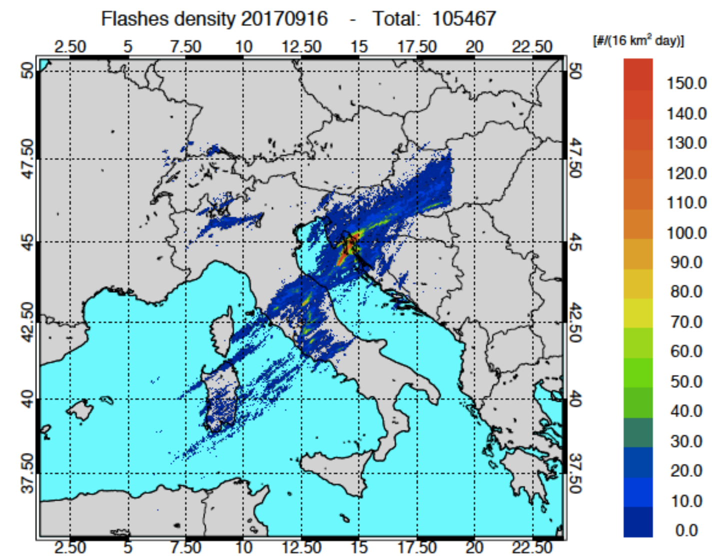

Figure 5: Lightning density (number of lighting per 16 km[2] for the whole day) recorded on 16 September 2017. The total number of flashes recorded is shown in the title.

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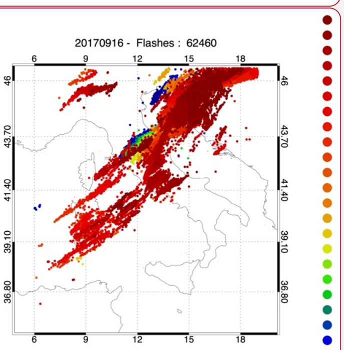
Formattato: Tipo di carattere: (Predefinito) +Corpo (Helvetica Neue), Colore carattere: Automatico, Bordo: : (Nessun bordo)

Formattato: Giustificato



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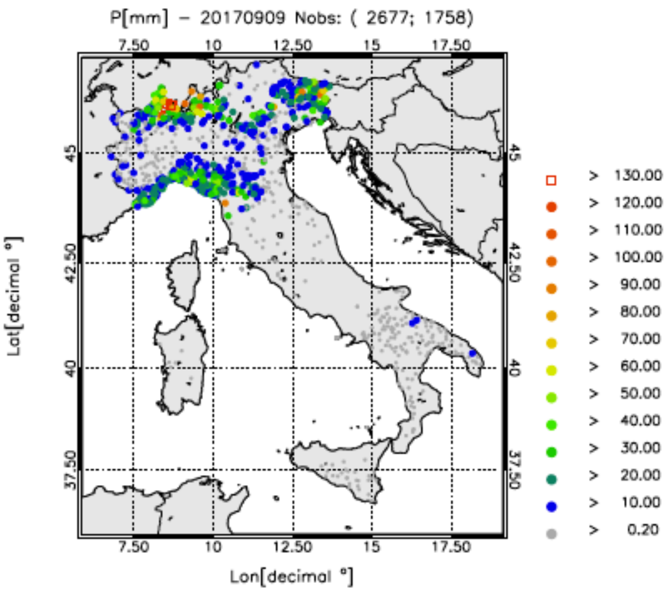
Formattato: Apice

Eliminato: Different colours represent the time (UTC) of occurrence of the lightning.

a)



Eliminato: b)

b)

Formattato: Tipo di carattere: Non Grassetto

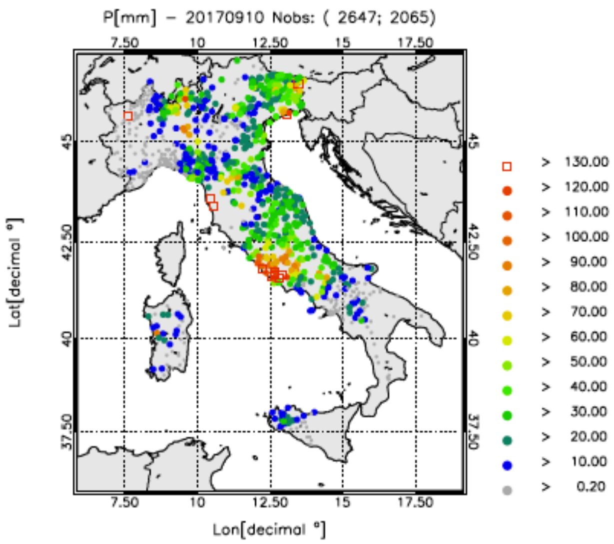
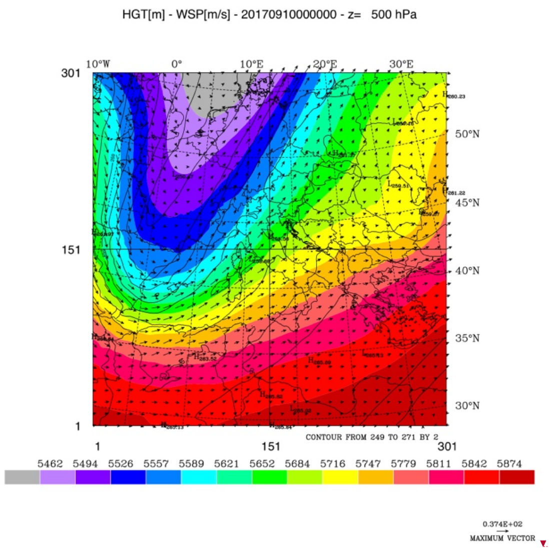


Figure 6: a) As in Figure 1 but for a) 9 September 2017 and b) 10 September 2017.

a)



b)

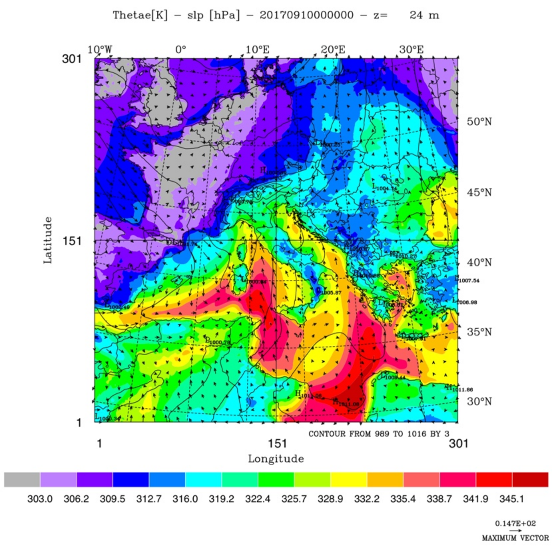


Figure 7: a) Geopotential height (filled contours), temperature (contours) and wind vectors at 500 hPa at 00 UTC on 10 September 2017. Maximum velocity is 37 m/s; b) equivalent potential temperature (filled contours), sea-level pressure (contours) and wind vectors at 24 m above the surface (first vertical level, maximum value 15 m/s).

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Formattato: Inglese (Regno Unito)

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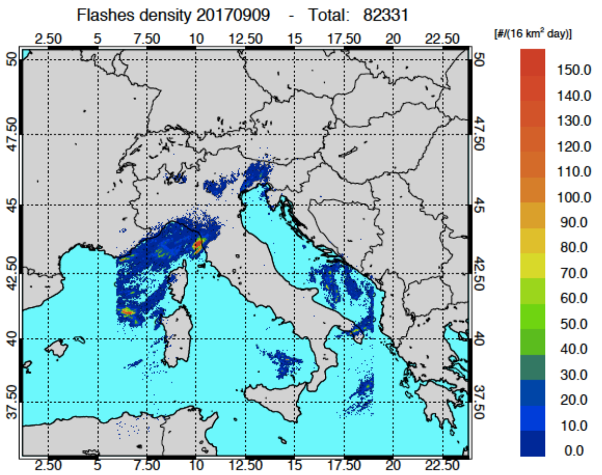
a)



b)

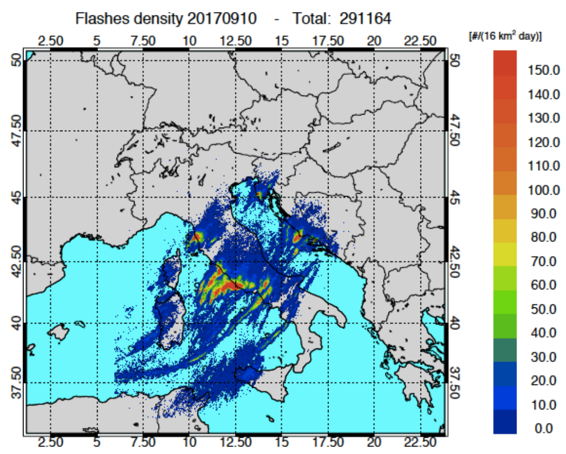
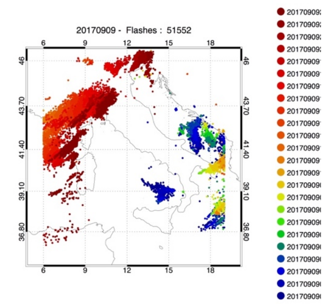


Figure 8: a) Lightning density (lightning number per 16 km^2 for the whole day) recorded on 09 September 2017; b) as in a) for 9 September 2017. The number of flashes recorded on each day is shown in the title.

Eliminato: b)



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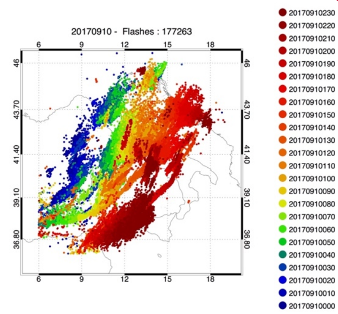

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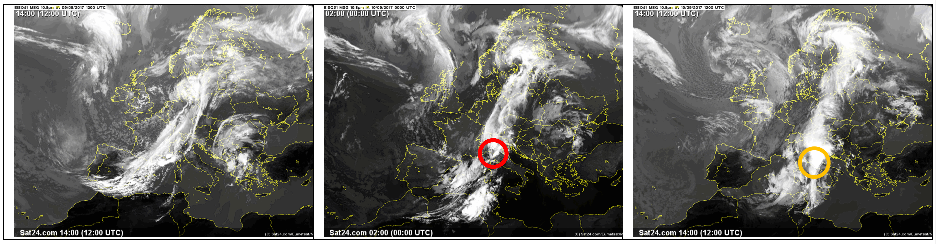
Formattato: Apice

Eliminato: Lightning recorded on 10 September

Eliminato: Different colours represent the time of occurrence of the lightning.

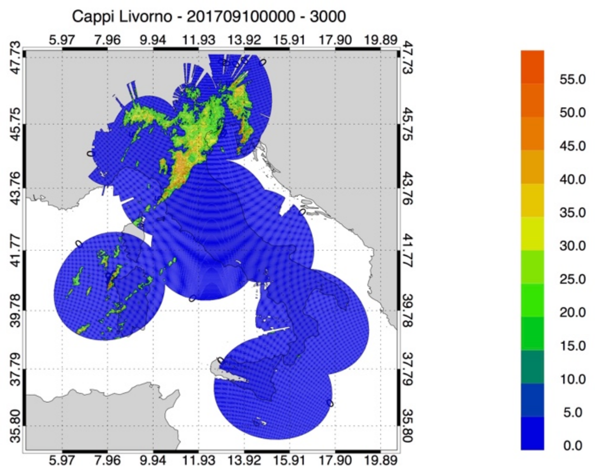
a) b) c)



12UTC 09 sep *00UTC 10 sep* *12UTC 10 sep*

Figure 9: a) Satellite images (METEOSAT second generation) of the infrared channel, 10.8 micron, at 12 UTC on 9 September 2017, at 00 UTC 00 UTC and 12 UTC on 10 September 2017. The red circle in Figure 9b and the orange circle in Figure 9c show the Livorno and Lazio area, respectively.

a)



b)

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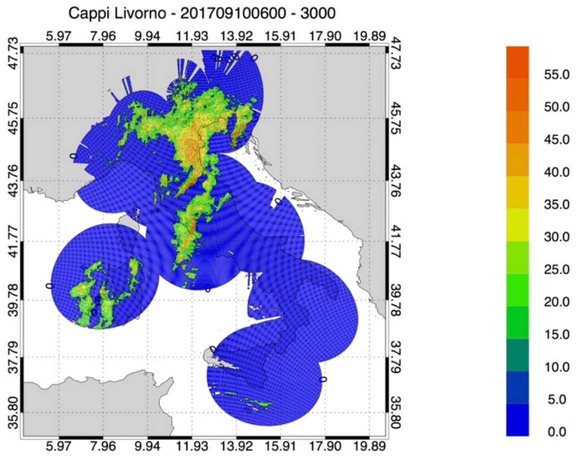

Figure 10: a) National radar mosaic at 3 km above the sea level observed at 00 UTC on 10 September 2017; b) as in a) at 06 UTC.

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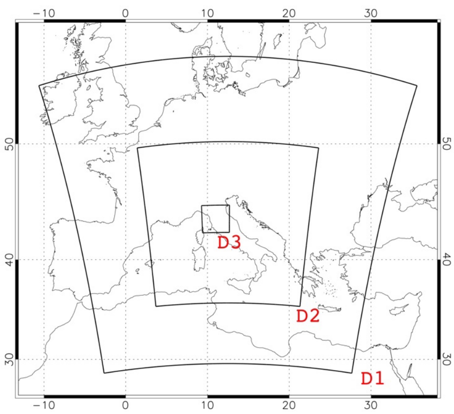

Formattato: Giustificato

Figure 11: The three domains used in RAMS@ISAC. The model grid over domain D1 has 301 grid points in the NS and WE directions and has 10 km horizontal resolution, the model grid over domain D2 has 401 grid points in the NS and WE directions and has 4 km horizontal resolution. The model grid over domain D3 has 203 grid points in the NS and WE directions and has 4/3 km horizontal resolution. All grids have the same thirty-six vertical levels spanning the 0-22.4 km vertical layer.

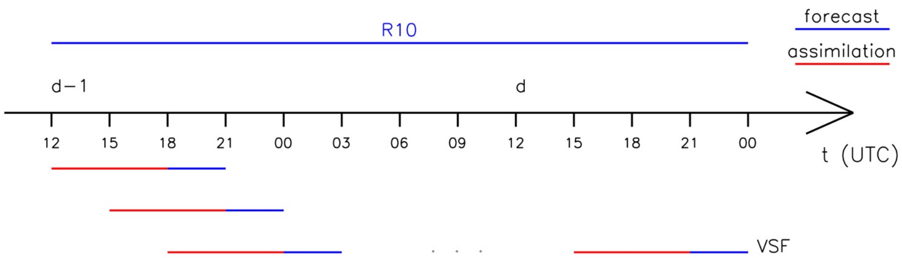

Figure 12: The implementation of the RAMS@ISAC very short-term forecast.

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Figure 13: The radar network of the Department of Civil Protection. Green radars operate with dual-polarisation, blue radars have single polarisation.

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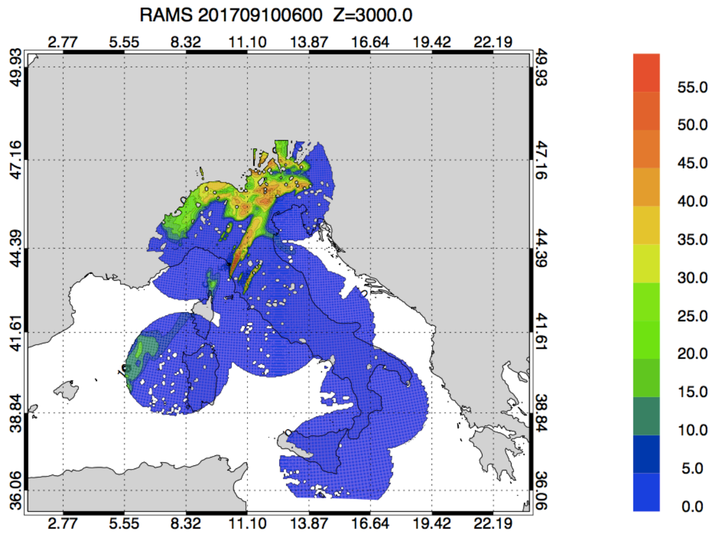
a)



b)

Formattato: Nessuno, Controllo ortografia e grammatica

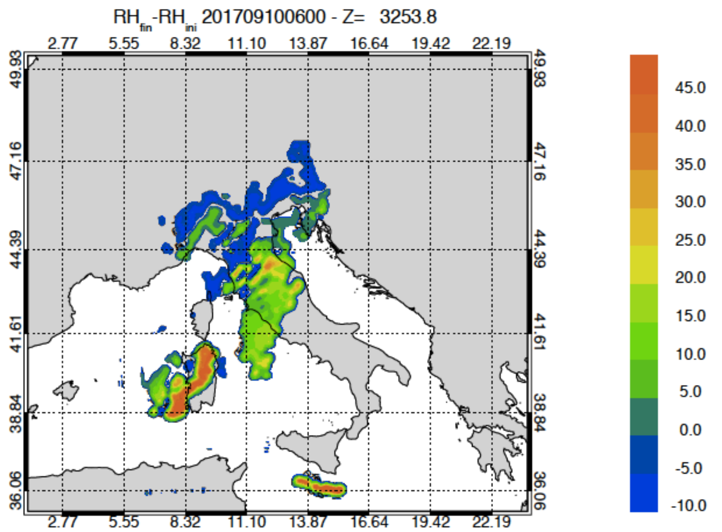


Figure 14: a) RAMS@ISAC reflectivity factor simulated 3 km above sea level at 06 UTC on 10 September 2017; b) relative humidity difference between the analysis and the background at 06 UTC at 3.2 km level in the terrain following vertical coordinate of RAMS@ISAC.

a)

Formattato: Nessuno, Controllo ortografia e grammatica

Formattato: Giustificato

Eliminato: ¶

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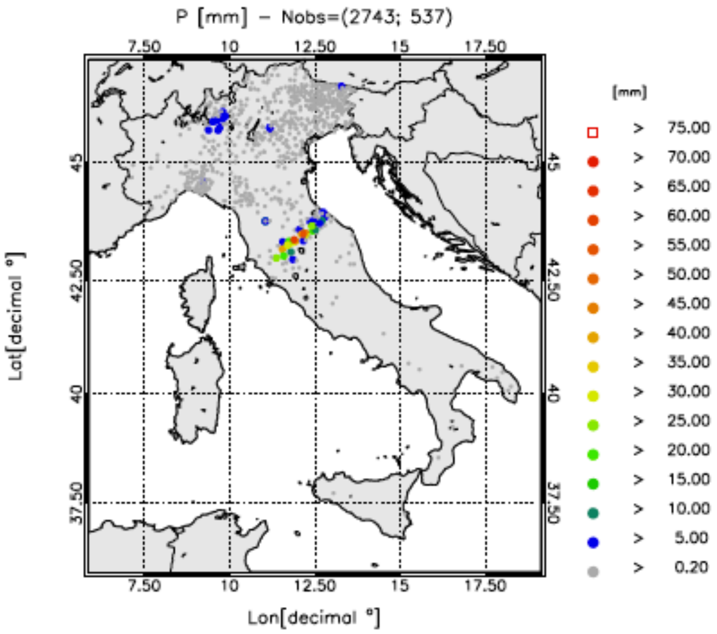
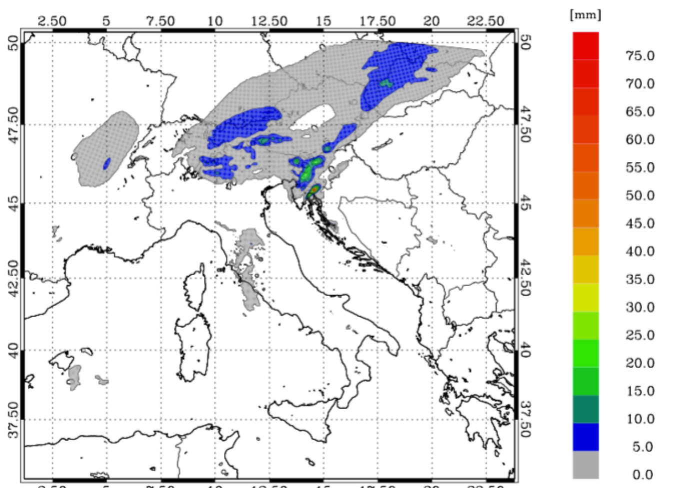
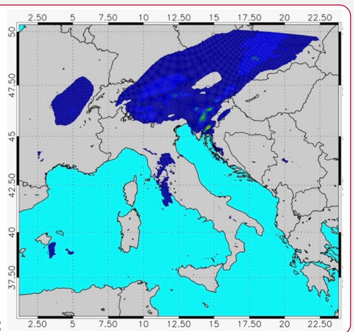
Eliminato: b)



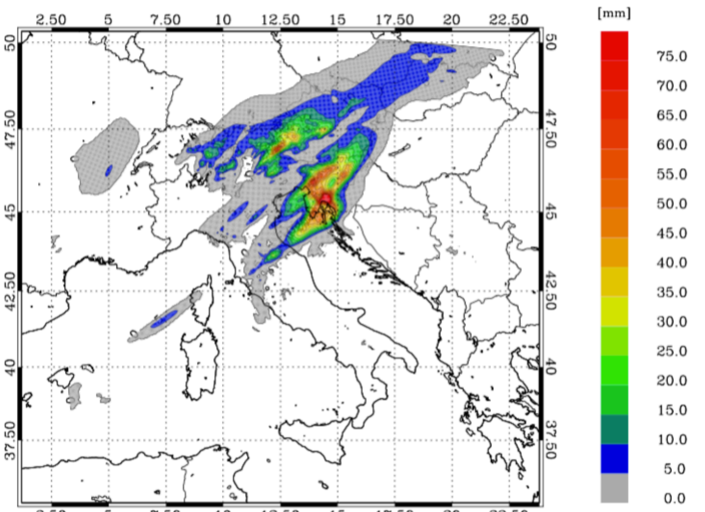
b)



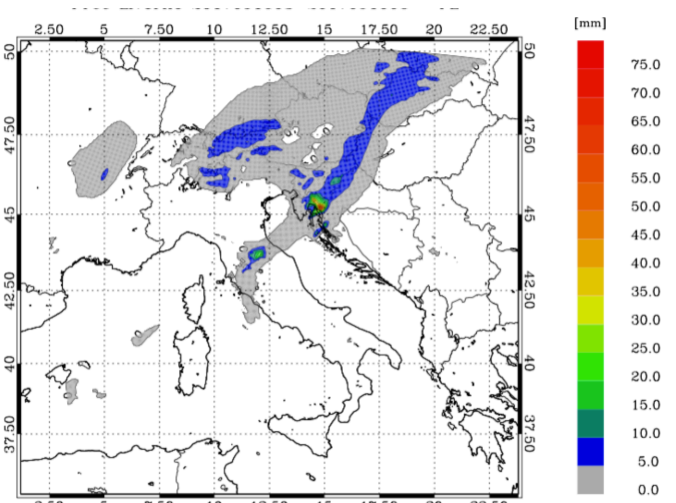
Eliminato:



c)

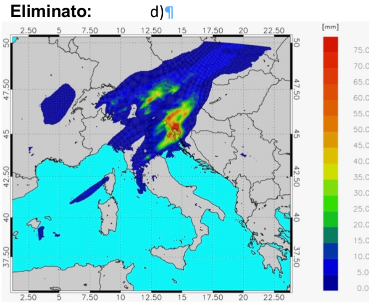


d)

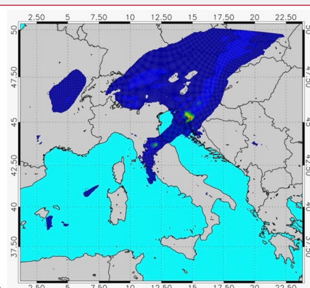


e)

Eliminato: d)



Eliminato:



Eliminato: f)

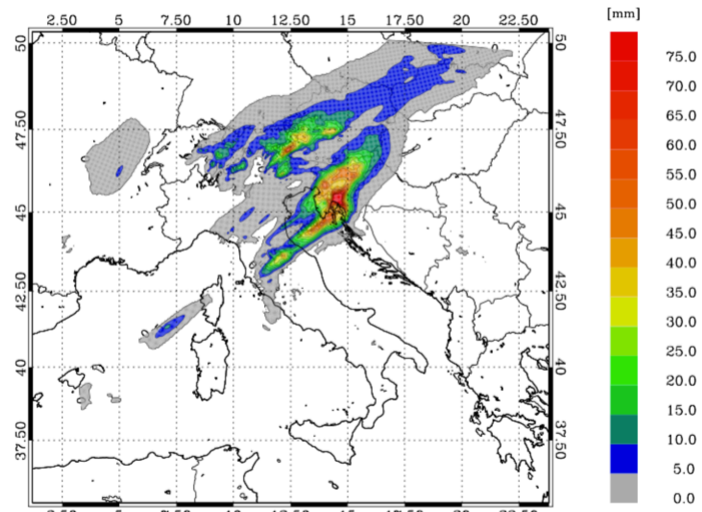
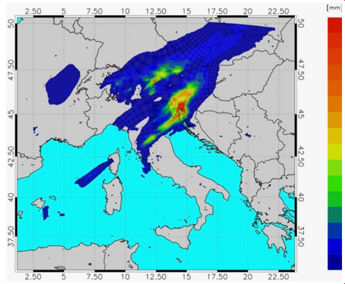
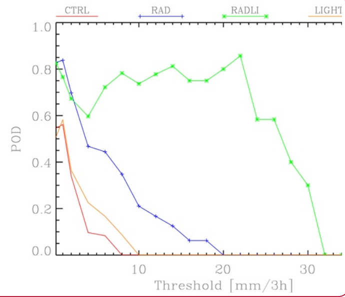


Figure 15: a) rainfall reported by raingauges between 03 and 06 UTC on 16 September 2017. Only raingauges observing at least 0.2 mm/day are shown. The first number in the title within brackets represents the available raingauges, while the second number represents those observing at least 0.2 mm/3h; b) rainfall VSF of CTRL for the same time interval as in a); c) as in b) for RAD forecast; d) as in b) for LIGHT forecast; e) as in b) for RADLI forecast.

Eliminato: 

Eliminato: 

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h)¶

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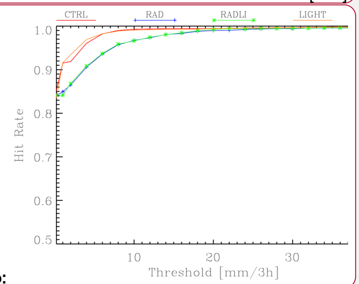
Eliminato: 

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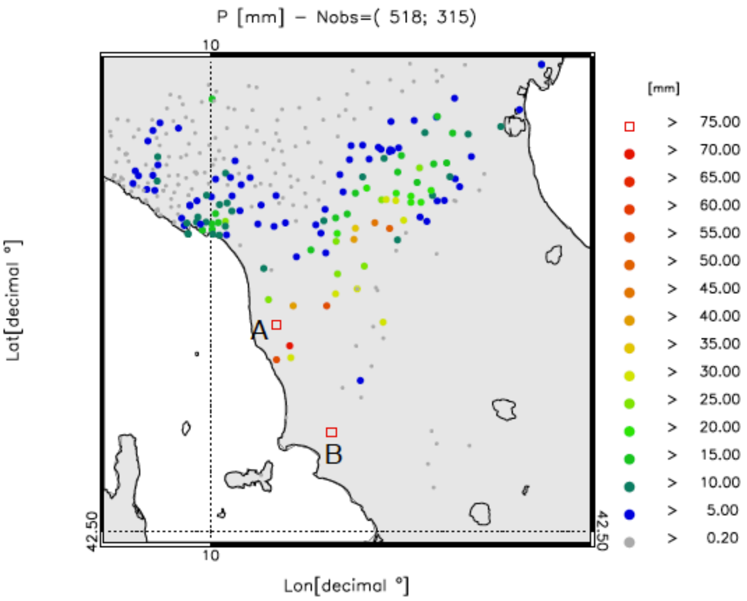
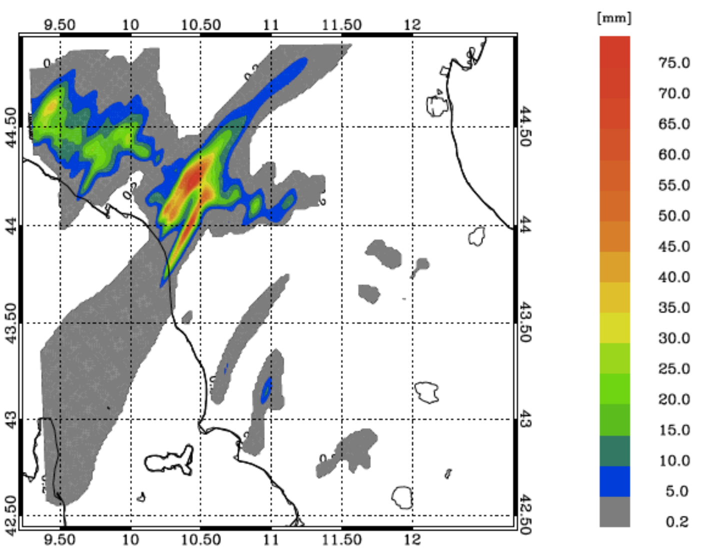
Eliminato: ; f) POD score for the period 03-06 UTC on 16 September 2017; g) as in f) for the ETS score. POD and ETS scores are computed over the domain of Figure 14a

a)



b)



c)

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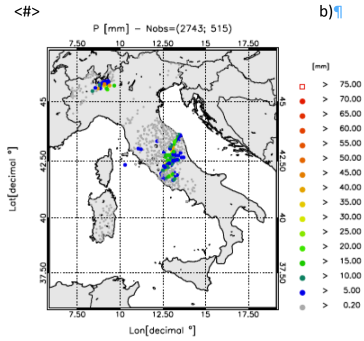
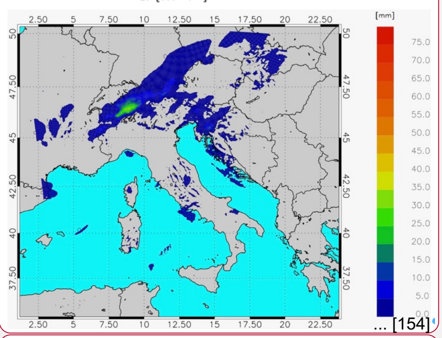
<#> b)¶





... [154]

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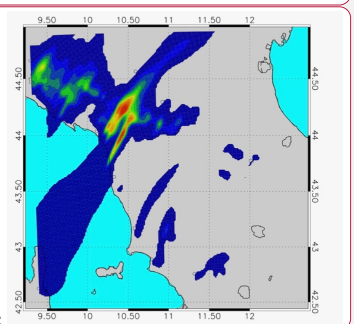

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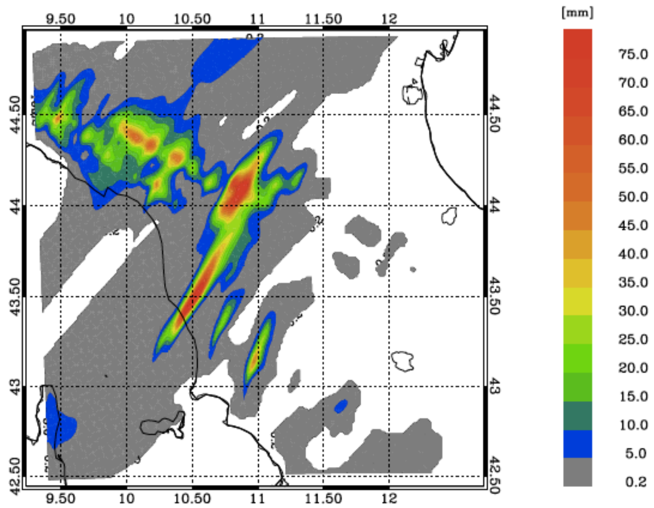

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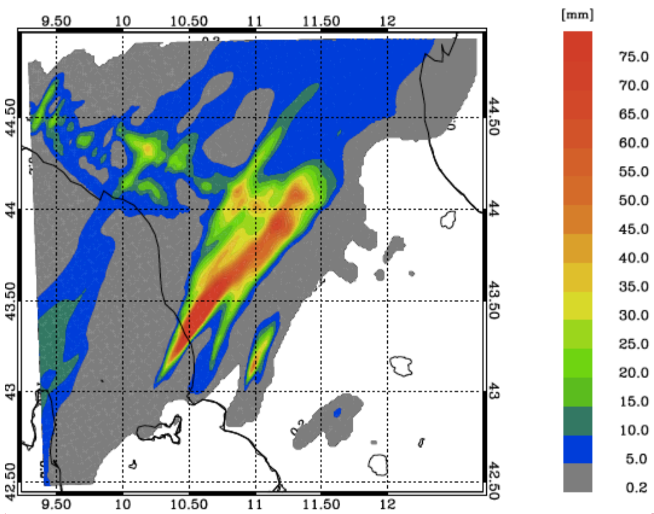

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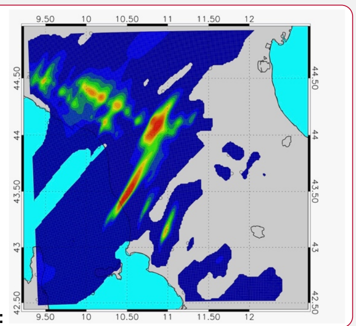
Eliminato: 

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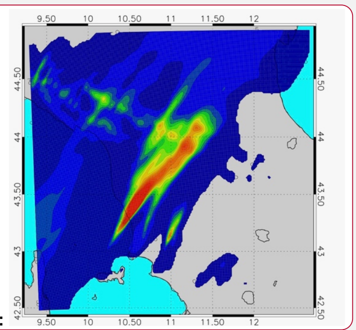
Eliminato: 

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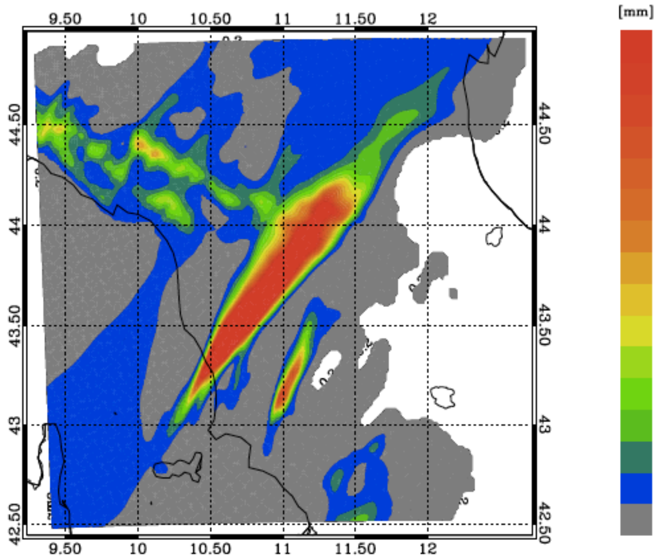
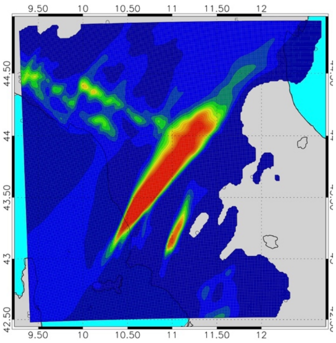


Figure 16: a) rainfall reported by raingauges between 00 and 03 UTC on 10 September 2017. Only stations reporting at least 0.2 mm/3h are shown. The first number in the title within brackets represents the number of raingauges available over the domain, while the second number shows those observing at least 0.2 mm/3h; b) rainfall VSF of CTRL for the same time interval as in a); c) as in b) for RAD forecast; d) as in b) for LIGHT forecast; e) as in b) for RADLI forecast. Labels A and B help to identify the positions of two rainfall maxima discussed into the text.



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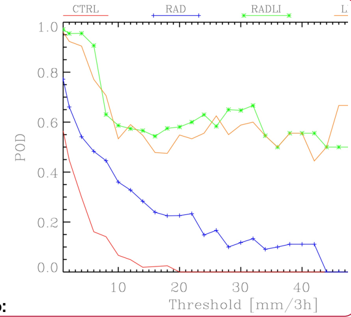

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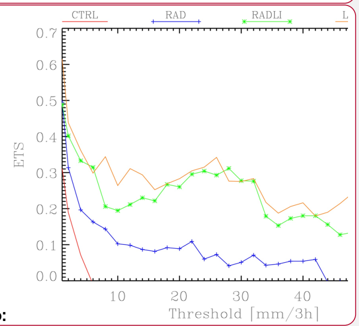
h)



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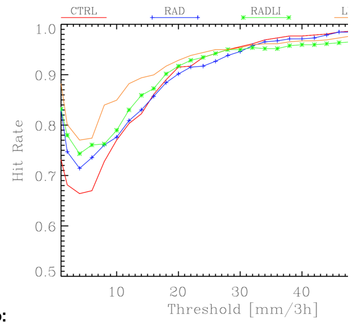
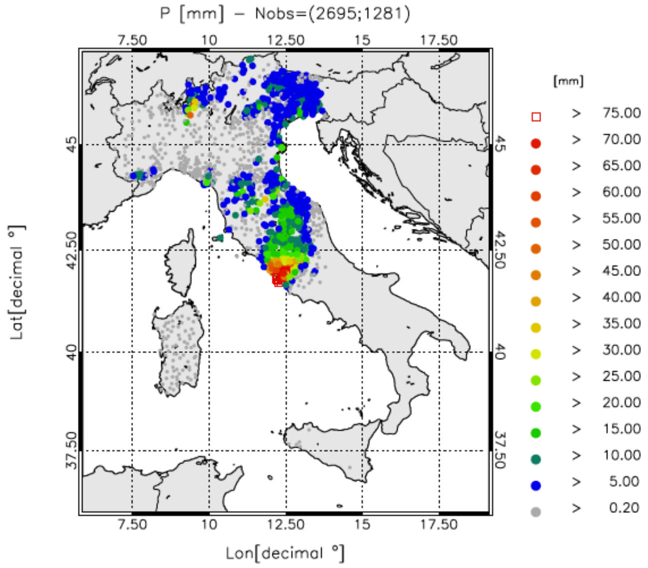


Eliminato:

Eliminato: 7: a) rainfall reported by raingauges between 00 ... [155]

Eliminato: POD and ETS scores are computed over the domain of Figure 17a.

a)



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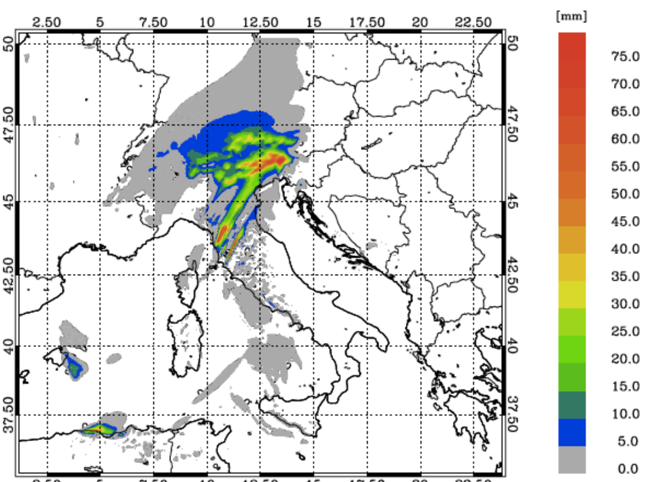

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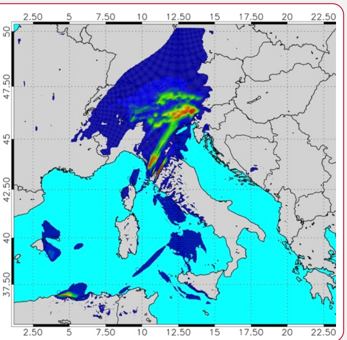

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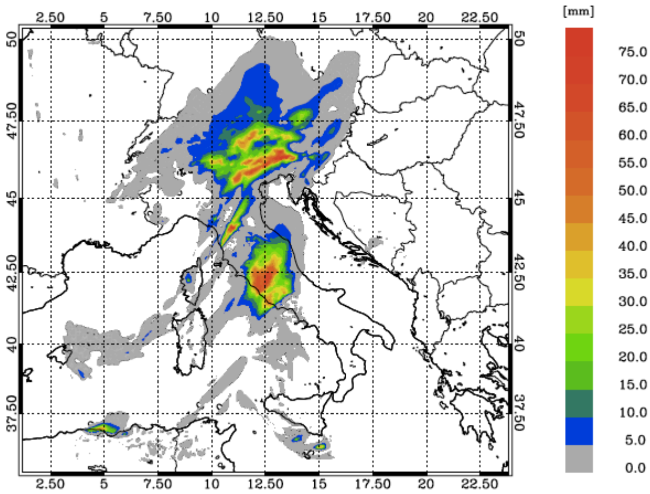

Eliminato: d)

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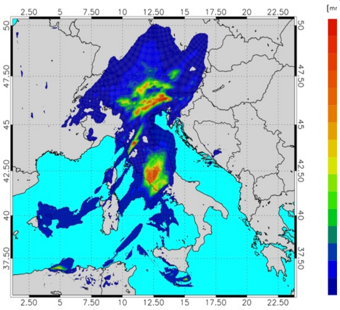

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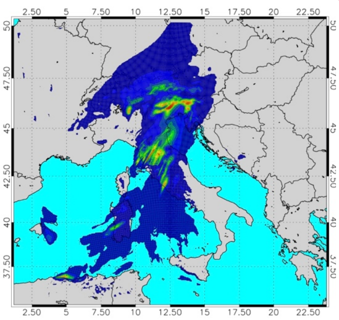

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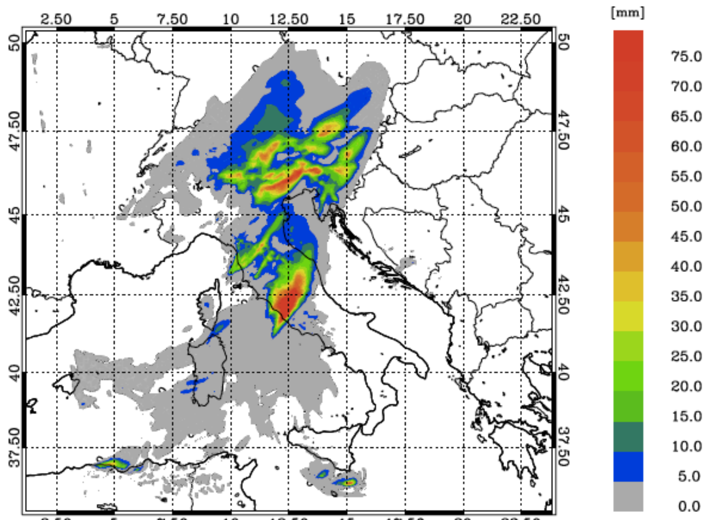
d)



e)

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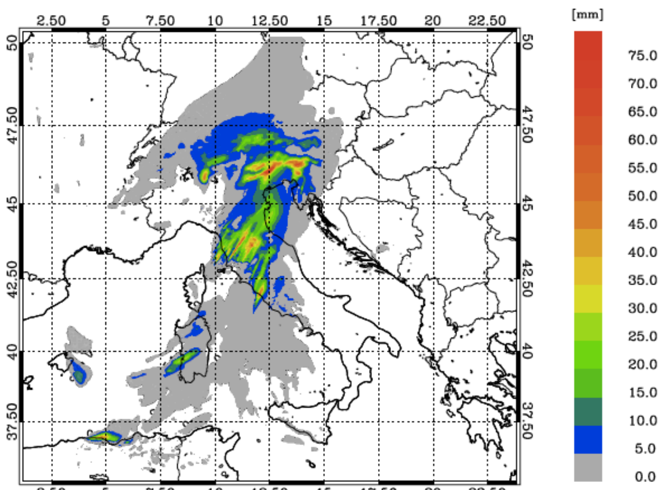
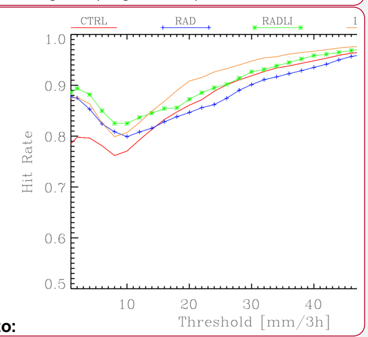


Figure 17; a) rainfall reported by raingauges between 06 - 09 UTC on 10 September 2017. For this time period 2695 raingauges reported valid observations in the domain, however only stations reporting at least 0.2 mm/3h are shown The first number in the title within brackets represents the number of raingauges available over the domain, while the second number shows those observing at least 0.2 mm/3h; b) rainfall VSF of CTRL in the same time interval as a); c) as in b) for RAD forecast; d) as in b) for LIGHT forecast; g) as in b) for RADLI forecast.

Eliminato: e) ... [156]

Formattato: Inglese (Regno Unito)



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Tipo di carattere: 12 pt

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Tipo di carattere: 12 pt

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Pagina 66: [117] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [118] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [119] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [120] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [121] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [122] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [123] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [124] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [125] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [126] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [127] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [128] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [129] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [130] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [131] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [132] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [133] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [134] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [135] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [136] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [137] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [138] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [139] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [140] Formattato	stefano federico	02/02/19 19:23:00

Bordo: : (Nessun bordo)

Pagina 66: [141] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [142] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [143] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [144] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [145] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [146] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [147] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [148] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [149] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [150] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [151] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 66: [152] Formattato	**stefano federico**	**02/02/19 19:23:00**

Bordo: : (Nessun bordo)

Pagina 81: [153] Eliminato	**stefano federico**	**14/01/19 14:35:00**
Pagina 82: [154] Eliminato	**stefano federico**	**14/01/19 14:07:00**
Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**
Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**
Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**
Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**
Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**
Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**
Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**

Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**

Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**

Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**

Pagina 84: [155] Eliminato	**stefano federico**	**25/01/19 06:06:00**

Pagina 87: [156] Eliminato	**stefano federico**	**14/01/19 14:31:00**