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Comparative verification of different nowcasting systems to support optimisation of thunderstorm warnings

K. Wapler[1,2], M. Goeber[1,3], and S. Trepte[1]

[1]Deutscher Wetterdienst, Offenbach, Germany
[2]Hans-Ertel-Centre for Weather Research, Atmospheric Dynamics and Predictability Branch, Germany
[3]Hans-Ertel-Centre for Weather Research, Optimal Application of Weather Forecasts Branch, Germany

Correspondence to: K. Wapler (kathrin.wapler@dwd.de)

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Abstract. The development and use of nowcasting systems should inevitably be accompanied by the development and application of suitable verification methods. A thorough verification strategy is needed to adequately assess the quality of the system and consequently to lead to improvements. Different verification methods for thunderstorms and its attributes are discussed along with the importance of observational data sets. They are applied to two radar-based nowcasting algorithms for a convective season using various observation data sets. The results show, that the combination of the two algorithms outperforms a single algorithm.

1 Motivation

Severe weather associated with deep convection poses a significant threat to life, property and economy. Fatalities, injuries and damages might be caused by lightning, gusts, hail, heavy precipitation or tornadoes. Therefore the provision of accurate and timely nowcast information, i.e. warnings provided by the national meteorological services, is essential for the general public as well as special users like emergency services and aviation.

Several algorithms exist which detect and nowcast deep convection. Most of them are based on either radar reflectivity measurements, like KONRAD (*KONvektionsentwicklung in RADarprodukten*, convection evolution in radar products, Lang 2001), CellMOS (Cell Model Output Statistics, Hoffmann, 2008) or on satellite measurements like RDT (rapid developing thunderstorm, Morel et al., 2000) and Cb-TRAM (Cumulonimbus TRAcking and Monitoring, Zinner et al., 2008). Some algorihtms rely on the combination of various observational input data (e.g. James et al., 2011; Pierce et al., 2000; Steinacker et al., 2000).

The evolution of forecast systems and the demand for more user oriented verifications has led to a reassessment of traditional verification strategies as well as to the development of new verification methods over the last decades (e.g. Gilleland et al., 2010 and references therein). However, no standard verification methods exist so far to evaluate the performance of nowcasting systems. The verification of convection and severe weather events is especially challenging (e.g. Doswell III, 1996). Due to their small horizontal extent, severe weather phenomena resulting from deep convection are rarely entirely and uniquely captured by current observational systems. However, verification is needed to assess the quality of the algorithms, to determine their strengths and weaknesses and consequently to lead to improvements. Given that several nowcasting systems exist and could be used in the warning process these should not only be verified independently but also comparatively using the same method.

The use of consistent verification methods is crucial to compare the different systems. Of particular interest is the question how these algorithms can optimally be used to issue warnings of thunderstorms as well as accompanying phenomena like gusts or hail. Nowcast verification experiments have been performed e.g. during the World Weather Research Program Forecast Demonstration Projects during the Sydney and Beijing Olympic Games (Ebert et al., 2004; May et al., 2004; Wilson et al., 2010) which compared nowcast provided by different national meteorological services.

In the study presented here we discuss some challenges and approaches of thunderstorm verification. To illustrate these discussions we show some results of verification of the radar based nowcast systems operated at DWD (*Deutscher Wetterdienst*, German Meteorological Service) CellMOS and KONRAD.

The remainder of this paper is organised as follows. In Sect. 2 an overview of the used algorithms and data sets is given. Section 3 discusses the verification methods; starting with a general introduction (Sect. 3.1) followed by a discussion of the specific verification challenges for thunderstorms (Sect. 3.2), convective gusts (Sect. 3.3) and hail (Sect. 3.4). Some verification results are shown in Sect. 4, and Sect. 5 provides a summary and some concluding remarks.

2 Data

The verification was performed for summer (April to September) 2010. The nowcasting algorithms verified in this study are the radar-based algorithms CellMOS and KONRAD which are based on 5 min 2-D data only. 3-D radar is currently provided only in 15 min interval within the German radar network. For the short lifecycle and rapid development of convection this observation frequency is not sufficient. However, 3-D data will be available at 5 min intervals in the future. KONRAD uses thresholds of 46 dBZ in a 9 km^2 area. CellMOS also uses a threshold of 9 km^2 but a lower dBZ threshold of 37. Additionally CellMOS uses lightning (at least one stroke had to appear within 10 km of the cell) and GME global model (Majewski et al., 2002) data (several parameters, e.g. wind speed and direction, relative humidity at various heights) applying a model output statistics approach (Klein and Glahn, 1974). Both systems provide as output the location of a cell along with some additional cell information, e.g. hail and gusts. KONRAD provides a hail flag (0, 1 or 2) based on the size of the area of more than 55 dBZ within the detected cell. Within KONRAD it is assumed that the expected convective gusts are equal to the movement speed of the cell. CellMOS provides estimates for the hail size and the gust speed as well as probabilities of hail sizes and gust above certain thresholds (defined in accordance with the warning categories) for up to 2 h. Both systems run operationally every 5 min.

The gusts verified in this study are measured at the about 260 German stations measuring gusts. The dataset provides hourly maximum gusts. Hail is observed at about 60 German stations with visual observations. Additional the hail dataset of the European Severe Weather Database (ESWD, Dotzek et al., 2009; Dotzek and Groenemeijer, 2009; Groenemeijer et al., 2009) was used. It collects events with hailstones having a diameter of 2 cm or more and smaller hailstones that form a layer of 2 cm thickness or more on flat parts of the earth's surface. The database includes information of the location (latitude/longitude) of the event, the time (with an uncertainty), a quality control flag and for some cases some additional information such as hail size. In the ESWD a three-level quality-control is applied. The QC-levels have the following meaning: QC0: "as received", QC0+: "plausibility checked", QC1: "report confirmed" by reliable sources and QC2: "event fully verified" i.e. all information about this event is verified, consistent and comes from reliable sources. For this study, we use data with quality flags QC1 and QC2.

The lightning measurements used are provided by the European LIghtning detection NETwork LINET (Betz et al., 2009). The lightning network consist of 30 antennas in Germany (and many more in Europe) and is considered to have a very high detection efficiency with a quasi continuous spatial and temporal resolution.

Table 1. Overview of DWD warning criteria related to thunderstorm.

Combination of attributes in addition to lightning	Level
Strong gusts (Bft. 7)	moderate
Storm force gusts (Bft. 8–10)	strong
Heavy rainfall (10–25 mm h^{-1})	strong
Storm force gusts, heavy rainfall	strong
Storm force gusts, heavy rainfall, hail	strong
Hurricane force gusts (Bft. 11–12)	severe
Very heavy rainfall (25–50 mm h^{-1})	severe
Storm force gusts, very heavy rainfall	severe
Storm force gusts, very heavy rainfall, hail	severe
Hurricane force gusts, very heavy rainfall, hail	severe

3 Verification methods for thunderstorms and its attributes

3.1 General remarks

One basic option for the verification of a nowcast system is to compare the location (and category) of the nowcast and the analysis. E.g. comparing the location of the cell detected at 12:30 UTC with the location of a cell of the +30 min nowcast based on the 12:00 UTC run. However, these results do not sufficiently indicate whether the system provides adequate support for the warning process since we do not warn cells (defined by dBZ areas) but precipitation, gusts etc. E.g. a nowcasting algorithm could be excellent in tracking a feature however this feature might not be equal to or useful for the event of interest and its warning. Thus, the nowcast system should be verified against and will depend on the warning criteria/categories (see Table 1 for an overview of the DWD thunderstorm warning categories). However, observations of severe convective weather phenomena are rare (see discussion in the following subsections).

Various verification methods are possible (for an overview see Gilleland et al., 2010 and references therein, specifically Davis et al., 2006). An areal approach could measure the

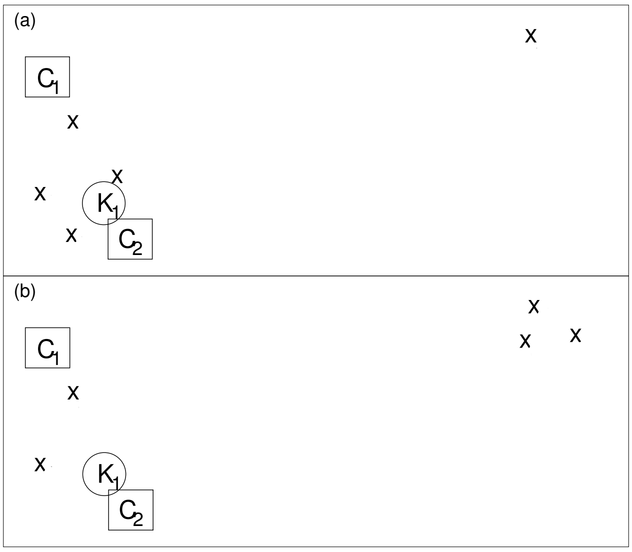

Figure 1. Example of two nowcast situations. Crosses indicate a lightning stroke, squares marked with a C indicate CellMOS cells and circles marked with a K indicate KONRAD cells.

areas affected by observed and nowcasted convective events and asses their overlap. A pointwise approach could consider each individual lightning or cell cluster. The results of these two approaches are shown in Sect. 4.2. Standard categorical verification measures are used (as described in Jolliffe and Stephenson, 2011).

3.2 Lightning

The verification of thunderstorms without considering accompanying phenomena seems to be much easier due to the high temporal and spatial coverage of lightning data. However, certain aspects have to be addressed when designing a verification methodology.

The most suitable method depends on the definition of a "good forecast". As an example a simple sketch is shown in Fig. 1. It shows two fictitious nowcast situations with the locations of detected lightning strokes and the locations of cells nowcasted by two algorithms (KONRAD (K) and CellMOS (C)). Looking at these figures, the following question should be answered to determine a suitable verification method. Should the result of the verification of the situation in Fig. 1a be the same as that in Fig. 1b? In both examples one of two storms (one storm on the left side of the figure and one on the right side) is detected. Thus, a verification could give a similar score for both cases. However, one could argue that in Fig. 1a the stronger storm (producing more lightning strokes) is detected and a relative weak storm (producing less lightning strokes) is missed; whereas in Fig. 1b the storms seem to have a comparable strength, thus, the miss and the hit could be weighted the same. Thus, the score should be higher in Fig. 1a compared to Fig. 1b. Furthermore, thresholds have to be defined e.g. the maximum distance in space and time to allow for a hit, to be able to calculate scores. Another aspect is the usability by an operational forecaster (not addressed in this study). Probably, the forecaster might prefer to work with the guidance provided by K because the algorithm nowcasts a single cell on the left side of the figures, whereas C nowcasts two cells, even though the detected lightning strokes on the left could be considered to belong to a single event. These discussions indicate that the decision about which of the interpretations of the situation shown in Fig. 1 applies and thus the definition of a "good forecast" might vary for different users of the warning guidance.

As suggested by the discussion above, the calculated scores as well as the possible maximum score depend on the chosen verification method. The chosen thresholds also influence the score. Another factor which influences the maximum possible score of a nowcast is the mean cell lifetime. In current nowcast systems cells usually do not dissolve, but are extrapolated in the future for the duration of the nowcast time frame. As an example of cell lifetimes the KONRAD statistics show that in the summer of 2010 40 % (6802) of all the cells (16 817) were detected just once and 14 % (1972) of the cells lived longer than 30 min. The high number of cells which were detected only once could be due to different reasons. E.g. on a convective day several cells develop, however, several cells might reach the threshold defined by KONRAD only shortly before dissolving and only a few cells intensify further. Additionally, the size of cells which have characteristics close to the thresholds defined in KONRAD might drop below the size threshold. After a renewed increase of the intensity these cells will be detected as new cells.

3.3 Gusts

The verification of convective gusts (see Table 1) is hampered by the poor representation of these phenomena by current observation systems. Furthermore, the SYNOP data usually provides information about the highest gust that occurred within an hour; not knowing the exact time of the gust complicates the attribution of the gust to a specific cell at days with numerous cells. Additionally, strong gusts may occur in the surroundings of cells (and not directly close to the highest reflectivity as detected by the algorithms) which further complicates the correlation of observations and nowcast. Not measuring a gust at a station only indicates that no gust occured at exactly this location. It does not mean that a cell which passed this station did not produce a gust. A severe gust might just have developed a few (kilo) meters farther. Furthermore, observations of severe convective gusts are rare (due to low number of events and especially due to relatively low number of stations). E.g. during summer 2010 only five times convective gusts with more than 11 Bft were measured at the about 260 German stations measuring gusts.

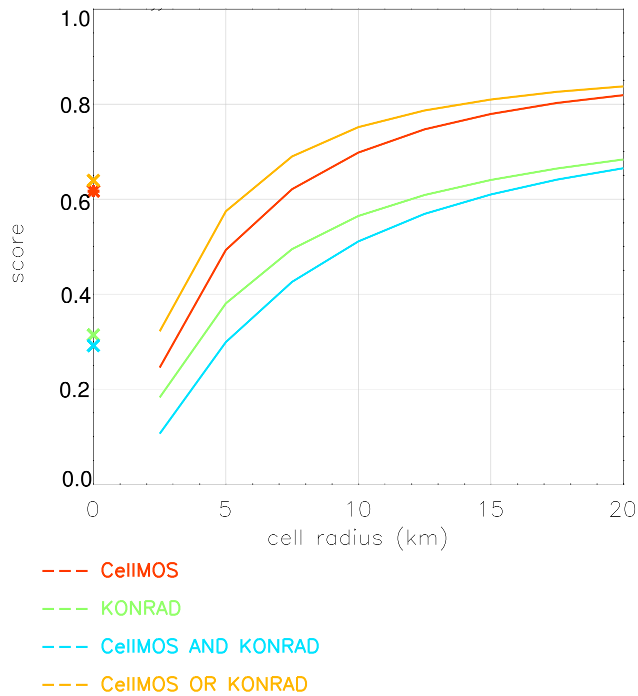

Figure 2. Pointwise approach. Probability of detection (percentage of hits of all observed events, 772 347) of lightning strokes that occurred (summer 2010) within the given radius of cells detected by CellMOS, KONRAD, CellMOS and KONRAD, CellMOS or KONRAD analysis. The crosses indicate the results using the cell radius given by the algorithm.

3.4 Hail

The problem of low numbers of observations also exists for hail. E.g. during the summer of 2010 at the about 60 German visual observation stations hail was observed just about 20 times. The ESWD provides very useful data. For the summer of 2010 the ESWD contains 82 hail entries with the highest quality flags QC1 or QC2.

However, to derive thorough statistics caution has to be applied when working with this data . It may happen that several data base entries exist for a single event (e.g. a cell in NE Germany had 21 entries (out of 82) in the ESWD, because it was analysed to have hit several villages). Other cells might just have a single entry in the data base which either means that the cell did not leave a long hail path or that the strong extent of the hail event was not observed in its full extent. Most importantly it has to be considered that the hail observations only provide information on "positive events", no entry in the data base or no observation at a station does not mean that no hail occurred, i.e. the hits (event observed and forecasted) and misses (event observed but not forecasted) can be determined but not the false alarms (event forecasted but not observed) nor the correct negatives (event neither forecasted nor observed). Thus a strategy has yet to be developed how to work best with this data in a quantitative way. In this study we show some qualitative characteristics.

Table 2. Percentage of lightning strokes that occurred (summer 2010) within 20 km of cells detected and nowcasted by CellMOS, KONRAD, CellMOS and KONRAD ($C \wedge K$), CellMOS or KONRAD ($C \vee K$).

Nowcast	CellMOS	KONRAD	$C \wedge K$	$C \vee K$
+0 min	82 %	68 %	67 %	84 %
+30 min	72 %	66 %	58 %	79 %
+60 min	51 %	50 %	34 %	67 %

4 Results and discussions

4.1 Cell tracking

The simple verification of comparing the analysis vs the nowcast of the same algorithm was done for KONRAD. It showed that for all cells during the summer of 2010 which lived at least 30 min, the cell position of the +30 min nowcast was on average 11 km with standard error 11 km away from the location of the analysis. The displacement error of the +60 min nowcast of all cells with a lifetime of at least 120 min was 14 km with standard error 12 km. Such studies could be used for a detailed analysis of the consistency and tracking quality of a system.

4.2 Lightning

As an example of thunderstorm nowcast verification, the results of the verification based on the comparison of all observed lightning strokes to detected cells (pointwise approach) is shown in Fig. 2.

These results show that a considerable part of lightning strokes occurred in cells with less than 9 km^2 of dBZ values of at least 46 and thus no KONRAD cells were detected. Furthermore, some lightning strokes occurred in cells with less than 9 km^2 of dBZ values of at least 37 or were to far away from the cell centre and thus no corresponding CellMOS cells were detected.

This comparison also shows the decrease of the detection rate with a more strict distance thresholds. Furthermore, it is shown that the combination of different algorithms improves the quality of the nowcast. This is due to the different reflectivity thresholds applied by the algorithms as well as due to additional data in CellMOS. Table 2 shows the decrease of the detection rate with longer lead times.

Another example of thunderstorm nowcasting verification is shown in Fig. 3. For this verification, a circular area (with a varying radius given in the figure) was defined to be affected by the event, either a lightning stroke or an analysed cell. Those areas were compared and their overlap calculated (areal approach, Davis et al., 2006). Similar to the

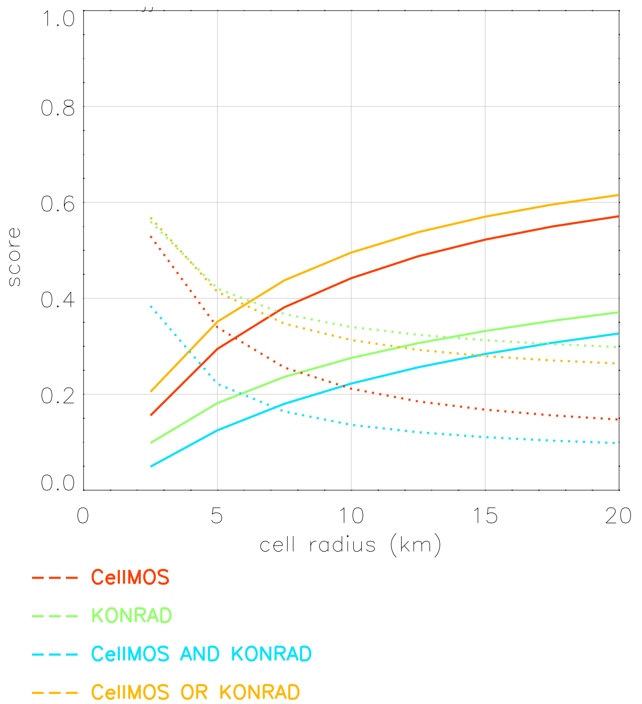

Figure 3. Areal approach. Probability of detection (solid, proportion of hits of all observed events) and false alarm ratio (dotted, proportion of false alarms of all forecasted events) for the comparison of areas affected by lightning strokes and areas affected by cells detected by CellMOS, KONRAD, CellMOS and KONRAD, CellMOS or KONRAD analysis. The cell radius determines the size of the area affected by a lightning stroke or a cell detected by one of the algorithms.

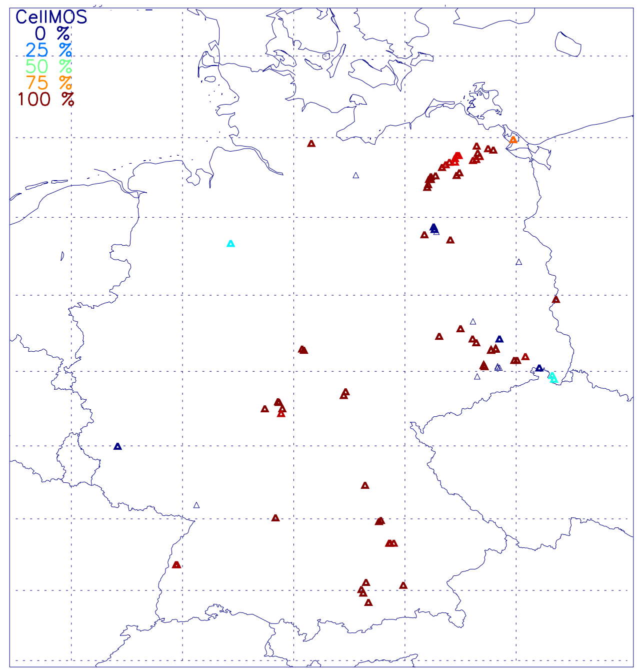

Figure 4. CellMOS analysis probability for hail larger than 15 mm (thick blue and red triangles) for all QC1 and QC2 hail entries (summer 2010) in the ESWD. Thin triangles show hail reports with no CellMOS cell within 20 km and ±5 min.

pointwise verification approach (Fig. 2), this method indicates, that the combination of two algorithms outperforms a single algorithm, and that the score improves with larger distance thresholds. However, the comparison of the scores in Figs. 2 and 3 show, that the scores are dependent on the verification method as already discussed in Sect. 3.2. The lower score in the areal approach (Fig. 3) can be explained as follows. The lightning strokes associated with a storm cover a much larger area than a single cell, i.e. area of high reflectivity. This leads to areas near the margin of the storm that are counted as misses which lowers the score.

4.3 Gusts

The comparative verification (not shown) for gusts stronger than 14 m s^{-1} and gusts stronger than 18 m s^{-1} revealed that nowcasts of CellMOS (which uses a model output statistics approach incorporating NWP model output) are superior to KONRAD (which bases its gust nowcast only on the estimated cell movement speed). In general 2-D radar data based algorithms have limited capability in analysing gust speed. Because convective gusts are not (only) determined by the reflectivity in a certain height but parameters such as downdraft convective available potential energy, maximum horizontal momentum and precipitation. The first two could be derived from soundings or models, the latter from vertically integrated liquid (VIL) as derived from 3-D radar measurements.

4.4 Hail

Comparison of observations with nowcast show that for most of the summer 2010 ESWD hail reports in Germany a CellMOS (Fig. 4) and a KONRAD (Fig. 5) cell has been detected (within 20 km and ±5 min of the event) which had a hail probability (CellMOS) of more than 75 % or hail warning flag (KONRAD), respectively. As discussed in Sect. 3.4 false alarms and correct negatives cannot be calculated using the existing hail dataset.

For all KONRAD cells detected in summer 2010 64 % had a hail warning flag of 0, 30 % had a hail flag of 1 and only 6 % had a hail flag of 2. Thus, the high number of KONRAD cells with a hail flag of 2 in Fig. 5 is not by chance. An example which shows the KONRAD hail flags for a line of convective cells which crossed Germany on 14 July 2010 is given in Fig. 6. The figure shows that the algorithm analyses a differentiated hail distribution which further supports that the high number of KONRAD cells with hail flag of 1 or 2 near observed hail events is not by chance.

However, in general 2-D radar data based algorithms have limited capability in analysing hail. The potential of

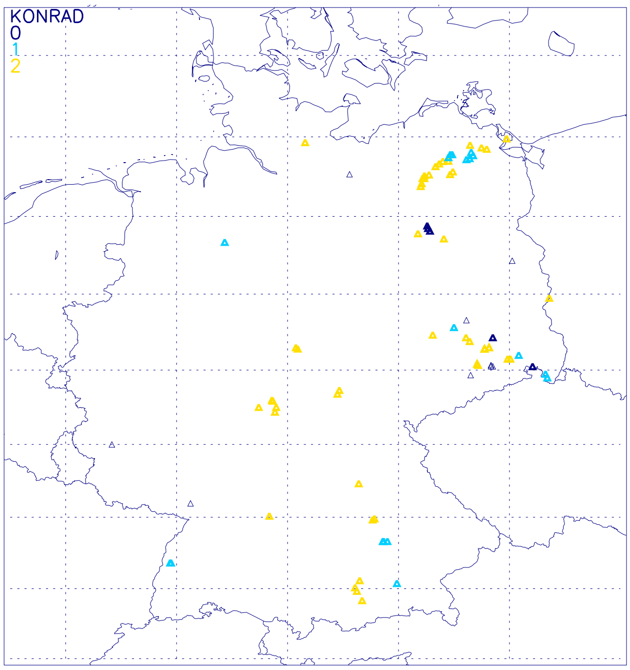

Figure 5. KONRAD analysis hailflag (thick dark blue, light blue and yellow triangles) for all QC1 and QC2 hail entries (summer 2010) in the ESWD. Thin triangles show hail reports with no KONRAD cell within 20 km and ±5 min.

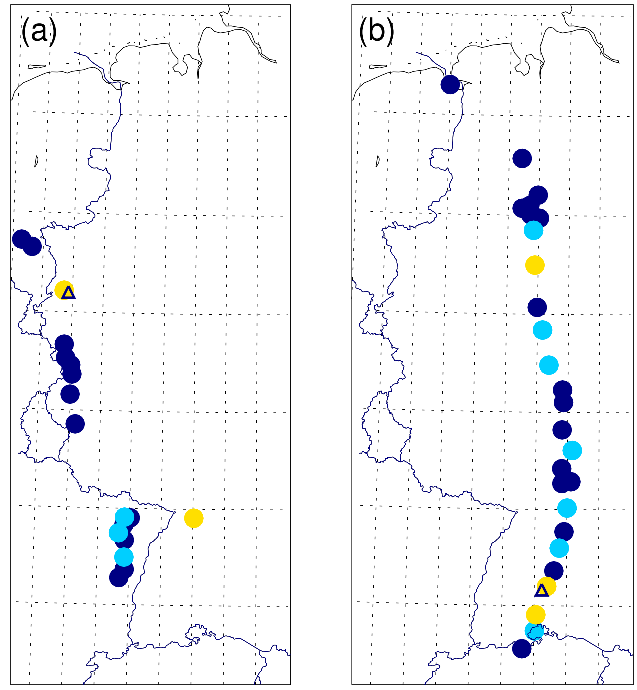

Figure 6. KONRAD hailflag (dark blue, light blue and yellow circles) and QC0 eswd hail reports (triangles) within ±5 min of 14 July 2010, 16:15 UTC **(a)** and 18:45 UTC **(b)**.

a convective cell to produce hail is not only determined by a very high reflectivity at a certain height but by high reflectivity values throughout the cell and an intense updraft. Thus, additional information from 3-D radar measurements such as the vertically integrated liquid VIL (Greene and Clark, 1972) provide useful information for the detection of hail.

5 Conclusions

In this study the challenges of comparative nowcast verification are discussed and some verification results for cell tracking, thunderstorms, gusts and hail are presented.

It is shown that the combination of different algorithms improves the quality of the nowcast. The low number of observations of rare events, e.g. severe gusts and hail, hampers thorough verification. For one summer season only very few events might be captured by observations. However, nowcasting algorithms need to be verified especially if they are new and no long statistics are available.

The results presented here provide an overview of ongoing work. It is planned to extend this study by using a larger data set, verifying additional phenomena, such as heavy precipitation, and integrating further nowcasting systems in the comparative verification.

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