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Quantitative comparison of METEOSAT thunderstorm detection and nowcasting with in situ reports in the European Severe Weather Database (ESWD)

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Abstract

Severe thunderstorms constitute a major weather hazard in Europe, with an estimated total damage of € 5-8 billion each year. Yet a pan-European database of severe weather reports in a homogeneous data format has become available only recently: the European Severe Weather Database (ESWD). We demonstrate the large potential of ESWD applications for storm detection and forecast evaluation purposes. The study of six warm-season severe weather days in Europe from 2007 and 2008 revealed that up to 47% of the ESWD reports were located exactly within the polygons detected by the Cb-TRAM algorithm for three different stages of deep moist convection. The cool-season case study of extratropical cyclone "Emma" on 1 March 2008 showed that low-topped winter thunderstorms provide a challenge for satellite storm detection and nowcasting adapted to warm-season storms with high, cold cloud tops. However, this case also demonstrated how ESWD reports alone can still be valuable to identify the hazardous regions along the cold front of the cyclone. The analysis of all warm-season (JJA) severe weather days in Europe in 2008 corroborated these findings. There is good agreement between ESWD reports and Cb-TRAM detected thunderstorms, even though no exact correspondence between ESWD reports and Cb-TRAM cells is required (e.g., due to storm morphology). Correspondingly, a large portion of ESWD reports regarded as misses by our strict in/out-of-Cb-TRAM-polygon criterion were still located close to a Cb-TRAM cell. Quantitatively, only the probability of detection (POD) can be evaluated due to the different characteristics of the two data sources. The POD for storm detection was 0.24 on average, with maximum values up to 0.58. The respective analysis for the 30 and 60 minutes nowcasts yielded average POD values of 0.11 and 0.08, respectively, with maximum values of POD exceeding 0.4 on 3 days for the 30 minutes nowcast and on one day for the 60 minutes nowcast.

Keywords: Severe thunderstorm, METEOSAT, Nowcasting, Satellite, European Severe Weather Database

1 Introduction

Severe thunderstorms, with their attendant strong winds, hail, flooding, and tornadoes, are common phenomena in many European countries, leading to a total damage estimate of EUR 5 to 8 billion per year (source: Munich RE). Extreme events in 2008, like an F4 tornado in France (Mahieu and Wesolek, 2009; Marquet and Santurette, 2009) and an F3 downburst in Austria (Pistotnik et al., 2009) exemplify these damage totals. However, documentation and analysis of European severe convective storms in the scientific literature have been relatively sparse from about 1950-2000 (e.g., Bissolli et al., 2007), and a pan-European database of in situ severe storm reports was unavailable even a few years ago.

Thunderstorms require three essential ingredients: moisture, instability, and lift. For convective storms to become severe, additionally strong vertical wind shear is required (cf. Doswell, 2001). An important question is which processes lead to the simultaneous occurrence of those ingredients at a certain point. In answering this question for European storms, a particular challenge is posed by the complex terrain and coastlines in Europe. These are likely important for creating regionally favourable severe thunderstorm environments, for example by the mesoscale flows that they induce. A better documentation of European severe thunderstorms could thus bring new insights into these issues and also foster climatological evaluation and forecasting of severe thunderstorms worldwide.

Accordingly, the European Severe Storms Laboratory (ESSL) was founded in 2002 as an informal network of scientists from all over Europe, and formally established in 2006 as a non-profit research organisation with the following primary statutory purposes:

- Basic and applied research on severe weather events;
- Development and quality-control of the European severe weather database, ESWD, which collects detailed in situ reports of severe weather events all over Europe;
- Coordination of the European Conferences on Severe Storms, ECSS.

Note that neither issuing forecasts nor warnings are among the activities of the ESSL, as these are core duties of the European national meteorological and hydrological services (NMHS). However, the present paper will demonstrate that the ESWD data provide many new opportunities to quantitatively evaluate not only thunderstorm detection and forecast products, but in principle also related warnings.

Seven NMHS are currently partners of the ESSL: AEMet (Spain), DWD (Germany), FMI (Finland), NIMH (Bulgaria), ZAMG and Austro Control (Austria), as well as ARPA-FVG (Italy). DWD and Austro Control are also institutional ESSL members, as well as

EUMETSAT. A cooperation agreement with the European Meteorological Society (EMS) was signed in September 2007. Collaboration with additional NMHS or EUMETNET (e.g. with respect to www.meteoalarm.eu), and the ECMWF is desired in establishing the ESSL within the European atmospheric science community. In this context, the ESWD database also contributes to ongoing severe weather research projects, like RegioExAKT (Regional Risk of Convective Extreme Weather Events: User-oriented Concepts for Trend Assessment and Adaptation, www.regioexakt.de) in Germany or the EU project EWENT (Extreme Weather impacts on European Networks of Transport, virtual.vtt.fi/virtual/ewent/).

Complementing the in situ reporting of severe thunderstorm occurrence, another vitally important field of severe weather research is thunderstorm detection and nowcasting from remote sensing. Geostationary satellite observations are particularly suited for this purpose, as they provide full European coverage, near real time availability, as well as high spatial and temporal resolution. A number of algorithms exist to monitor, track, and nowcast deep moist convection from space (e.g., Carvalho and Jones, 2001; Morel and Sénési, 2002; Feidas and Cartarlis, 2005). They are mostly based on temperature thresholds in thermal infrared (IR) observations where the coldest and highest cloud tops, presumably of convective origin, can be distinguished from warmer and more shallow clouds. Recently, Zinner et al. (2008) developed Cb-TRAM, a fully-automated detection and nowcasting algorithm for convective storms using multi-channel METEOSAT data, which is also applied here.

In the present paper, we synthesize Dotzek and Forster (2008) as well as Forster and Dotzek (2009) to explore the potential benefits of coupling satellite-based storm detection and nowcasting algorithms to ESWD ground reports of actual events. Sec. 2 provides an overview of the data sources: the cloud tracker Cb-TRAM and the ESWD. In Sec. 3, six warm-season cases and one cold-season event with severe thunderstorm reports over Europe are evaluated for relations to convective clouds detected by Cb-TRAM. Sec. 4 extends this to a quantitative analysis of storm detection and nowcasting during a full thunderstorm season (June, July, and August 2008) over Europe to statistically test the robustness of our case-based findings. In addition, we also check the correlation of ESWD reports with Cb-TRAM nowcasts up to one hour. Sec. 5 presents ours conclusions.

2 Data

2.1 Cb-TRAM

The cloud-tracker Cb-TRAM (Cumulonimbus TRacking And Monitoring, Zinner et al., 2008; Zinner and Betz, 2009) is a fully automated multi-channel algorithm for detection and nowcasting of deep moist convection using METEOSAT Spinning Enhanced Visible and Infra-Red Imager (SEVIRI) data. The channels broad-band high-resolution visible (HRV), water vapour (WV) 6.2 µm, thermal infrared (IR) 10.8 µm, and IR 12.0 µm are combined to classify three different stages of thunderstorm development, see Fig. 1:

- Strong local development of convective low-level clouds (“convection initiation”);
- Rapid cooling of cloud tops by vertical cloud development (“rapid development”);
- Mature thunderstorms reaching or even overshooting their equilibrium levels in the tropopause region.

For this study, we use METEOSAT 9 data which are available every 15 minutes. Over Europe, their spatial resolution is approximately 1.5 x 1.5 km for the HRV and about 5 x 5 km for the IR and WV channels. During daytime, the HRV channel is used to localise the most intense convective updrafts by exploring the cloud-top structure (“roughness”) from reflectivity gradients. During nighttime, or in regions where HRV imagery is not available, the texture in the WV 6.2 µm channel data is used to identify convective turbulence. In the “mature thunderstorm” detection, the temperature difference between the WV 6.2 µm and the IR 10.8 µm channel is used to capture regions where clouds reach or overshoot the tropopause.

Tracking in Cb-TRAM is based on the geographical overlap between current detections and first-guess patterns of cells detected in preceding time steps. At time *t*, the first-guess patterns are retrieved by using the approximate propagation direction and velocity of a detected cloud pattern at the previous time step *t-1* in combination with an image-matching algorithm (cf. Zinner et al., 2008). This algorithm extracts the general transformation vector field from two consecutive satellite images, thereby describing the cloud motion and local cloud developments. Similar to the first-guess patterns, nowcasting intervals from 15 to 60 minutes (cf. Fig. 1) are generated by extrapolation and exploitation of a pyramidal image-matching algorithm. Additional details as well as application and validation studies of Cb-TRAM were provided, for instance, by Forster et al. (2008), Tafferner et al. (2009) as well as Zinner and Betz (2009). In this paper, we focus on the three-level diagnostic detection polygons of Cb-TRAM and also include a comparison of the nowcasting steps (30 and 60 minutes ahead in time, respectively).

2.2 European Severe Weather Database ESWD

The main goal of the ESWD (cf. Dotzek et al., 2006, 2009) is to gather and provide detailed and quality-controlled in situ reports of severe convective weather events (e.g., flash floods, large hail, damaging winds, tornadoes) all over Europe using a homogeneous data format and web-based, multi-lingual user-interfaces where collaborating NMHS, voluntary observer networks (e.g., Skywarn) and the public can contribute and retrieve observations. Involving the public via www.essl.org/ESWD/ (or equivalently www.eswd.eu) helps to raise completeness of the ESWD data. After two years of test operations, 2006 was the first year with operational ESWD service, and the database has been operational since then, undergoing a major software update by the end of 2008. By now, almost 27,000 reports (historic and current) are included in the database (Fig. 2).

ESWD development was based on the fact that severe convective weather events strongly depend on micro- and mesoscale atmospheric conditions, and in spite of the threat they pose to people and property, they usually escape the meshes of existing operational monitoring networks. Besides, such events are often embedded in systems acting on a larger scale, and even if damage is local, severe weather can continue for hours or days and affect more than one European country during its lifespan.

The following types of severe weather are included in the ESWD: Large hail (diameter >2 cm), heavy precipitation[1], damaging wind gusts (>25 m s^{-1}), tornadoes, funnel clouds, gustnadoes, and lesser whirlwinds. To extend the range of covered phenomena is among ESSL’s objectives, and envisaged by the flexible design of the data format (see ESSL, 2006, 2009). The database is maintained and developed by the ESSL, and aside from its main public web portal, ESWD development is documented at essl.org/projects/ESWD/ or by Dotzek et al. (2009) and Groenemeijer et al. (2009).

The quality-control (QC) procedure foresees that the ESSL is responsible for QC of ESWD reports coming in via the public interface while the cooperating NMHS are responsible for QC of the severe weather reports in their country, as entered, for instance, through their customised ESWD interface. Each NMHS partner performs a three-level QC on

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[1] „Damage caused by excessive precipitation is observed, or no damage is observed but precipitation amounts exceptional for the region in question have been recorded, or one of the following limits of precipitation

the data gathered from its own sources, while the ESSL is responsible for the three-level QC of the public reports from Europe and those entered by its ESWD maintenance team.

The three-level QC process specifies that any initial report to the database receives the lowest QC-level QC0 (or QC1 in reports entered by partner NMHS or ESSL if the initial information is already confirmed by several sources). Further verification of the report, including editing and augmenting the information contained therein, can lead to an upgrade to levels QC1 or QC2. The meaning of the three QC levels in the ESWD and the underlying regulations for their assignment are as follows:

- QC0: “as received” (new report , quality-control pending);
- QC0+: “plausibility checked” (assigned by partner organisation, partner NMHS or ESSL). The report is plausible, given the overall meteorological situation in, or data from the affected region and timeframe;
- QC1: “report confirmed by reliable sources” (assigned by partner organisation, partner NMHS or ESSL). Only some aspects of the report are still under discussion;
- QC2: “event fully verified” (assigned by partner NMHS or ESSL). All information available about this event is verified, consistent and comes from reliable sources.

ESWD quality-control levels denote the reliability of the contained information, and do not refer to the mere quantity of information (number of filled database fields). The significant step in report quality takes place from QC0+ to QC1. Both QC1 and QC2 reports are confirmed and suitable for quantitative analysis. However, for some analyses, even the QC0+ reports will still be adequate.

The ESWD public web portal displays the above terminology for the QC-levels, and highlights fresh QC0 reports in the tabular list compared to the already checked QC0+ entries. This visual distinction between QC0 and QC0+ reports in the list facilitates the quality-control process during the main severe weather season when many new reports come in, and when it has to be clear at first glance which reports still require at least the initial plausibility check. Ideally, a few days after an extreme weather episode, all QC0 reports should have been either raised at least to QC0+ or deleted.

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accumulation is exceeded: 30 mm in 1 hour, 60 mm in 6 hours, 90 mm in 12 hours, 150 mm in 24 hours.“

3 Case studies

Six warm-season storm days were investigated in order to get a first detailed impression of how well Cb-TRAM polygons agree with reports from ESWD. In a cold-season case study the usefulness of ESWD reports for the analysis of winter storms is demonstrated.

3.1 Warm-season storms

Fig. 3 shows an example of convective clouds detected and nowcast by the Cb-TRAM algorithm in comparison to ESWD reports on 25 June 2008. Note that the Cb-TRAM contours can be directly compared to the ESWD reports, as the contours are corrected for the parallax error resulting from the viewing angle of METEOSAT. The figure demonstrates that a variety of different phenomena observed at the ground and reported to ESWD are closely related to thunderstorm clouds detected from space. Another example, 25 May 2007, is shown in Fig. 4. Widespread, but mostly isolated thunderstorms evolved from France to Poland on this day. In Fig. 4a, at 0110 UTC, there is a heavy precipitation ESWD report at the border between the Netherlands and Germany. In the available satellite image 15 minutes later (Fig. 4b at 0125 UTC), Cb-TRAM marks this cell with a “rapid development” polygon. Obviously, at 0110 UTC the heavy precipitation was observed to start during the development stage of the storm when the related clouds had not yet reached high levels and were therefore not identified by Cb-TRAM. The ESWD report indicates a 1-hour local duration of the heavy precipitation for this storm. This still overlaps with the Cb-TRAM identification at 0125 UTC. A European radar composite of rain rate at 0130 UTC (Fig. 5) still shows heavy precipitation (radar reflectivity factor between 46 and 55 dBZ, not shown), further substantiating the detection by Cb-TRAM and the ESWD report. This example illustrates that Cb-TRAM and observers reporting to ESWD capture complementary aspects, phenomena and phases of the same thunderstorm. Figs. 4c,d, at 1410 and 1610 UTC, respectively, show ESWD reports of large hail and heavy precipitation connected to detected “mature thunderstorm” or “rapid vertical development” polygons.

For this day, 47% of all ESWD reports were falling exactly within the Cb-TRAM polygons, and on three other of the six days studied, this ratio also exceeded 40% (cf. Table 1). Note that the severe weather events need not exclusively occur within Cb-TRAM's detected polygons, but can be shifted laterally or up-/downstream from the storms due to their

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(ESSL, 2006).

specific thunderstorm morphology[2]. Besides, the temporal resolution of the satellite images is 15 min, so all ESWD reports from 10 min before to 5 min after image time have been compared with the Cb-TRAM contours. Thus, ESWD reports sometimes appeared at a detected cell, but just before or just after a Cb-TRAM detection period (like in Figs. 4a,b). So, given that no exact correspondence between Cb-TRAM polygons and ESWD reports is strictly required, the correspondence ratios of more than 40% are encouraging.

Of course, even though ESWD reports of any QC-level have been used here, there may also be cells detected by Cb-TRAM which indeed caused severe weather at the ground, but for which no ESWD report was received. Therefore, the absence of severe weather reports cannot be regarded as proof that a convective storm was not severe. But in any case, the presence of an ESWD report provides strong evidence for the validity of any Cb-TRAM detection polygon assignment.

3.2 Cool-season storms

Warm-season thunderstorms in Central Europe usually have cloud tops between 12 and 14 km AGL, while cool-season Cb clouds often have tops well below 10 km AGL. Consequently, in the case of low-topped winter thunderstorms embedded in extratropical cyclones, even an opposite situation compared to the discussion in the previous section may arise: There may be many ESWD reports of severe convective weather at the ground, whereas satellite-based storm detection optimised for warm-season convection with high cloud tops does not readily grasp the severe potential of the low-topped cold-season storms. Among the recent severe winter storms in Europe, local damage at the ground was often highest close to the cyclone’s cold front (cf. Ulbrich et al., 2001). Fig. 6 illustrates such a case on 1 March 2008 with cyclone “Emma”.

On this day, Munich International Airport operations were severely affected by a line of thunderstorms at about 1000 UTC. In Fig. 6, two main cloud bands associated with the advancing leading edge of the cold air can be seen on the satellite images. They resemble a large comma-cloud structure. The first frontal line has a high Ci cloud shield, while the secondary line has only much warmer, and hence, lower-topped clouds and looks less impressive than the primary frontal band. However, the corresponding ESWD reports reveal

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[2] For the thunderstorm type with the highest potential for severe weather, the supercell, we can expect the location of heavy precipitation and large hail in the left forward quadrant of the storm, while damaging winds most likely occur in the right rearward quadrant, and a tornado would have to be expected in the central region of the storm.

that severe weather was almost exclusively collocated with the secondary line of the cold front, correspondingly leading to bands of severe storm reports at the ground.

The severe weather at the secondary cold frontal line was indeed caused by thunderstorms, despite the low Cb cloud tops at about 6 km ASL. Fig. 7 shows the total lightning (cloud-to-ground and intracloud) discharges on 1 March 2008 during the passage of cyclone “Emma”, in comparison to the ESWD reports on that day. Thunderstorms were coupled to the fast-moving embedded secondary cold front visible in Fig. 6 and moved through central Europe in the course of the day. So in this case, ESWD reports helped to diagnose that the greatest weather hazard was posed by the low-topped thunderstorms in the secondary line, and not by the primary frontal line with the high-topped cloud shield.

Such cold-frontal convection is often vigorous enough for sustained thunderstorm formation. In winter storm “Kyrill” on 18 January 2007, frontal thunderstorms caused damaging wind gusts, hail and also tornadoes of up to F3-intensity (ESWD reports). Non-zero prefrontal convective available potential energy (CAPE), abundant low-level wind shear, and the large propagation speed of the cold front contributed to the formation and high intensity of the tornadoes. Similar conditions prevailed with the damaging convective gusts on 23 March 2001 (Dotzek et al., 2007). Finally, on 1 March 2008, aside from hail, heavy precipitation and tornadoes, the most remarkable extreme event was an F3-downburst in Austria (Pistotnik et al., 2009). We conclude that the frequent severe weather from low-topped convective clouds in high-wind and high-shear environments can present a special challenge to satellite-based storm detection and nowcasting. Fast storm propagation limits lead-time, and the low Cb cloud tops are more difficult to distinguish from other, stratiform clouds at similar altitude. Higher cloud shields above the small Cb might further disguise the low-top storms’ characteristics as observed from satellites.

4 Analysis of the full 2008 warm season

The growing completeness of the ESWD over the recent years enables to study a large set of warm-season cases. Thus, we checked the robustness of our findings from the warm season case studies in Sec. 3.1 by performing an analysis of both Cb-TRAM detection and nowcasting during the whole summer season 2008, that is, June, July, and August (JJA). Out of this period, 51 days were used for the statistical evaluation. The remaining 42 days were excluded, as these were days with no, only weak, or sparse high-impact convection (less than

10 ESWD reports and/or zero clouds detected by Cb-TRAM) which might have been obscured by high cloud shields.

The comparison between the two data types is complex, because not all actual severe weather at the ground is reported to the ESWD, and because Cb-TRAM may also detect or nowcast thunderstorms which do not produce severe weather sometime during their lifespan. From the standard 2 x 2 contingency table (cf. Wilks, 2006), quantitatively, only the probability of detection

$$POD = \frac{Hits}{Hits + Misses} \quad . \qquad (1)$$

can be evaluated. As in Sec. 3, a hit is an ESWD report exactly located within or on the boundary of a detected Cb-TRAM cell, while a miss is an ESWD report located outside of a Cb-TRAM polygon. Therein, the ESWD reports from 10 minutes before and 5 minutes after the detection time of the Cb-TRAM cells are used. This criterion for a hit is very strict, but it is necessary for the calculation of the classical dichotomous skill scores which are widely used in the literature (e.g., Wilks, 2006). Current work aims to evaluate Cb-TRAM also against precipitation data by using more sophisticated skill scores from verification methods like object-oriented (e.g. Davis et al. 2006a,b; Wernli et al., 2008) or optical flow techniques (e.g. Keil and Craig, 2009). These methods allow accounting for time and location differences between structures that from eyeball comparison appear connected to each other. Other scores which do not lose their skill for increasingly rare events (cf. Doswell et al., 1990; Stephenson et al., 2008; Hogan et al., 2008) might also be suitable here.

Settling with the standard scores for the time being, our analysis revealed that the POD was 0.24 on average for JJA 2008. However, 14 days with strong convection exceeded POD-values of 0.4, with a maximum of POD = 0.58 (Fig. 8). Keeping in mind that the severe weather events do not have to occur exclusively within Cb-TRAM's detected polygons, but can be shifted laterally or up-/downstream from the storm cores due to the specific thunderstorm morphology, the agreement between satellite detected thunderstorms and severe weather reports is rather good.

The respective analysis for the 30 and 60 minutes nowcasts yielded average POD values of 0.11 and 0.08, respectively, with maximum POD exceeding 0.4 on 3 days for the 30 minutes nowcast and on one day for the 60 minutes nowcast, as also illustrated in Fig. 8. This result indicates that the nowcasting skill of Cb-TRAM rapidly decreases with forecast lead time. Work is currently going on to improve Cb-TRAM’s nowcasting performance.

5 Conclusions

The warm-season thunderstorm cases, the cool-season frontal-type low-top storms and the analysis of the 2008 warm-season thunderstorms underpin the applicability of ESWD ground-truth severe storm reports for verification purposes. In principle, any forecast field or nowcasting product (cf. König et al., 2007; Zinner et al., 2008; Dotzek et al., 2009) related to thunderstorm occurrence or to area-based warnings could be evaluated against ESWD reports. This would in turn help to improve these nowcasting techniques or forecast and warning procedures. Our study further showed:

- Six warm-season case studies showed that ESWD reports were consistently correlated to convective clouds detected by Cb-TRAM. Up to 47% corresponded exactly (report within detection polygon), while substantially more reports lay close by these polygons;
- The cold-season “Emma” cyclone case study of 1 March 2008 illustrated how ESWD reports can be useful in detecting potentially hazardous regions in the often complex frontal structure of such synoptic systems, in particular when satellite-detection of embedded thunderstorms is not available.
- With respect to winter extratropical cyclones, we also stress that low cloud base and high low-level shear are factors which favour tornado genesis in the presence of strong convection. Therefore, already observations of embedded electrical discharges alone in extratropical cyclones should be an especially alarming signal for operational forecasters and warning decision-makers.
- For the 2008 warm season, the POD for storm detection was 0.24 on average, with maximum values up to 0.58; the POD for the 30 and 60 minutes nowcasts were 0.11 and 0.08, respectively, indicating that the nowcasting skill of Cb-TRAM needs to be improved.
- There is a good agreement between ESWD reports and Cb-TRAM detected thunderstorms, even though no exact correspondence between ESWD reports and Cb-TRAM cells is required (e.g., due to storm morphology). Correspondingly, a large portion of ESWD reports regarded as misses by our strict in/out-of-Cb-TRAM-polygon criterion were still located close to a Cb-TRAM cell;
- If a detected Cb-TRAM cell is not related to an ESWD report, this does not falsify the Cb-TRAM polygon, but the convective storm might simply have not been severe;

- Likewise, absence of Cb-TRAM detections on some days cannot be regarded as proof that there was no severe weather. The ESWD reports on such days might have come from rather short-lived, small or low-topped convective storms, or those developing below cirrus layers;
- The ESWD provides increasingly homogeneous pan-European coverage of severe thunderstorm reports in a detailed and flexible data format including metadata information. Collaboration with more European NMHS is desired to enhance completeness and reusability of the database.

Ongoing work includes using the ESWD data also in the evaluation of satellite-based convection initiation (CI) detection algorithms against total lightning detection. With growing completeness of the ESWD, studies of a large set of cases may further reveal if, for instance, hail-producing cells have other Cb-TRAM detection or nowcast characteristics than thunderstorms producing damaging winds or heavy precipitation.

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Tables

Table 1: Number of ESWD reports as well as numbers and percentage of ideal correspondences between Cb-TRAM and ESWD reports, that is, ESWD reports within marked Cb-TRAM areas (“hit”). On 15 June 2007, the large set of reports contains about 40 funnel clouds over the UK reported without exact time of occurrence. Hence, the percentage of ESWD vs. Cb-TRAM correspondences has also been computed without these funnel cloud reports (marked by an asterisk).

Case	Number of ESWD reports	Number of ESWD reports within Cb-TRAM object	Percentage of ESWD reports within Cb-TRAM object
13 May 2007	25	4	16%
25 May 2007	67	32	47%
15 June 2007	102*	23	22% (37%*)
21 July 2007	25	11	44%
25 May 2008	77	32	42%
29 July 2008	27	11	41%

Figure captions

Fig. 1: Cb-TRAM example of 12 August 2004, 1700 UTC. Yellow = onset of convection, orange = rapid development, red = mature thunderstorm. Grey polygons show nowcasts of mature cells for 15, 30, 45, and 60 min, respectively. Thin coloured lines represent the tracks of the cells, coloured stars their centre of area. Green colour indicates convective cells that were detected during the last 30 minutes, but not in the current image.

Fig. 2: Top: all 26919 ESWD reports (red: tornadoes, yellow: damaging wind, green: large hail, blue: heavy precipitation, white: funnel clouds). Bottom: all 2065 ESWD reports from 1 June to 31 August 2008. Date of ESWD inquiry: 12 March 2010.

Fig. 3: METEOSAT-9 HRV image on 25 June 2008 at 1610 UTC with thunderstorms detected by Cb-TRAM superimposed as coloured contours (yellow: convection initiation, orange: rapid development, red: mature thunderstorm). Thin coloured lines indicate the tracks of the storms. Also shown are the 15 and 30 minutes nowcasts (grey contours) and ESWD reports (letters on cyan background, H: large hail, W: wind gust, T: tornado, P: heavy precipitation). ESWD reports fall in the timeframe from 10 min before to 5 min after image time.

Fig. 4: Snapshots of Cb-TRAM storm detection (polygons, yellow: onset of convection, orange: rapid vertical development, red: mature thunderstorm) on 25 May 2007. METEOSAT-9 satellite image times: (a) 0110, (b) 0125, (c) 1410, (d) 1610 UTC. ESWD reports from 10 min before to 5 min after image time: cyan squares with letters H = large hail and P = heavy precipitation. At other times, also damaging winds, tornadoes or funnel clouds were reported.

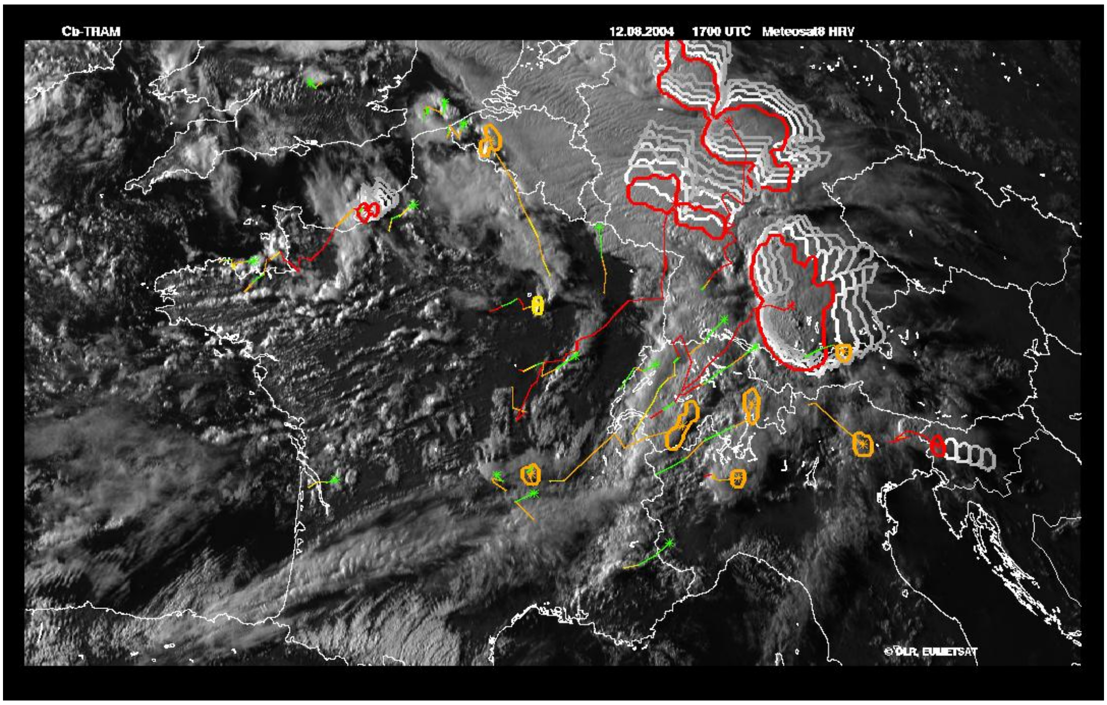
Fig. 5: European radar composite of rain rate in mm h^{-1} on 25 May 2007 at 0130 UTC (courtesy of www.meteox.com).

Fig. 6: Evolution of cyclone “Emma” on 1 March 2008: METEOSAT IR images (a,c,e) and ESWD reports in the corresponding hour (b,d,f, colours as in Fig. 2). (a) 0645 UTC, (b) 0600-0700 UTC, (c) 0745 UTC, (d) 0700-0800 UTC, (c) 0945 UTC, (d) 0900-1000 UTC, at about the time when Munich International Airport was hit.

Fig. 7: Lightning detection and ESWD reports with cyclone “Emma” on 1 March 2008: (a) 67813 flashes (red: positive, blue: negative polarity) from the LINET system, www.nowcast.de, (b) 190 ESWD reports (red: tornadoes, yellow: damaging wind, green: large hail, blue: heavy precipitation).

Fig. 8: Statistical evaluation of the ESWD comparison with Cb-TRAM over summer (JJA) 2008 for days with more than 10 ESWD reports and at least one cloud detected by Cb-TRAM. Red columns represent the probability of detection (POD) that ESWD reports are within a detected Cb-TRAM cell. The cyan and yellow columns show the POD that ESWD reports correspond with the 30- or 60-minute Cb-TRAM nowcast, respectively.

Figures



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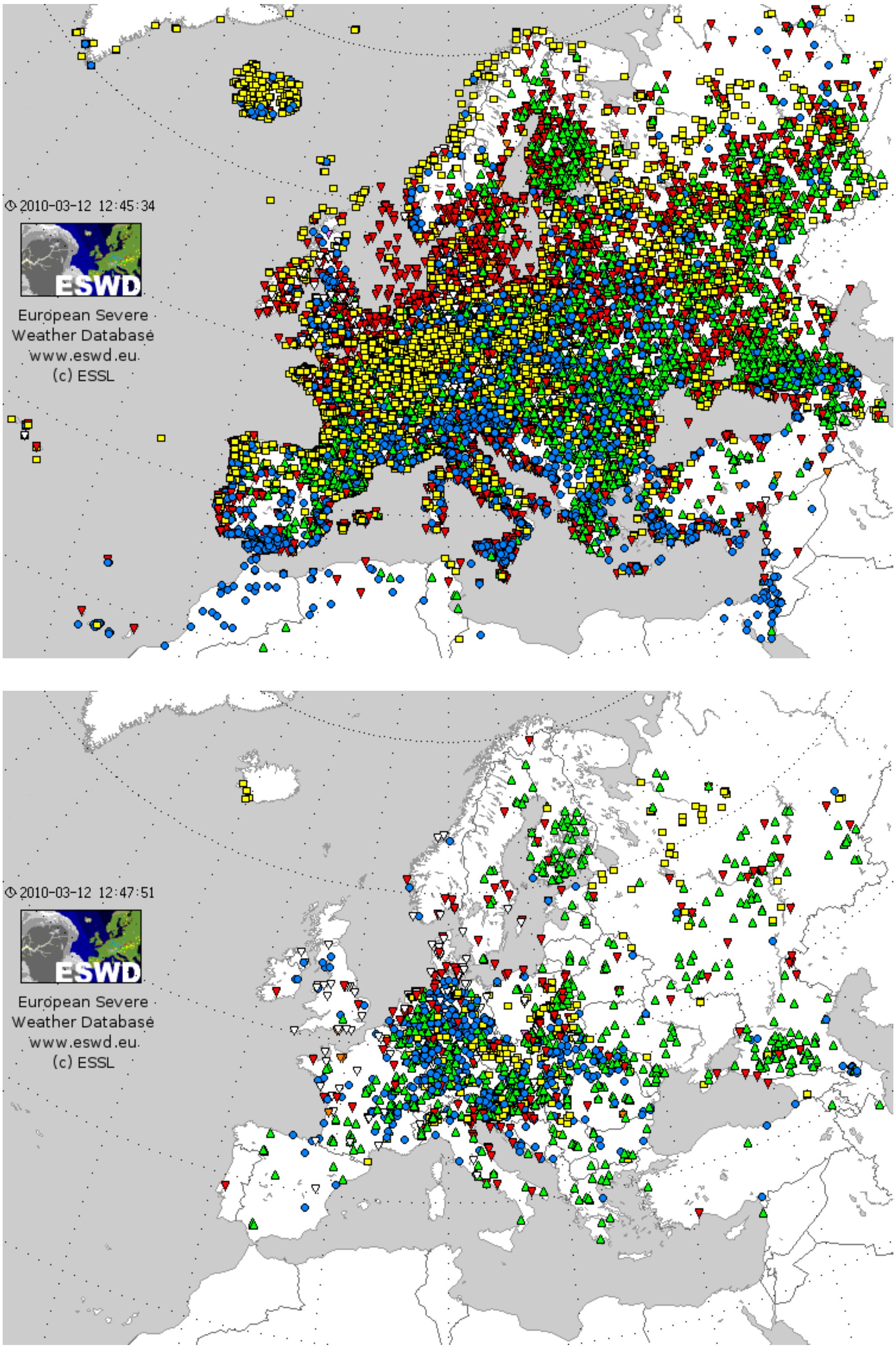

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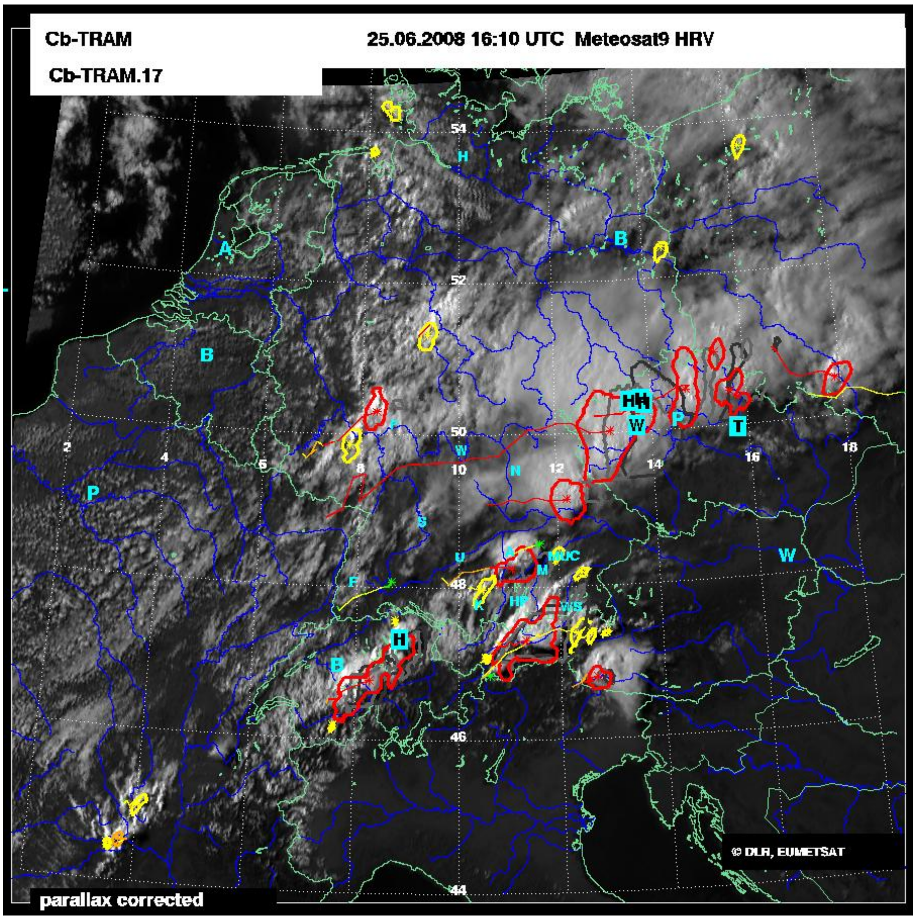

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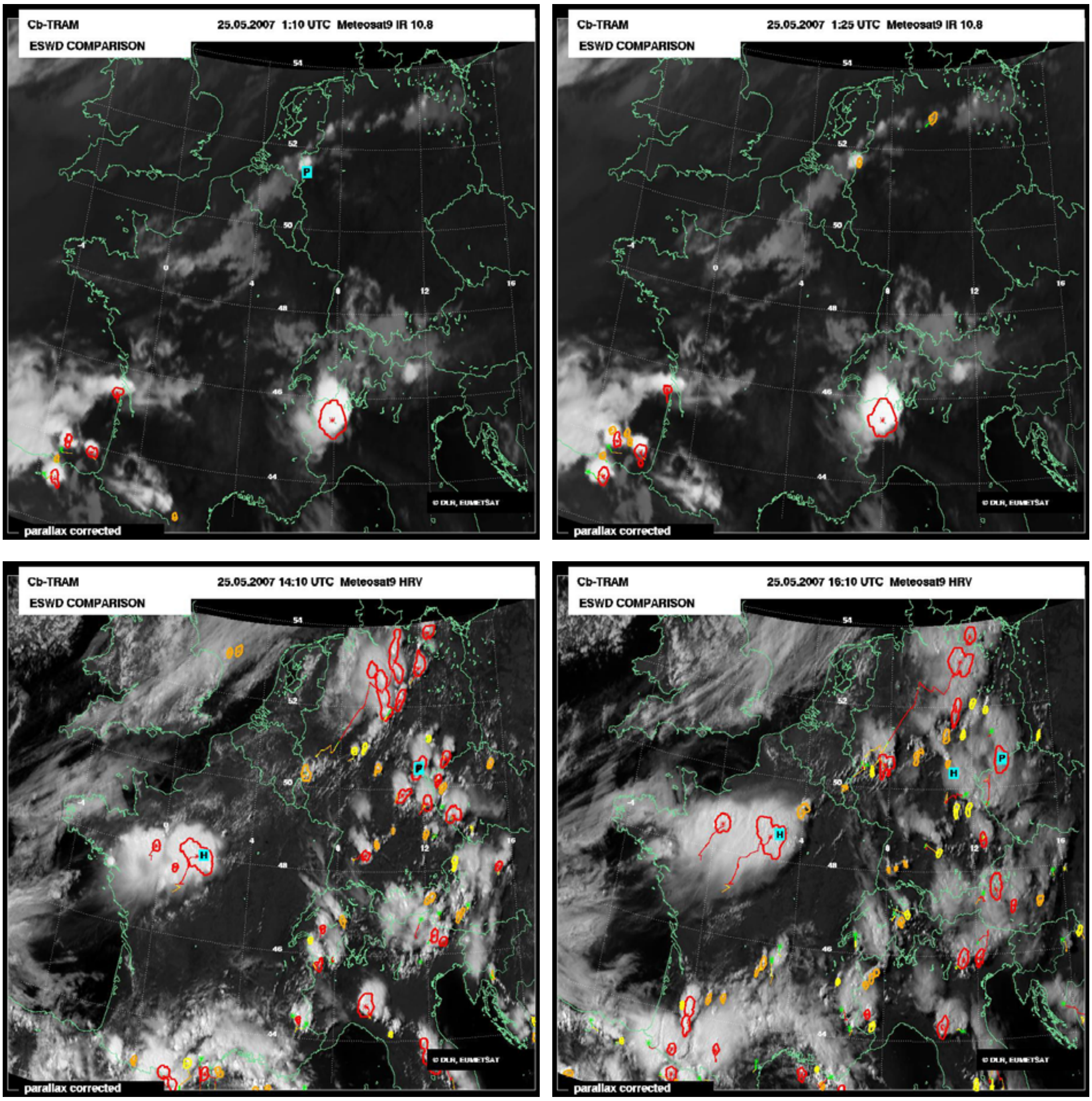

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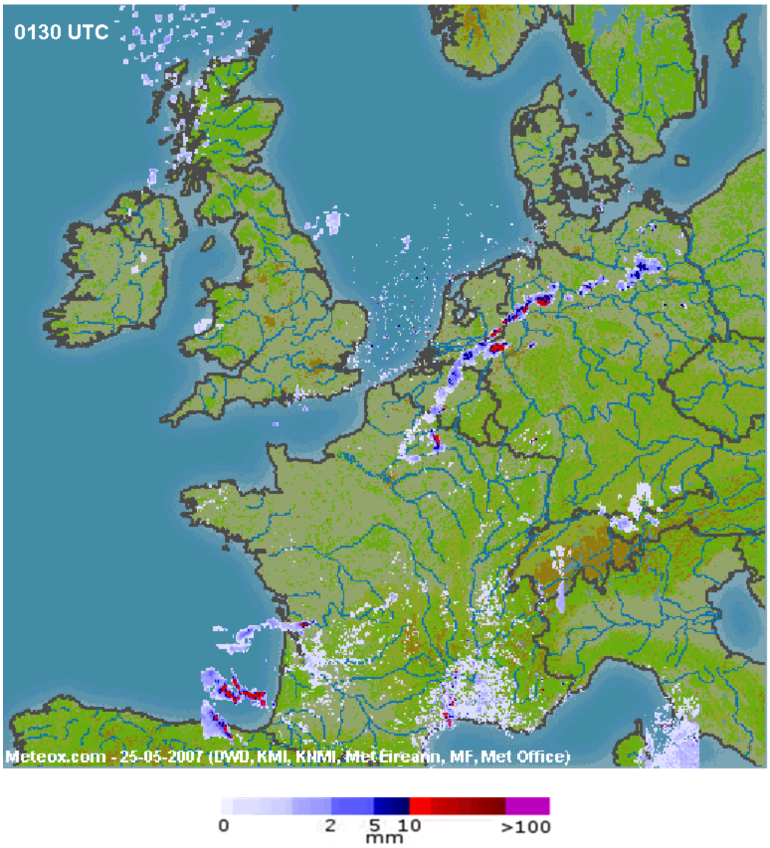

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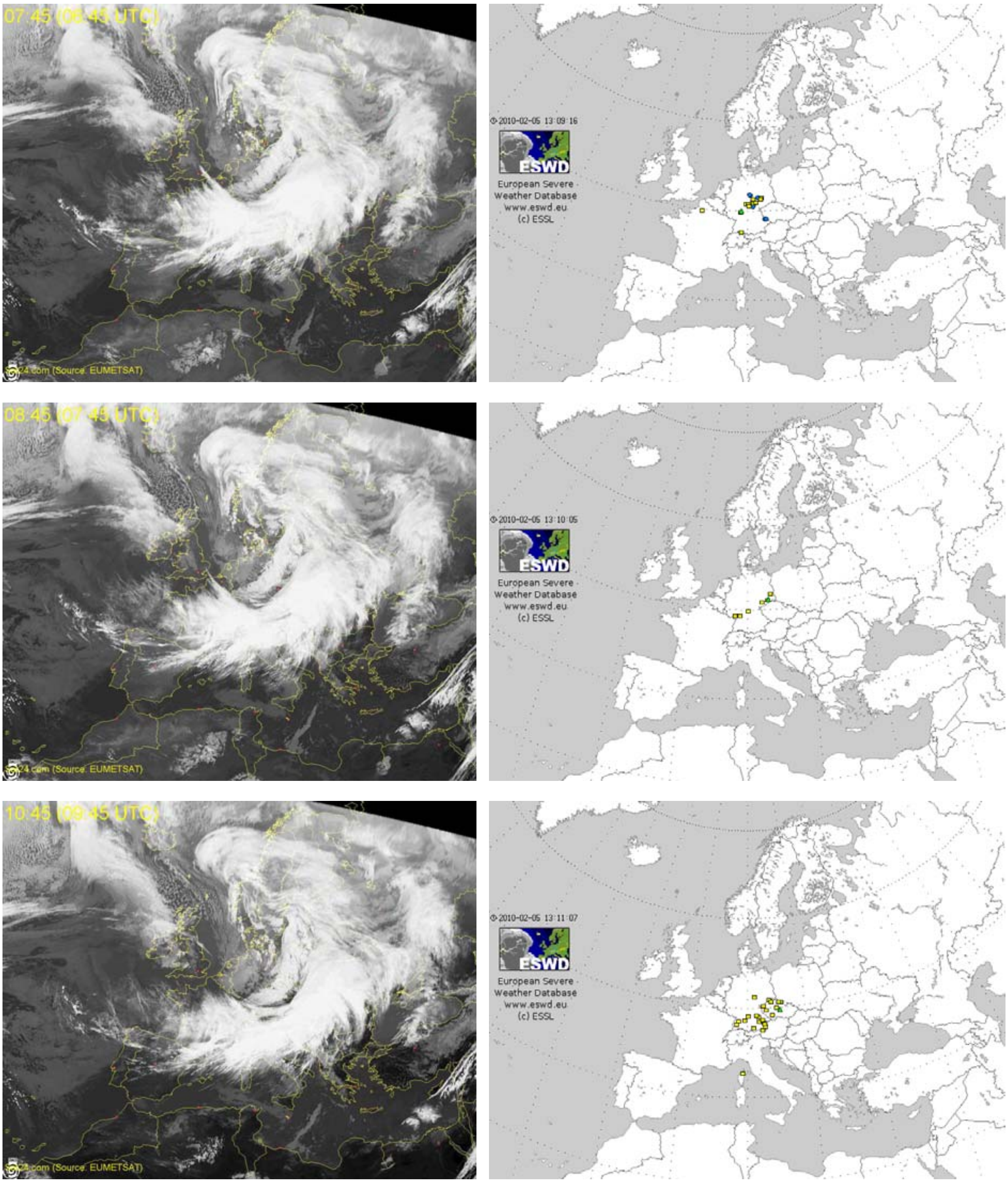

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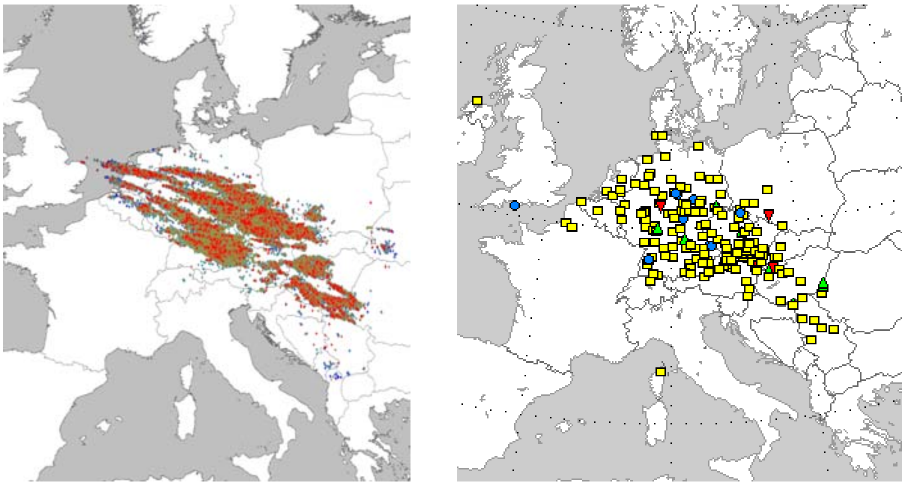

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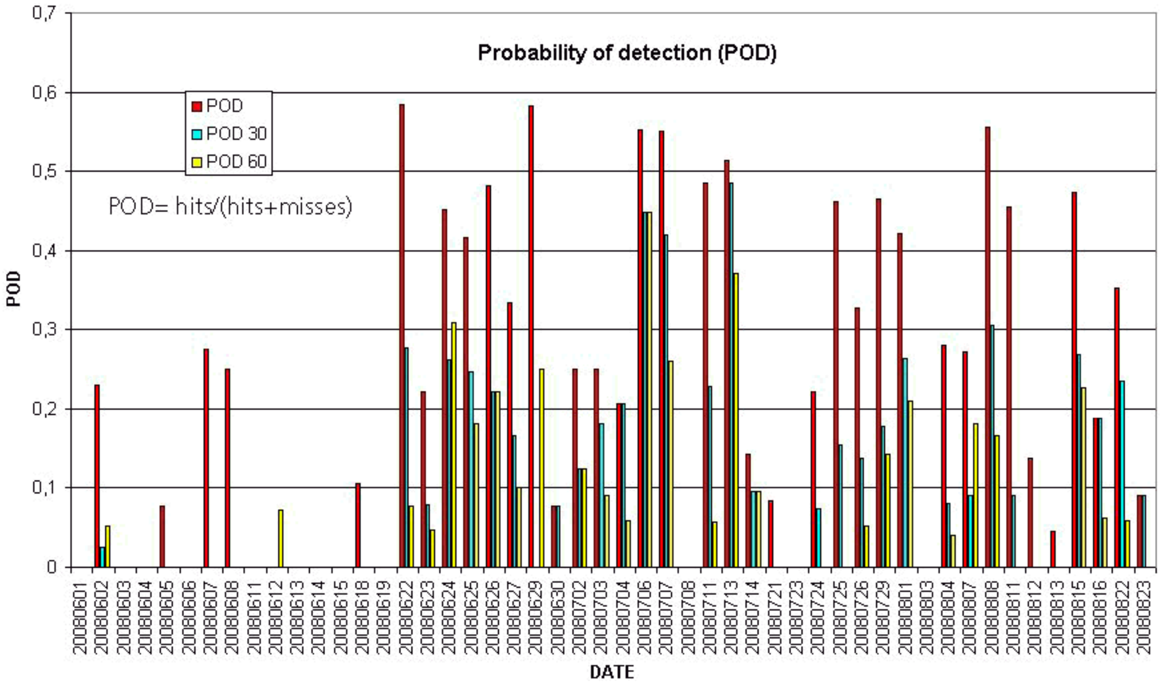

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