

USE OF THE EUROPEAN SEVERE WEATHER DATABASE TO VERIFY SATELLITE-BASED STORM DETECTION OR NOWCASTING

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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 or nowcasting/warning verification purposes. The study of five 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 can 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.

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 5 to 8 billion euros per year (source: Munich Re Group). Extreme events like an F4 tornado in France and an F3 downburst in Austria in 2008 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, and a pan-European database of in situ severe storm reports was unavailable even a few years ago.

Severe thunderstorms require essential ingredients such as the presence of moisture and instability, a source of upward motion and strong vertical wind shear (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 likely play important roles in creating regionally favourable circumstances for severe thunderstorms, for example by the mesoscale flows that they induce. A better knowledge of European severe thunderstorms could 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 European scientists and formally established in 2006 as a non-profit research organisation (registered association, *eingetragener Verein, e. V.*) 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;
- support or organisation 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 verify not only thunderstorm detection and nowcasting products, but in principle also related forecasts or warnings.

Already four NMHS are partners of the ESSL: AEMet (Spain), DWD (Germany), NIMH (Bulgaria) and ZAMG (Austria). DWD is also an institutional ESSL member, 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 the present paper, we focus on verification case studies of the satellite tracking and monitoring algorithm Cb-TRAM recently developed at DLR. These studies aim at demonstrating the potential benefits of coupling satellite-based storm detection algorithms to ESWD ground reports of actual events. 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.

2. DATA

2.1 Cb-TRAM

The cloud-tracker Cb-TRAM (Cumulonimbus TRacking And Monitoring, Zinner et al., 2008) is a new fully automated multi-channel algorithm for the detection and nowcasting of deep moist convection using Meteosat-8 SEVIRI (Spinning Enhanced Visible and Infra-Red Imager) data. The channels broad-band high-resolution visible (HRV), water vapour (WV) 6.2 μm , and thermal infrared (IR) 10.8 μm are combined to classify three different stages of thunderstorm development, see Fig. 1:

- Strong local development of convective low-level clouds (“convective initiation”);
- Rapid cooling of cloud tops by vertical cloud development (“rapid development”);
- Mature thunderstorms.

The HRV channel is used to localise regions of enhanced cloud-top structure (“roughness”) from reflectivity gradients. In the “mature thunderstorm” identification, also tropopause temperatures from ECMWF model forecasts are taken into account, thereby implicitly assuming that mature thunderstorm cells level out in the tropopause region.

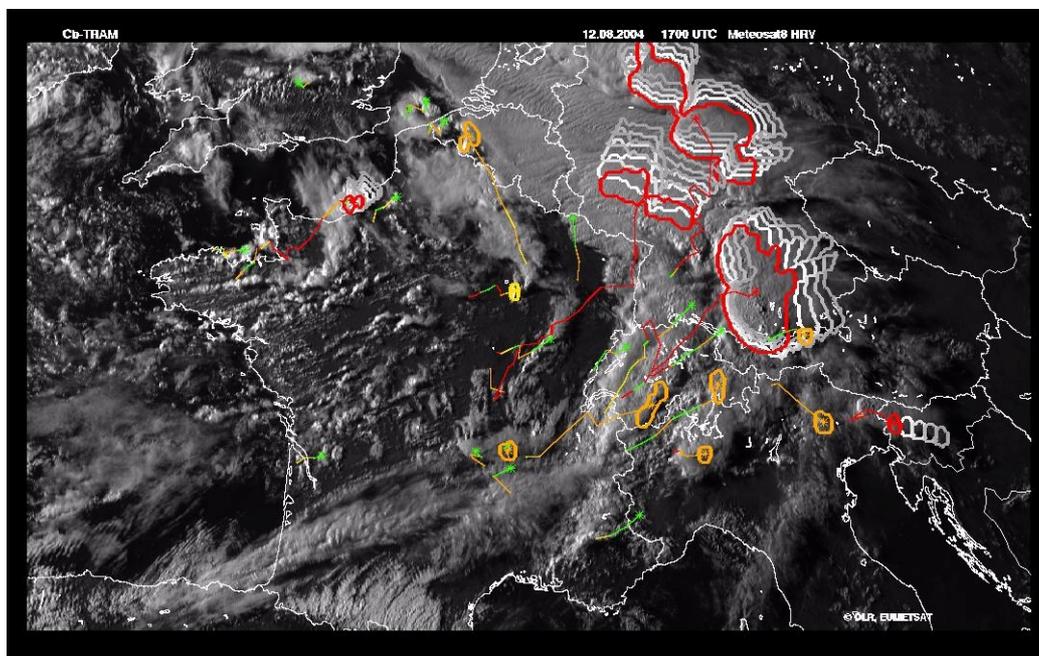


Figure 1: Cb-TRAM example of 12 August 2004, 1700 UTC. Yellow = onset of convection, orange = rapid development, red = mature thunderstorm. Grey polygons show nowcasts of mature cells for 15, 30, 45, and 60 min, respectively.

The 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 a novel 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 the pyramidal image-matching algorithm. Additional details on Cb-TRAM were provided by Tafferner et al. (2008) and Forster et al. (2008). In the present study, we only focus on the three-level diagnostic detection polygons of Cb-TRAM and defer the verification of the nowcasting step to future collaborative work.

2.2 European Severe Weather Database ESWD

The main goal of the European Severe Weather Database, ESWD (cf. Dotzek et al., 2006, 2008), is to gather and provide detailed and quality-controlled in situ reports of severe convective weather events (e.g., flash floods, hail, straight-line winds, tornadoes) all over Europe using a homogeneous data format and web-based, multi-lingual user-interfaces where both the collaborating NMHS 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 significantly (Fig. 2). After two years of test operations, 2006 was the first year with operational ESWD service.

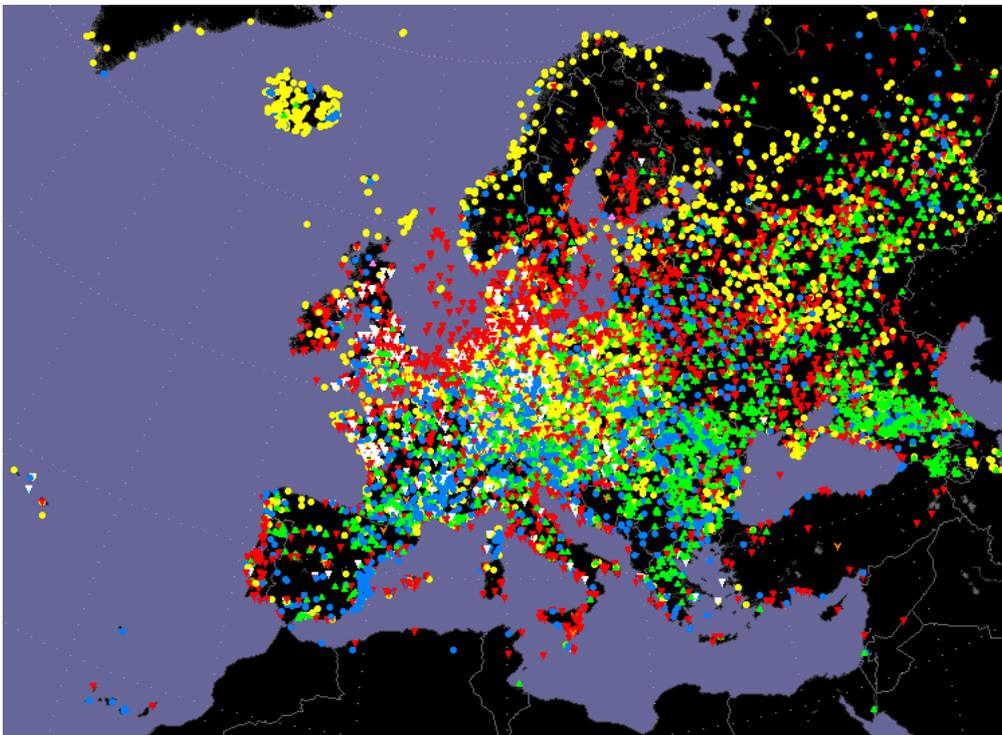


Figure 2: All 19063 ESWD reports (red: tornadoes, yellow: damaging wind, green: large hail, blue: heavy precipitation, white: funnel clouds). Date of ESWD inquiry: 15 October 2008.

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: Straight-line wind gusts ($>25 \text{ m s}^{-1}$), tornadoes, large hail (diameter $>2 \text{ cm}$), heavy precipitation, 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 www.essl.org/reports/tec/ESSL-tech-rep-2006-01.pdf).

The database is maintained and developed by the ESSL, where also further information on its development is available from the websites www.essl.org as well as www.eswd.eu and www.ecss.eu. Aside from its main public web portal, ESWD development is documented at essl.org/projects/ESWD/.

The basic quality-control (QC) procedure foresees that the ESSL is responsible for QC of all 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 locally installed ESWD software. Each NMHS partner performs a three-level quality-control on the data gathered at its ESWD installation, while the ESSL is responsible for the three-level QC of the public reports from Europe and those entered by its ESWD maintenance team. Data exchange between the ESSL and the cooperating NMHS takes place in regular intervals, currently usually once a day. Herein, the NMHS partners upload their new or revised data to the ESSL main server, and download the new or updated public reports of severe weather in their respective countries. 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 meanings of the three QC-levels in the ESWD are:

- QC0: “as received” (new report, only retained if at least plausibility can be ascertained);
- QC0+: “plausibility checked” (assigned by partner organisation or ESSL);
- QC1: “report confirmed” by reliable sources (assigned by partner organisation or ESSL);
- QC2: “event fully verified” i.e. all information about this event is verified, consistent and comes from reliable sources (assigned by partner NMHS or ESSL).

The ESWD public web portal displays the above terminology for the QC-levels, and highlights the 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.

3. CASE STUDIES

3.1 Warm-season storms, 25 May 2007

Fig. 3 provides a verification example of convective clouds detected by the Cb-TRAM algorithm. Note that the Cb-TRAM contours are parallax-corrected, so they can be directly compared to the ESWD reports. Our complete study was performed for the five days in Table 1 with warm-season severe convection. On 25 May 2007, widespread activity of mostly isolated thunderstorms evolved from France to Poland. In Fig. 3a, at 0110 UTC, there is a heavy precipitation report at the border between the Netherlands and Germany. At 0125 UTC, Cb-TRAM marks this cell with a “rapid development” polygon. Figs. 3c,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.

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%
29 July 2008	27	11	41%

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. On 15 June 2007, the large number of reports contains about 40 funnel clouds associated with low clouds over the UK at 1200 UTC. Hence, the percentage of ESWD vs. Cb-TRAM correspondences has also been computed without these funnel cloud reports (marked by an asterisk).

For 25 May 2007, 47% of all ESWD reports were falling exactly within the Cb-TRAM polygons, and on two other of the five 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 specific thunderstorm morphology. Besides, the temporal resolution of the satellite pictures 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. 3a,b). So, in light of the fact that no exact correspondence between Cb-TRAM polygons and ESWD reports is strictly required, the correspondence ratios of more than 40% are encouraging.

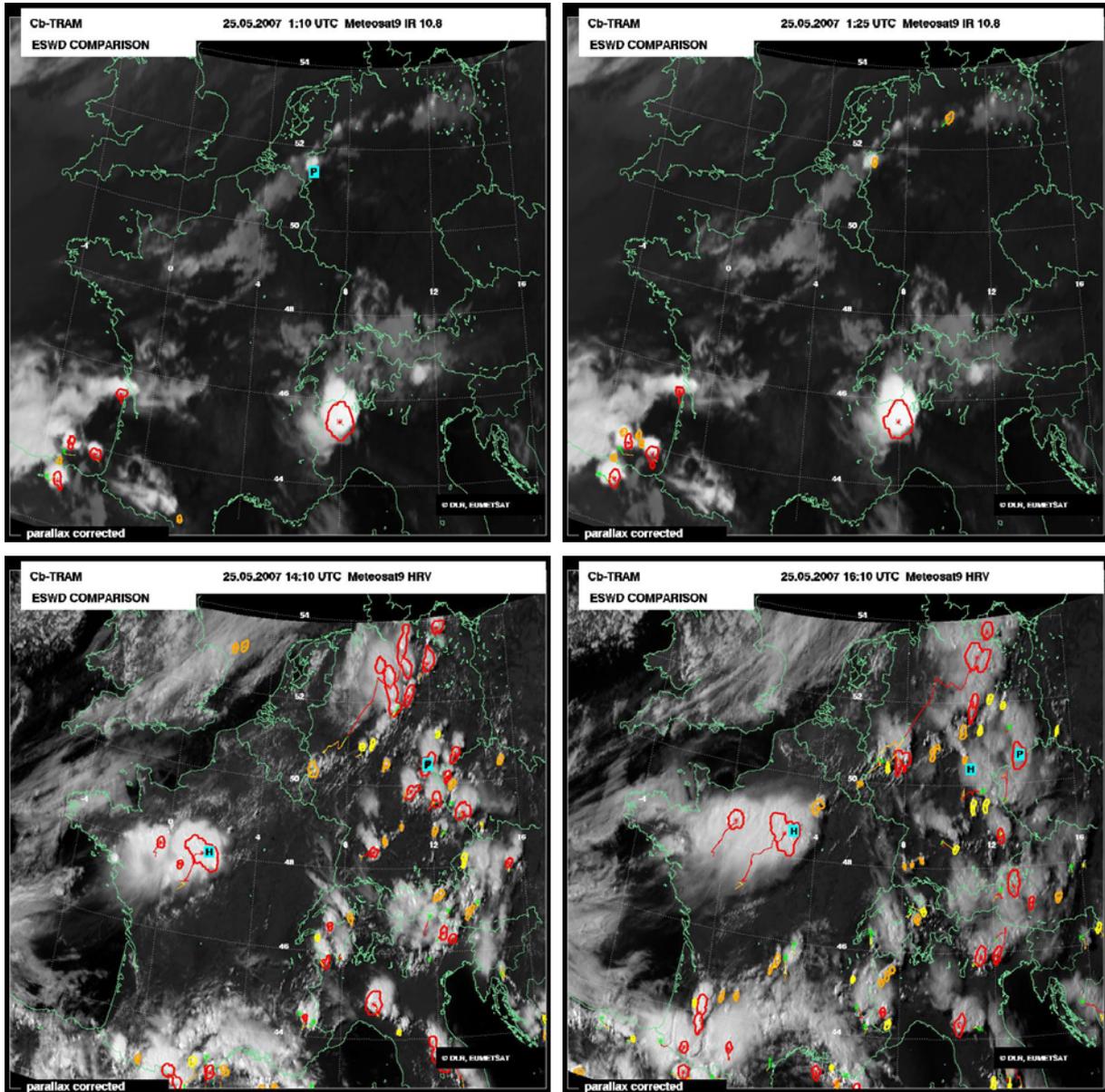


Figure 3: Snapshots from the Cb-TRAM storm detection (polygons, yellow: onset of convection, orange: rapid vertical development, red: mature thunderstorm) for 25 May 2007. Meteosat-8 satellite image times: (a) 0110, (b) 0125, (c) 1410, (d) 1610 UTC. ESWD reports from 10 min before to 5 min after image time: light blue squares with letters H = large hail and P = heavy precipitation. At other times, also damaging winds, tornadoes or funnel clouds were reported.

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. The next step will be to test the validity of Cb-TRAM nowcasts using ESWD reports. With growing completeness of the ESWD, studies of a large set of cases may eventually reveal if, for instance, hail-producing cells have other Cb-TRAM detection or nowcast characteristics than thunderstorms producing damaging winds or heavy precipitation.

3.2 Cool-season storms, 1 March 2008

Interestingly, 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. 4 illustrates such a case on 1 March 2008 with cyclone "Emma".

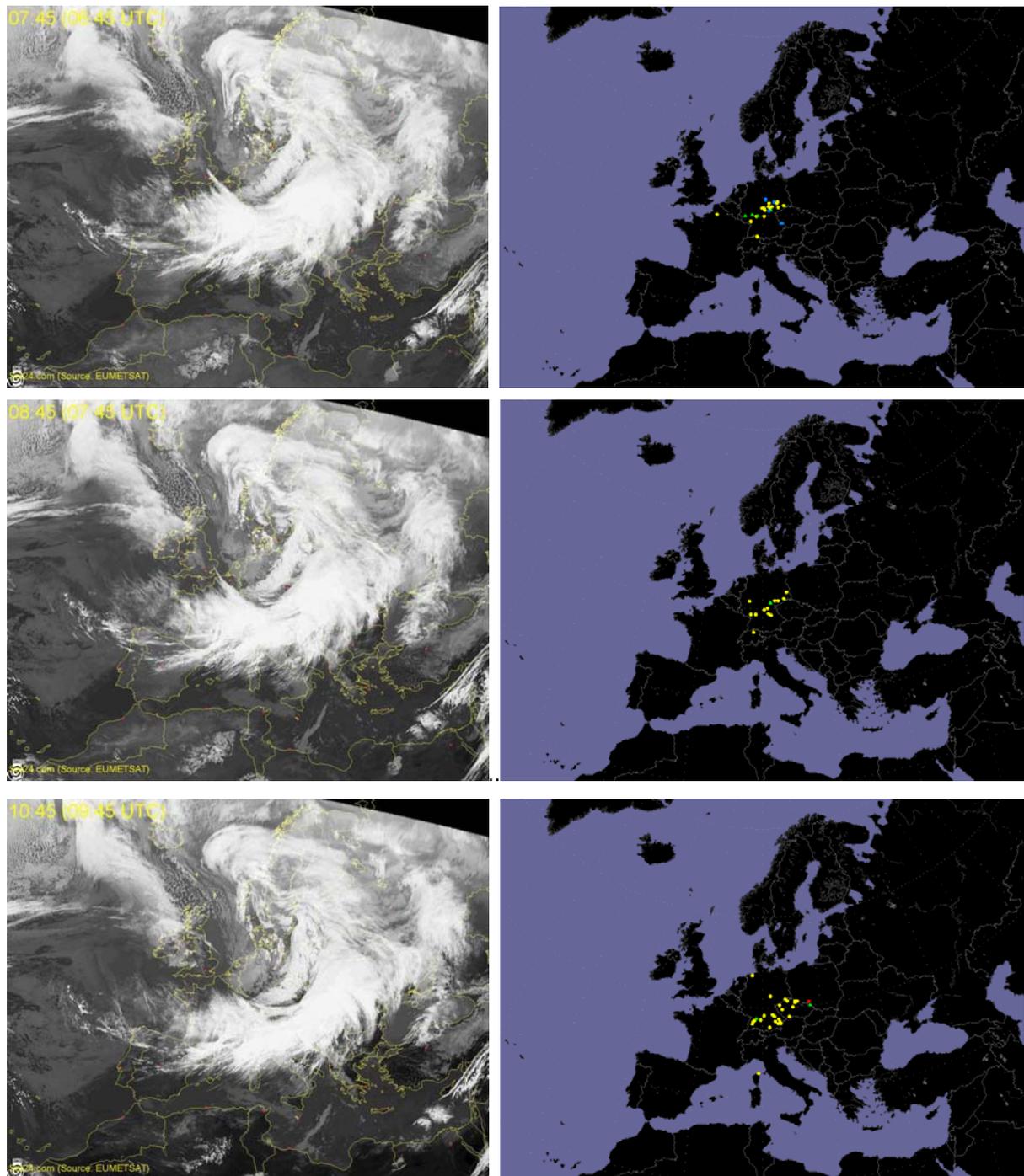


Figure 4: Evolution of cyclone "Emma" on 1 March 2008: satellite visible pictures (a,c,e) versus ESWD reports in the corresponding hour (b,d,f, colours as in Fig. 2). (a) 0645 UTC, (b) ESWD reports from 06-07 UTC, (c) 0745 UTC, (d) ESWD from 07-08 UTC, (e) 0945 UTC, (f) ESWD reports from 09-10 UTC, at about the time when Munich airport was hit.

On this day, Munich international airport operations were severely affected by a line of thunderstorms at about 1000 UTC. In Fig. 4, two main cloud bands associated with the advancing leading edge of the cold air can be seen on the satellite pictures. The first frontal line has a high cloud shield, while the secondary line has only much lower-topped clouds and looks less impressive than the primary frontal band. However, the corresponding ESWD reports reveal that the severe weather was almost exclusively collocated with the secondary line of the cold front, correspondingly leading to linear bands with severe storm reports at the ground.

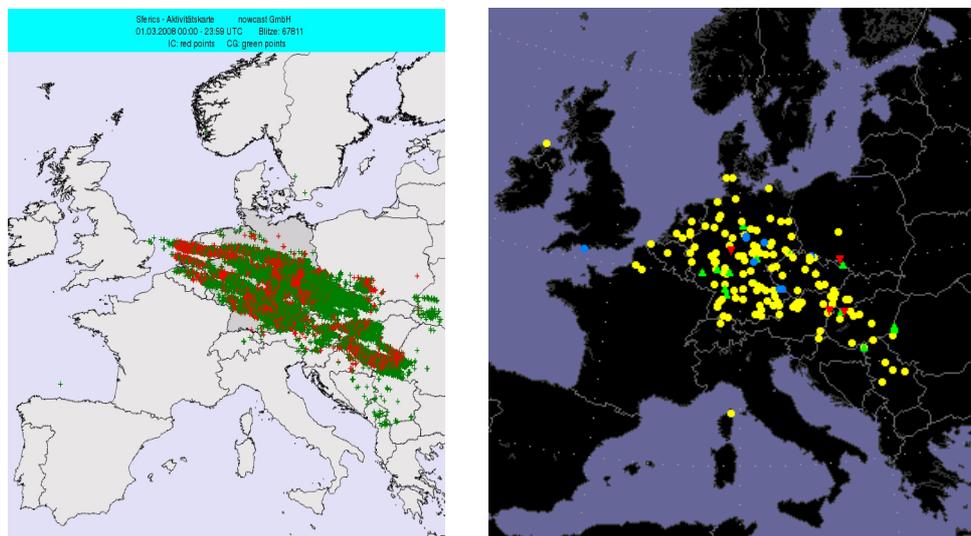


Figure 5: Lightning detection and ESWD reports with cyclone “Emma” on 1 March 2008, as analysed in the RegioExAKT project. (a) 67811 flashes (red: intracloud, green: cloud-to-ground from LINET system, www.nowcast.de), (b) 163 ESWD reports (red: tornadoes, yellow: damaging wind, green: large hail, blue: heavy precipitation).

The severe weather at the secondary cold frontal line was indeed caused by thunderstorms, despite the low cloud tops. Fig. 5 shows the total lightning (cloud-to-ground and intracloud) activity 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. 4 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 convectively 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. 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 cloud tops are more difficult to distinguish from other, stratiform clouds at similar altitude. And higher cloud shields aloft might further disguise the low-top storms’ characteristics as observed from satellites.

4. CONCLUSIONS

The warm-season thunderstorm cases and the cool-season frontal-type low-top storms example presented here 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; Dotzek et al., 2008) 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:

- The ESWD provides increasingly homogeneous pan-European coverage of severe thunderstorm reports in a detailed and flexible data format including metadata information;
- The NMHS: AEMet, DWD, NIMH and ZAMG are present cooperation partners. Collaboration with more European NMHS is desired to enhance completeness and reusability of the database;
- Five 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 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 the “Emma” case study of 1 March 2008, we also stress that low cloud base and high low-level shear are also factors which favour tornado genesis in the presence of strong convection. Therefore, already observations of embedded electrical activity alone in extratropical cyclones should be an especially alarming signal for operational forecasters.

ACKNOWLEDGEMENTS

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REFERENCES

- Doswell, C. A. III, (Ed.), 2001: *Severe Convective Storms*. Meteor. Monogr., **28**(59), Amer. Meteor. Soc., Boston, 561 pp.
- Dotzek, N., T. Kratzsch, and P. Groenemeijer, 2006: The European Severe Weather Database (ESWD): An inventory of convective high-impact weather events for forecast and warning evaluation, climatology, and risk assessment. Preprints, *2nd THORPEX International Science Symposium (STISS)*, Landshut, 4-8 December 2006, WMO/TD No. 1355, WWRP/THORPEX No. 7, 228-229.
- Dotzek, N., P. Lang, M. Hagen, T. Fehr, and W. Hellmiss, 2007: Doppler radar observation, CG lightning activity, and aerial survey of a multiple downburst in southern Germany on 23 March 2001. *Atmos Res.*, **83**, 519-533.
- Dotzek, N., P. Groenemeijer, B. Feuerstein, and A. M. Holzer, 2008: Overview of ESSL's severe convective storms research using the European Severe Weather Database ESWD. *Atmos. Res.*, in press.
- Forster, C., A. Tafferner, T. Zinner, and C. Keil, 2008: Validation of severe weather forecasts based on synthetic satellite data as part of an integrated thunderstorm forecast system for air traffic. Proc. *2008 EUMETSAT Meteor. Sat. Conf.*, Darmstadt, Germany, 8-12 September 2008, 8 pp. [Available at www.eumetsat.int/Home/Main/Publications/Conference_and_Workshop_Proceedings/]
- König, M., M. Pajek, and P. Struzik, 2007: MSG Global Instability Indices for storm nowcasting – validation studies on product quality and analysis of sensibility to input model data. Proc. *Joint 2007 EUMETSAT Meteor. Sat. Conf. and 15th AMS Sat. Meteor. & Oceanogr. Conf.*, Amsterdam, The Netherlands, 24-28 September 2007, 7 pp. [Available at www.eumetsat.int/Home/Main/Publications/Conference_and_Workshop_Proceedings/]
- Tafferner, A., C. Forster, S. Senesi, Y. Guillou, P. Laroche, A. Delannoy, B. Lunnon, D. Turb, T. Hauf, and D. Markovic, 2008: Nowcasting thunderstorm hazards for flight operations: the Cb-WIMS approach in FLYSAFE, Proc. *26th Int. Congress of the Aeronautical Sci. (ICAS)*, Anchorage, Alaska, 14 -19 September 2008.
- Ulbrich, U., J. G. Pinto, H. Kupfer, G. C. Leckebusch, T. Spanghel, and M. Reyers, 2001: Three extreme storms over Europe in December 1999. *Weather*, **56**, 70-80.
- Zinner, T., H. Mannstein, and A. Tafferner, 2008: Cb-TRAM: Tracking and monitoring severe convection from onset over rapid development to mature phase using multi-channel Meteosat-8 SEVIRI data, *Meteorol. Atmos. Phys.*, doi:10.1007/s00703-008-0290-y.