

Synoptic-mesoscale analysis of the flash flood producing thunderstorm over the Vallée de l'Ernz on 22 July 2016

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1. Introduction

On 22 July 2016, the Vallée de l'Ernz in the middle eastern part of Luxembourg was hit by torrential convective rainfall that triggered catastrophic flash floods during the evening hours, accounting for substantial damage in the amount of at least 6 million euros. According to eyewitness reports in several media (see appendix), the flash floods in the Vallée de l'Ernz started at different times along the valley, with an approximate time frame from 1815 to 1900 UTC. The orography of the Vallée de l'Ernz and Larochette is dominated by a north-south orientated river valley with altitudes of 240 to 270 m, surrounded by a hilly landscape with altitudes up to 420 m and steep slopes, especially between Medernach and Larochette (Figs. 1a,b). The river White Ernz (fr. *Ernz Blanche*) flowing through the towns of Ermsdorf, Medernach and Larochette (Fig. 1a) reached an exceptionally high water level of 224 cm at Larochette. It was one of the most severe hydro-meteorological events in the Luxembourgish territory in the last decades and comparable events took place in regions close to the Vallée de l'Ernz on 1 July 1958 (D'Letzeburger Land 1958, Luxemburger Wort 2018) and on 1 June 2018. This case study is focused on the meteorological features of this hazardous weather event, with the following main objectives:

1. To identify the atmospheric synoptic-scale and mesoscale conditions that favoured the development of this extreme rainfall event.
2. To provide a spatial and temporal characterization of the convective activity producing the observed precipitation that triggered the flash floods and landslides.

This article is structured as follows. Section 2 describes the data used in this study and an overview of the synoptic-scale situation will be provided in section 3. An analysis of the flood producing storm is given in section 4 and the precipitation observations are examined in section 5. The last section includes a short summary and the conclusions.

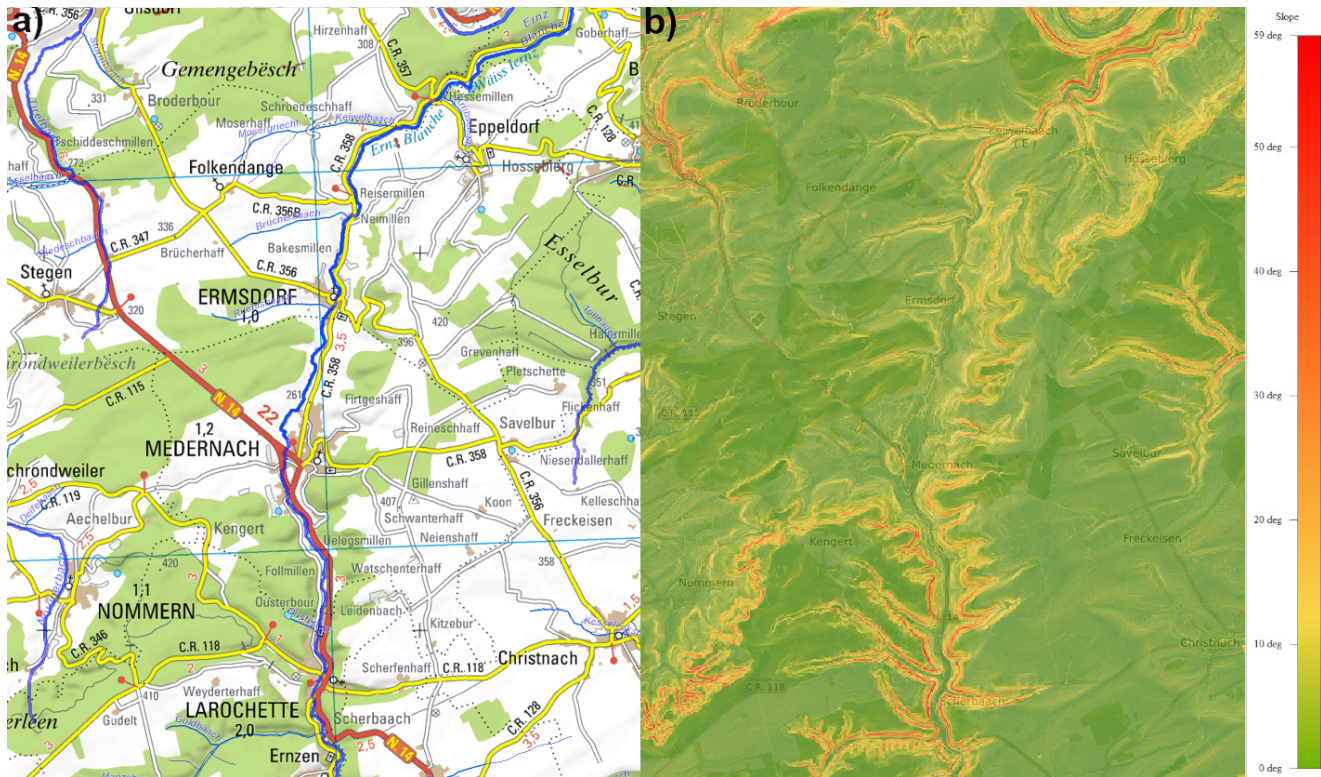


Figure 1: Overview of the investigation area Vallée de l'Ernz. (a) Topographic map with watercourses (blue lines). (b) Colored terrain slope (in degrees). Source: <https://geoportail.lu/>

2. Data

The in situ measurements of precipitation include data from the surface weather station network operated by the meteorological department of the Administration des Services Techniques de l'Agriculture (ASTA). The data has a temporal resolution of 10 minutes. Moreover, the radar analysis will be based on a low-level reflectivity product with a horizontal resolution of 250 m, which is provided by the German Weather Service (DWD) and visualized by the Kachelmann GmbH (2018). Data from the radar-based quantitative precipitation estimation (QPE) method RADOLAN developed

by the DWD will be analysed as well, which is however not gauge-adjusted over the Luxembourgish territory. The RADOLAN composite has a spatial resolution of 1 km. In addition to the in situ and radar data, ERA5 reanalysis data from the European Centre for Medium-Range Weather Forecasts (ECMWF) will be used to examine the synoptic-scale conditions. The hourly reanalysis data output has a grid spacing of approximately 31 km (Hersbach and Dee 2016). Lastly, lightning data from nowcast (Betz et al. 2009) will be considered.

3. Synoptic-scale conditions and storm environment

On 22 July 2016, a meridional circulation was active in the upper troposphere over Western Europe. At 1200 UTC, an upper-level trough was located over England, western France and the Iberian Peninsula, exhibiting asymmetric structures (Fig. 2a). On its rear side, a jet stream with wind speeds of up to 42 m s^{-1} was present over the Bay of Biscay and Spain (Fig. 2b). The front side of the long-wave trough was more diffuse with weaker geopotential and temperature gradients. Hence, the southerly upper-tropospheric flow was weak over eastern France, western Germany and Benelux. However, a small and anticyclonically curved jet streak with a local wind maximum of 36 m s^{-1} was situated over Belgium and northern France (Fig. 2b). As the flow curvature in 300 hPa remained anticyclonic due to the persistence of the upper-level ridge over eastern Germany and in combination with a nearly straight flow in 500 hPa (cf. Figs. 2a and 2b), no significant large-scale forcing for ascent was identifiable over the Greater Region.

The examination of the low-level conditions was not straight forward due to a weak mean sea level pressure (MSLP) gradient over Central Europe. Indeed, the 1200 UTC surface analysis from three meteorological services (DWD, UK MetOffice and Royal Netherlands Meteorological Institute KNMI) resulted in three different interpretations (not shown). Based on ERA5 reanalysis data, an ill-defined and wavy zone with temperature and moisture gradients extended from France to the North Sea (cf. Figs. 3a and 3b), separating subtropical air masses in the east from heated maritime polar air masses west of this front-like gradient zone. Moreover, a strong moisture gradient was evident over northeastern Germany and a bow-shaped low-level convergence zone was situated over northern Germany (Fig. 3a). According to supplementary surface observations in the Greater Region, this

convergence zone even extended to the Belgian Ardennes. The MSLP distribution revealed a weak low pressure area over southern Germany and northeastern France at 1200 UTC (Fig. 3b), but it remained amorphous until the evening hours, as the ongoing activity of convective storms further significantly affected the conditions near the surface.

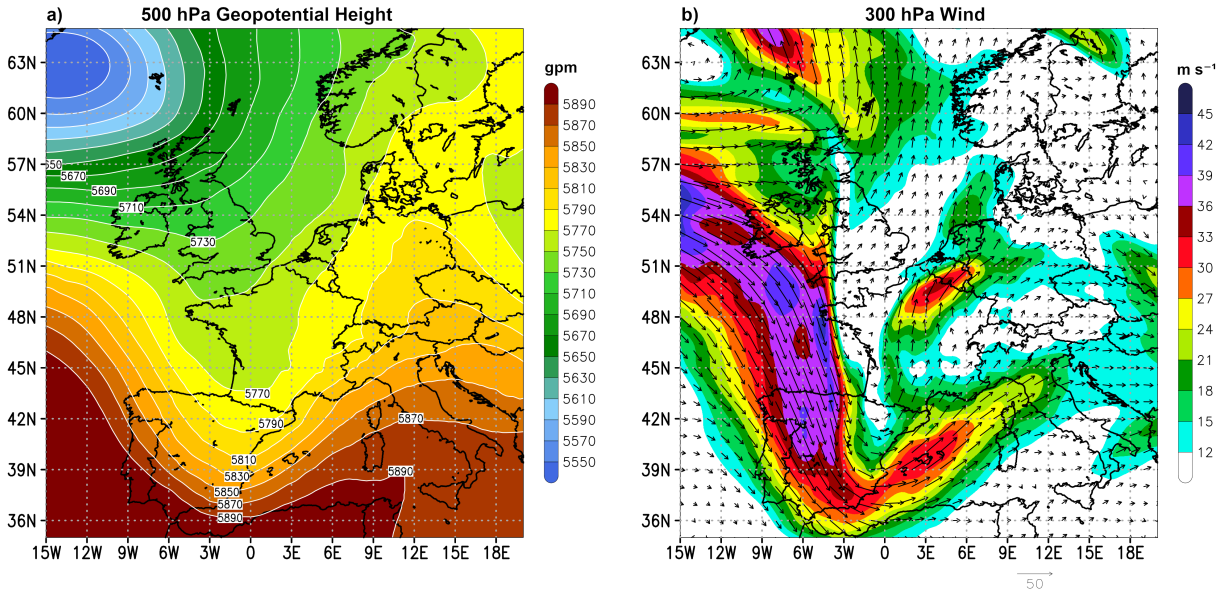


Figure 2: ERA5 reanalysis of the upper-level synoptic-scale conditions at 1200 UTC over Western Europe. (a) 500 hPa geopotential height (gpm). (b) 300 hPa wind speed and vector direction (m s^{-1}).

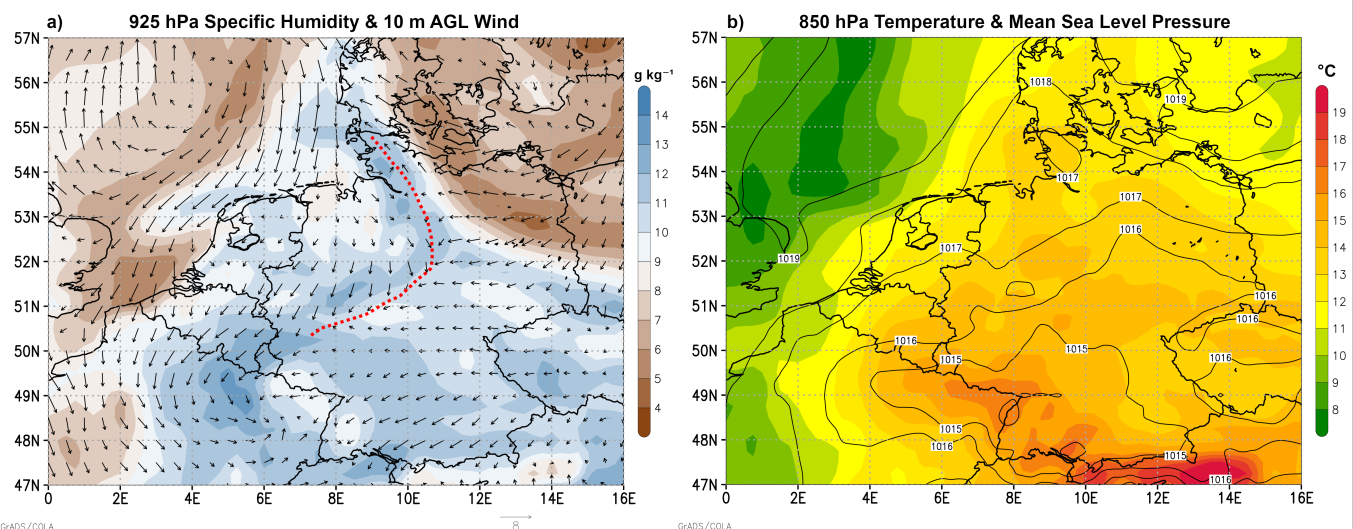


Figure 3: ERA5 reanalysis of the low-level synoptic-scale conditions at 1200 UTC over Central Europe. (a) 925 hPa specific humidity (shaded; g kg^{-1}) and 10 m AGL wind vector (m s^{-1}). (b) 850 hPa temperature (shaded; $^{\circ}\text{C}$) and mean sea level pressure (black lines; hPa). The dotted red line in (a) denotes a wind convergence zone.

Furthermore, high amounts of tropospheric water vapour were observed in the regime of the subtropical air mass over Benelux and the western part of Germany. Upper-air observations from Beauvechain (Belgium), De Bilt (Netherlands), Norderney, Meppen, Essen and Idar-Oberstein (Germany) indicated total precipitable water (PWAT) contents of 30 to 40 mm on 22 July 2016. The 1700 UTC sounding from Idar-Oberstein (80 km east of the Vallée de l'Ernz) is considered representative of the atmospheric conditions prevailing over Luxembourg due to an easterly flow in the lower troposphere and negligible contamination by convection. The sounding revealed a well-mixed boundary layer up to 850 hPa with a mean mixing ratio of 12.4 g kg^{-1} in the lowest 50 hPa and a mean relative humidity of 64 % between the surface and 600 hPa (Fig. 4). An elevated mixed layer (EML) was present between 810 hPa and 720 hPa with lapse rates of about $8.5 \text{ }^\circ\text{C km}^{-1}$. The combination of a moist boundary layer and steep lower-tropospheric lapse rates resulted in a 50-hPa mixed-layer convective available potential energy (CAPE) of about 1500 J kg^{-1} , with very low or zero convective inhibition (CIN) values (Fig. 4).¹ The convective temperature was at about 27 to 28 °C, which was reached by the majority of the synoptic stations in the Greater Region during the afternoon hours. Due to very weak lower- to mid-tropospheric air flow, the vertical wind speed shear between 0 and 6 km remained between 5 and 10 m s^{-1} (Fig. 4), such that well-organized deep moist convection (DMC) was not to be expected. However, the speed shear was stronger in the upper troposphere with roughly 20 m s^{-1} between 6 and 11 km (Fig. 4).

In brief, the synoptic-scale environment was highly favourable for the development of DMC. A high boundary layer moisture, steep lapse rates and weak dynamics characterized the lower troposphere. The forcing to initiate DMC storms was mainly provided by sub-synoptic-scale processes (e.g., low-level convergence zones, outflow boundaries, boundary layer thermals reaching the level of free convection), but also by forced ascent along the German and Belgian low mountain ranges. This regime of moderate latent instability, high total column water vapour and weak lower-tropospheric kinematics generally allows the formation of slow moving and training thunderstorms which can produce extreme rainfall amounts on the micro- α to meso- γ scale (Doswell et al. 1996; Púčik et al. 2015; Schumacher 2017).

¹ The CAPE and CIN values are calculated using the virtual temperature, see Doswell and Rasmussen (1994).

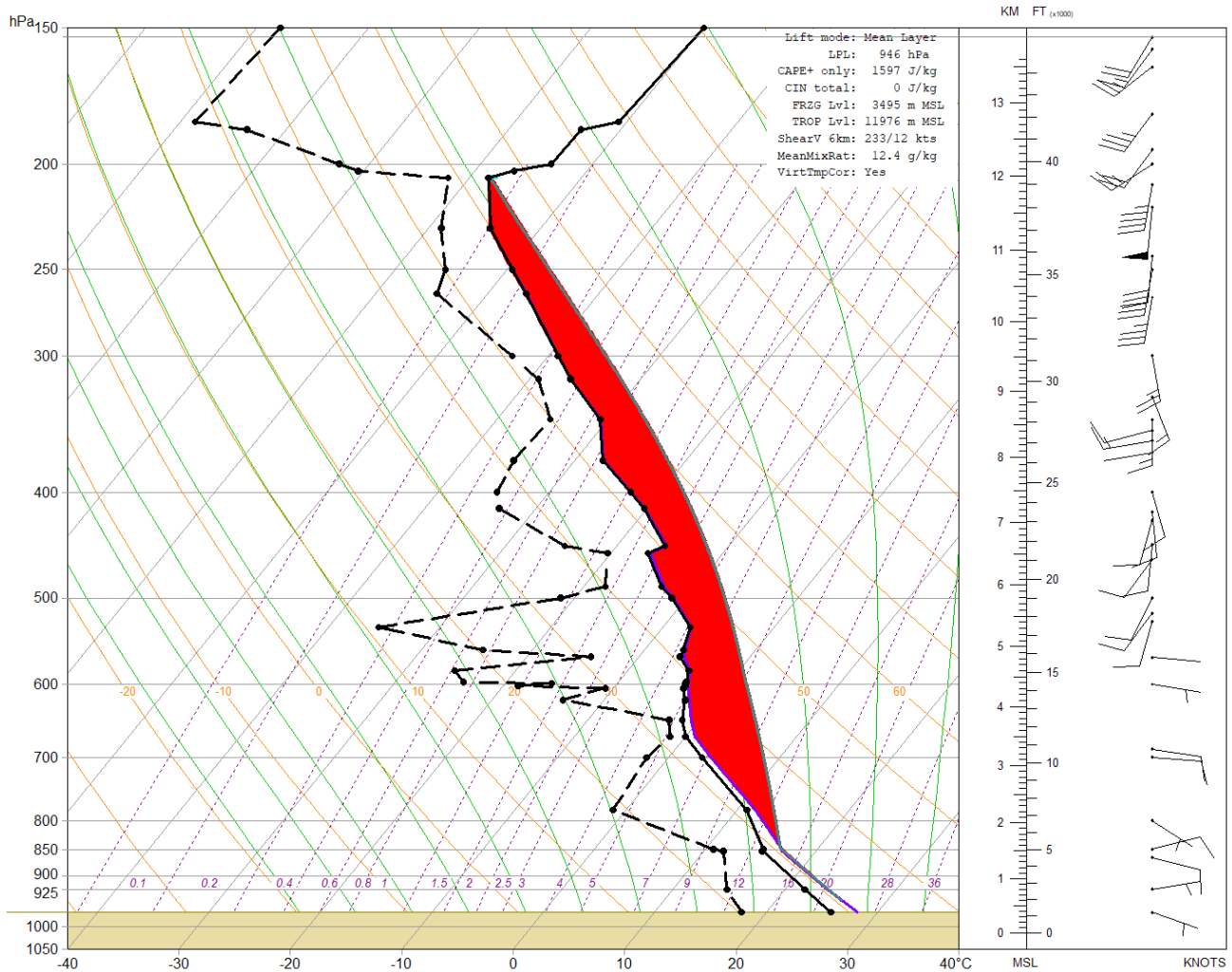


Figure 4: Skew T-log p diagram of a sounding from Idar-Oberstein (WMO 10618) launched at 1700 UTC on 22 July 2016. The solid (dashed) curve represents the temperature (dew point). The area shaded in red denotes the mixed-layer convective available potential energy (CAPE) which is calculated using the virtually corrected temperature (purple line).

4. Evolution of the Convective Activity and Storm Characteristics

The first convective cells appeared over far northwestern Luxembourg near the Belgian border at 1300 UTC, which were initiated by the outflow boundary from convection over the Ardennes. These weak cells dissolved around 1400 UTC and at the same time new convective cells formed over Trier. One of these cells moved slightly to the west while strengthening and reached the region of Merttert and Mompach at 1500 UTC. This storm cell weakened then rapidly until 1540 UTC, whereas a new thunderstorm developed to the south over Flaxweiler and Grevenmacher in eastern Luxembourg (Fig. 5b). While this storm cell dissolved until 1615 UTC, a new convective cell formed between Luxembourg City and Niederanven around 1555 UTC (Fig. 5a), which moved slightly to the west and began to weaken at 1620 UTC. The weather station at the Findel airport (located directly southwest of Niederanven) reported a precipitation amount of 29.7 mm that accumulated between 1600 and 1700 UTC (of which 14.6 mm fell within 10 minutes), indicating the potential for high precipitation amounts within a short period of time. In addition, a line of moderate convective cells formed from Ettelbrück to the French city Thionville at 1700 UTC (Fig. 5b), which extended a bit further north and reached the northwestern part of Luxembourg at 1830 UTC.

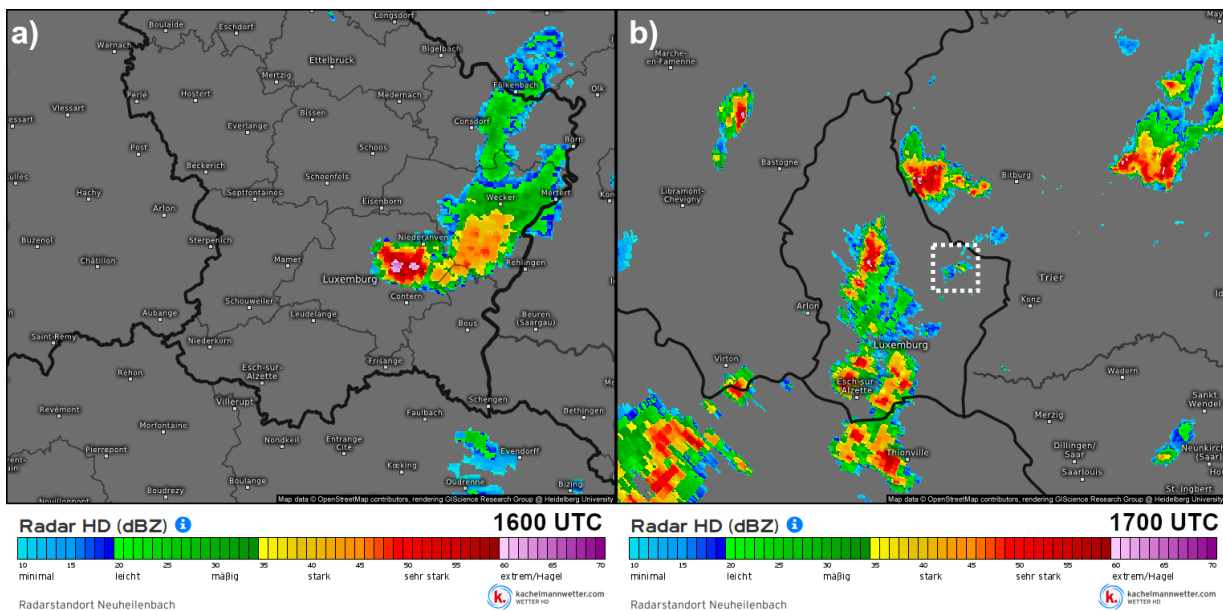


Figure 5: Low-level radar reflectivity measured by the DWD radar Neuheilenbach at (a) 1600 UTC and (b) 1700 UTC. Source: <https://kachelmannwetter.com/lu/regenradar>

The parent cell of the flash flood producing thunderstorm over the Vallée de l'Ernz was already visible near Consdorf in the radar imagery at 1700 UTC (white dotted box in Fig. 5b). Furthermore, a multicellular thunderstorm formed directly north of Vianden west of the German city Bitburg between 1630 and 1700 UTC (see Fig. 5b). This storm propagated slightly to the south, with the strongest precipitation core located over Fahren and Longsdorf at 1730 UTC (feature "1" in Fig. 6a). At the same time, the aforementioned parent cell rapidly intensified north of Larochette at 1730 UTC (Fig. 6a). This storm further strengthened while remaining quasi-stationary over the Vallée de l'Ernz and merged with the storm cell near Longsdorf between 1800 and 1815 UTC (cf. Figs. 6a and 6b with 6c). Hence, a heavy thunderstorm extended from Larochette over Nommern and Medernach to Longsdorf at 1820 UTC. Simultaneously, a single cell storm developed rapidly near Echternach and then moved to the west to merge with the quasi-stationary thunderstorm over the Vallée de l'Ernz at 1830 UTC (feature "2" in Figs. 6c and 6d). These two merging/feeding processes were likely crucial for the long-lasting intense convective precipitation, since several past studies showed that the merging process often has an intensification effect on the storm development and thus, significantly enhancing the precipitation rate (e.g., Bennetts et al. 1982; Westcott 1984, 1994; Fu and Guo 2006, 2012; Sinkevich and Krauss 2014; Sinkevich et al. 2018). Finally, the rainfall stopped over the valley of the White Ernz at about 1930 UTC.

Looking in greater detail at the measured radar pixel values over the Vallée de l'Ernz, local low-level reflectivity maxima of 60 to 63 dBZ were observed over the concerned area (see Fig. 1a) between 1825 and 1845 UTC (Figs. 6d and 6e), whereby low-level reflectivity values of 45 to 55 dBZ were present during an entire hour (from 1750 until 1850 UTC, see Fig. 7). This flash flood producing storm cell also possessed a vertically stacked reflectivity core with values above 55 dBZ between 1820 and 1840 UTC, reaching an altitude of about 8 km (not shown). During that exact period, an impressively high rate of intra-cloud lightning flashes with more than 50 flashes min^{-1} was observed (Fig. 7b). More precisely, three major lightning jumps (i.e., rapid increases in total lightning) were subjectively identified around 1815 UTC, 1821 UTC and 1829 UTC (Fig. 7b). These jumps often indicate the occurrence of severe weather at the ground (Schultz et al. 2011; Jurković et al. 2015; Farnell et al. 2017; Wapler 2017) and they are associated with a growth of the updraft volume and graupel mass in

the mixed phase region of the storm cloud (Deierling and Petersen 2008; Schultz et al. 2017). Indeed, the inclusive total lightning increase between 1810 and 1821 UTC coincides well with the period of the first merging process which took place between Larochette and Longsdorf. Overall, the thunderstorm over the Vallée de l'Ernz produced about 3000 lightning strokes between 1745 and 1900 UTC (Figs. 7a,b).

5. Observed Precipitation

As already shown in section 4, relatively long-lasting and intense precipitation rates caused the extreme rainfall amounts over the Vallée de l'Ernz. The RADOLAN precipitation estimates indicated an hourly accumulation of 30 to 50 mm within a broader area between Stegen and Christnach over the southern part of the White Ernz for the time period 1750 – 1850 UTC, with a peak pixel value of 51.6 mm (Fig. 8). However, when comparing the unadjusted RADOLAN pixel values with in situ precipitation data, it becomes evident that RADOLAN underestimated the rainfall within the aforementioned area (see Fig. 8). The ASTA weather station in Christnach reported an hourly precipitation amount of 53.9 mm (30.7 mm between 1810 and 1830 UTC) and a private semi-professional station located in Stegen even measured 59.6 mm between 1750 and 1850 UTC (Fig. 8). These in situ measurements match well with unadjusted radar-based QPE using data from the DWD radar Neuheilenbach with a higher resolution of 250 m compared to RADOLAN, which showed a few peak pixel values of about 85 mm over the Vallée de l'Ernz.² Moreover, the Z-R-relationship used in RADOLAN might not have been appropriate for this specific case. Altogether, it can be reliably estimated that precipitation amounts of 50 to 80 mm accumulated within an hour over the relatively broad area stretched by the towns Stegen, Ermsdorf, Christnach and Larochette (cf. Fig. 8).

2 <https://kachelmannwetter.com/de/regensummen/diekirch/live-niederschlag-1std/20160722-1850z.html>

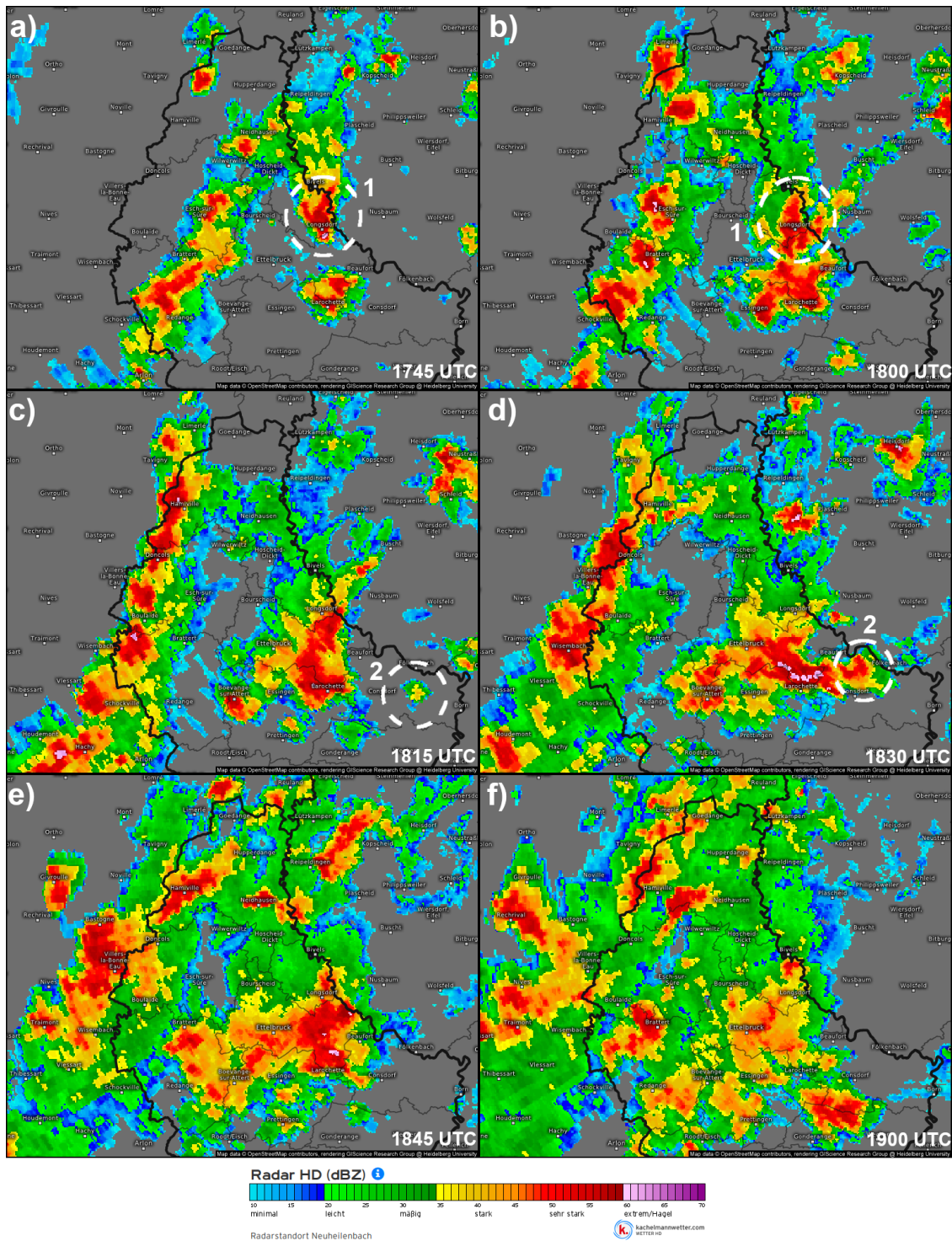


Figure 6: Low-level radar reflectivity measured by the DWD radar Neuheilenbach at (a) 1745UTC, (b) 1800 UTC, (c) 1815 UTC, (d) 1830 UTC, (e) 1845 UTC and (f) 1900 UTC. The features “1” and “2” in (a)-(d) are quoted in the text. Source: <https://kachelmannwetter.com/lu/regenradar>

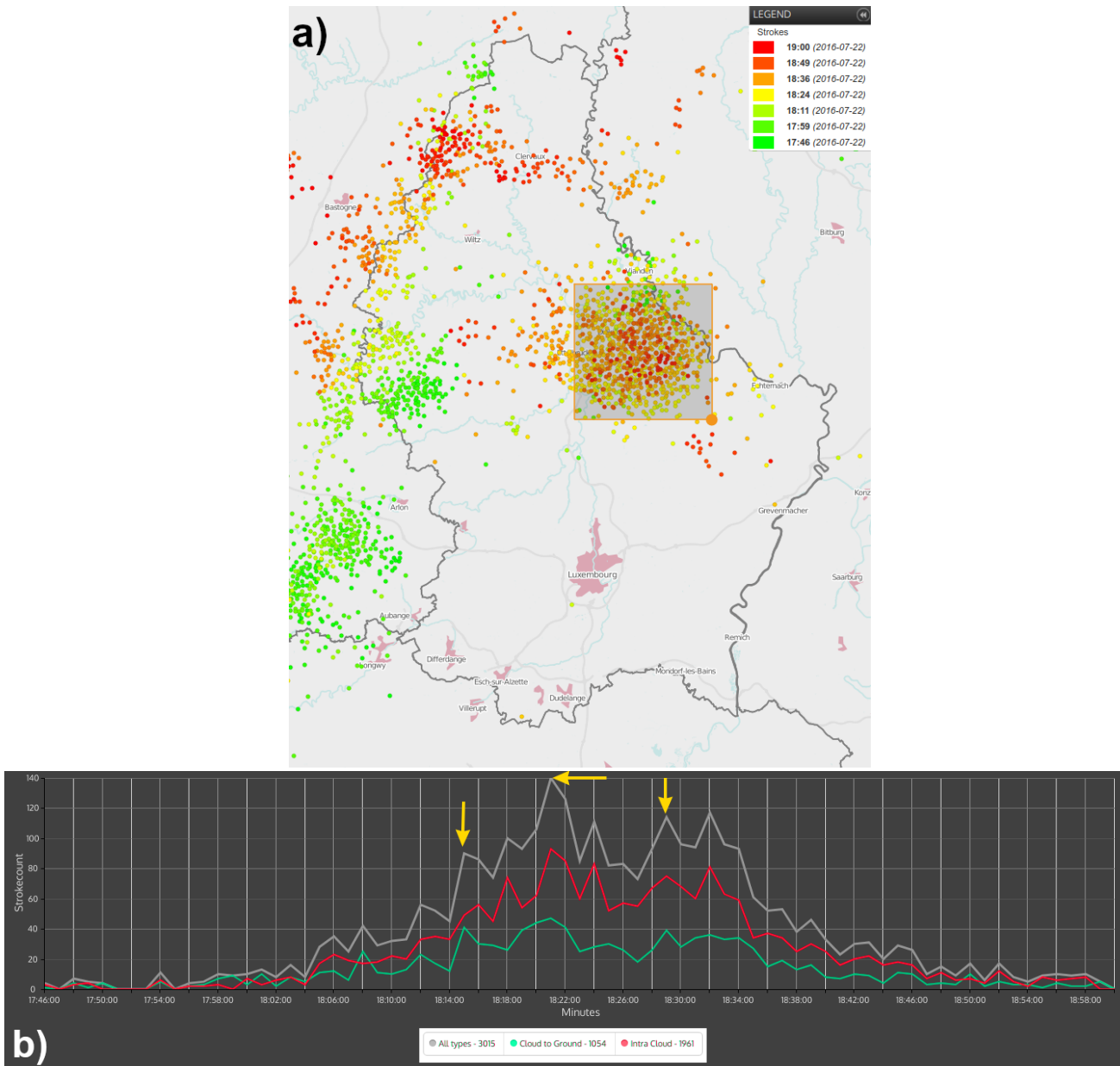


Figure 7: (a) Detected lightning strokes over Luxembourg between 1745 and 1900 UTC. (b) Temporal evolution of cloud-to-ground (green line) and intra-cloud (red line) lightning within the area indicated by the grayish box in (a). The yellow arrows in (b) denote the subjectively analysed lightning jumps.

6. Summary and Conclusions

The 22 July Vallée de l'Ernz flash floods were investigated with regard to the synoptic-scale and mesoscale meteorological context focusing on the atmospheric ingredients of this event and on the storm characteristics as observed with radar and lightning data. The large-scale atmospheric conditions were elementary for the occurrence of DMC over the Grand Duchy of Luxembourg. Moderate latent instability ($CAPE \approx 1500 \text{ J kg}^{-1}$) and sub-synoptic-scale lifting mechanisms were sufficient requirements to initiate strong thunderstorms on 22 July 2016. Furthermore, the radar analysis executed in this paper suggests that the merging of convective cells was most likely a crucial dynamical and microphysical process for the enhanced precipitation generation over the Vallée de l'Ernz, together with the presence of high total column atmospheric water vapour and weak lower- to mid-tropospheric kinematics. The hydrological ingredients have not been dealt with in this study, but include such topics as soil moisture, surface runoff, infiltration rate, topographic relief and land use.

Regarding the significance of this severe weather event for future operational purposes, near real time radar and total lightning data with a high temporal and spatial resolution were shown to be essential for nowcasting convective hazards, especially 5-minute radar-based QPE in case of a prevailing large-scale weather pattern allowing the occurrence of convective storms with flood potential. Additionally, storm cloud merging seems to be a fundamental process, which a forecaster on duty should be aware of. However, further research is needed to find out which atmospheric conditions favour the merging of convective cells and subsequent storm intensification.

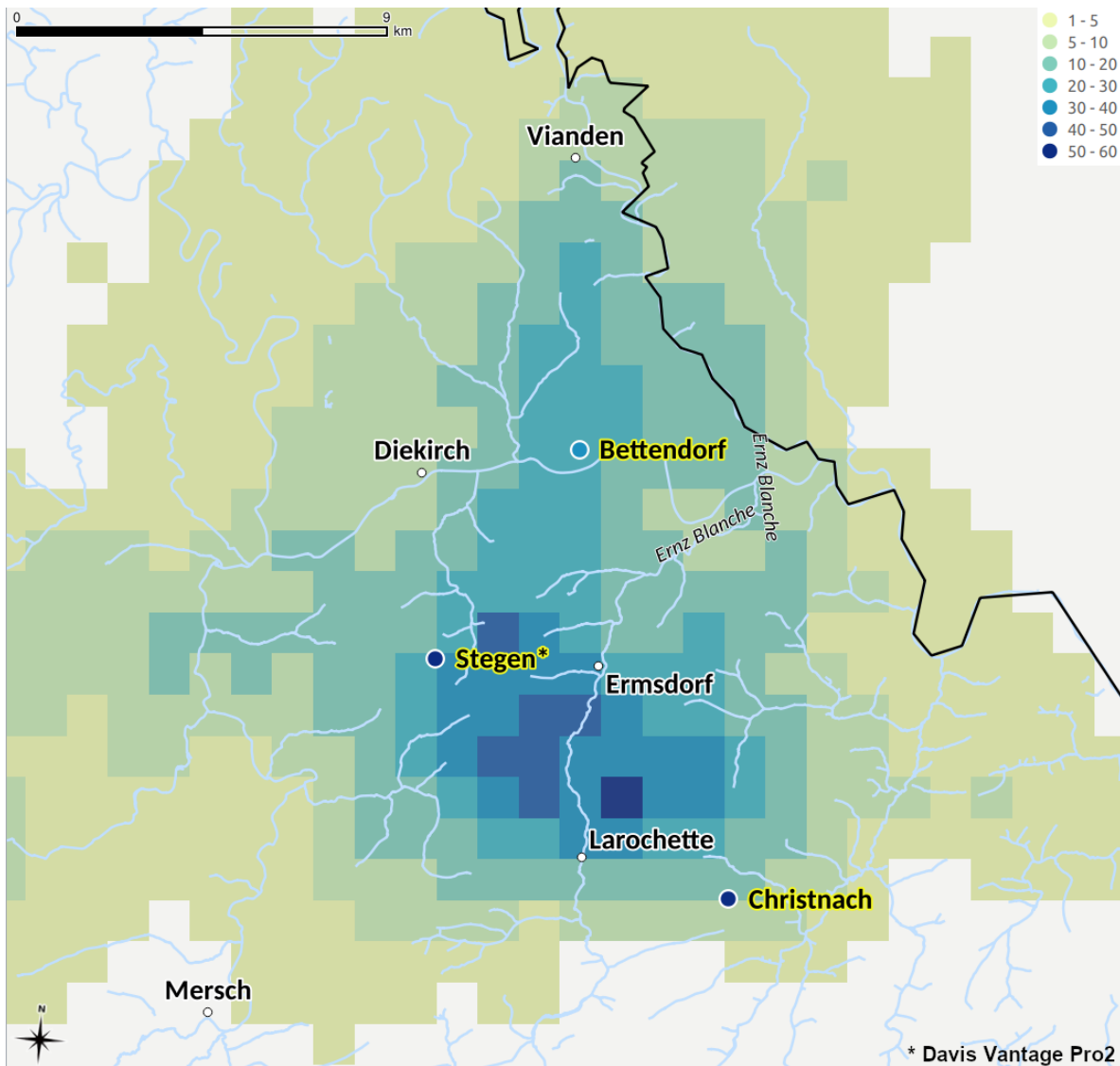


Figure 8: Accumulated precipitation between 1750 and 1850 UTC on 22 July 2016 in the study area, derived by RADOLAN (shaded; mm) and measured by surface weather stations (towns with yellow text buffer; Bettendorf: 39.6 mm, Christnach: 53.1 mm, Stegen: 59.6 mm).

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Appendix: Media Reports

Luxemburger Wort

- <http://www.wort.lu/de/lokales/ermsdorf-so-etwas-habe-ich-noch-nicht-gesehen-57935111ac730ff4e7f63f0e>
- <http://www.wort.lu/de/lokales/ermsdorf-am-tag-1-nach-der-flut-et-wor-wei-eeen-tsunami-5793aee9ac730ff4e7f63f5e>
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