Center for Disaster Management and Risk Reduction Technology

CEDIM Forensic Disaster Analysis Group (FDA)

Winter storm series: Ylenia, Zeynep, Antonia (int: Dudley, Eunice, Franklin) February 2022 (NW & Central Europe)

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SUMMARY

Event	Begin	End	Duration
Series of Winter Storms	**Feb 16 2022**	**Feb 21 2022**	**7 days**

Outstanding events and measurements:

Extreme wind gusts	161.6 kph Lighthouse Alte Weser (DE)
Extreme wind gusts	196 kph, Isle of Wight (UK), possibly new England record
~ 10 fatalities	Northwestern and central Europe
Insured losses >1 billion €	Northwestern and central Europe

Figure 1: Satellite image, Feb 18 2022 (TERRA and AQUA VIS; Source: https://www.dlr.de/eoc/).

1. Summary

Over a period of about a week, a series of powerful low-pressure systems swept across northwestern Europe and northern Central Europe. The wind fields of the very intense low pressure systems particularly affected the south of Ireland and England, northern Belgium, the Netherlands, the northern half of Germany, and the southwestern Baltic Sea region. Gale-force winds were recorded in many places, and even inland the wind reached speeds of more than 118 kph in places. The Needles station on the Isle of Wight possibly set a new wind speed record for England with as much as 196 kph. These extraordinary wind speeds were most likely caused by a so-called sting jet. New peak wind speeds for the month of February were also recorded at some stations in Germany. Hundreds of thousands of people were affected by power outages, and there were also considerable restrictions, particularly on rail services, which were completely shut down in some regions. Hamburg recorded a very severe storm surge for the first time since 2013, with water levels exceeding 3.5 meters above mean high tide. The hurricane-force low pressure systems claimed several lives and caused major property damage, which initial estimates put at more than 1 billion euros for Germany alone.

2. Meteorological Information

2.1. Large scale pressure pattern over the Atlantic Ocean and Europe

The conditions for the formation of intense low pressure areas were created by a well-established frontal zone, which had an impressive appearance in the middle of February 2022. The 6-day average of the 500-hPa geopotential height shows a well-bundled, nearly smooth and largely zonally oriented frontal zone directed from North America across the entire North Atlantic towards northwestern Europe (Figure 2 left). In terms of long-term averages (1991-2020), this results in a vast area of negative geopotential anomalies extending from eastern Canada through southern Greenland, Scotland, and Scandinavia. Over the northern North Sea, the anomalies are more than 24 gpdam below their long-term comparative values. In contrast, an area of higher geopotential than average extends from the east coast of the USA across Bermuda and the Azores towards Spain and the western Mediterranean (Figure 2 right), with values about 10 gpdam above normal.

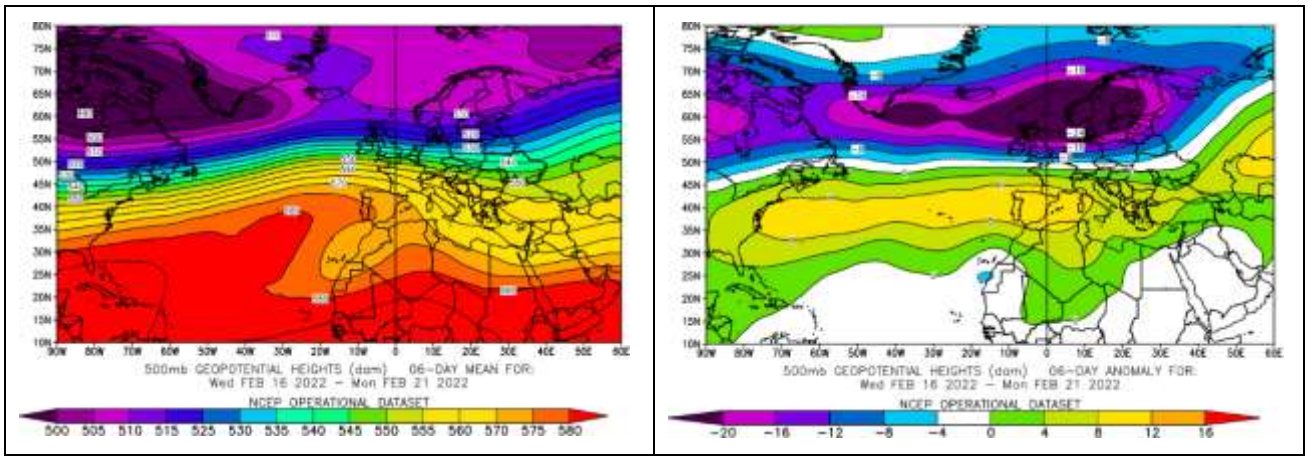


Figure 2: 500 hPa geopotential height (gpdam), left, and deviation from long term mean (1991-2020), right. 6 day-mean Feb 16-21 2022 (Data source: https://psl.noaa.gov).

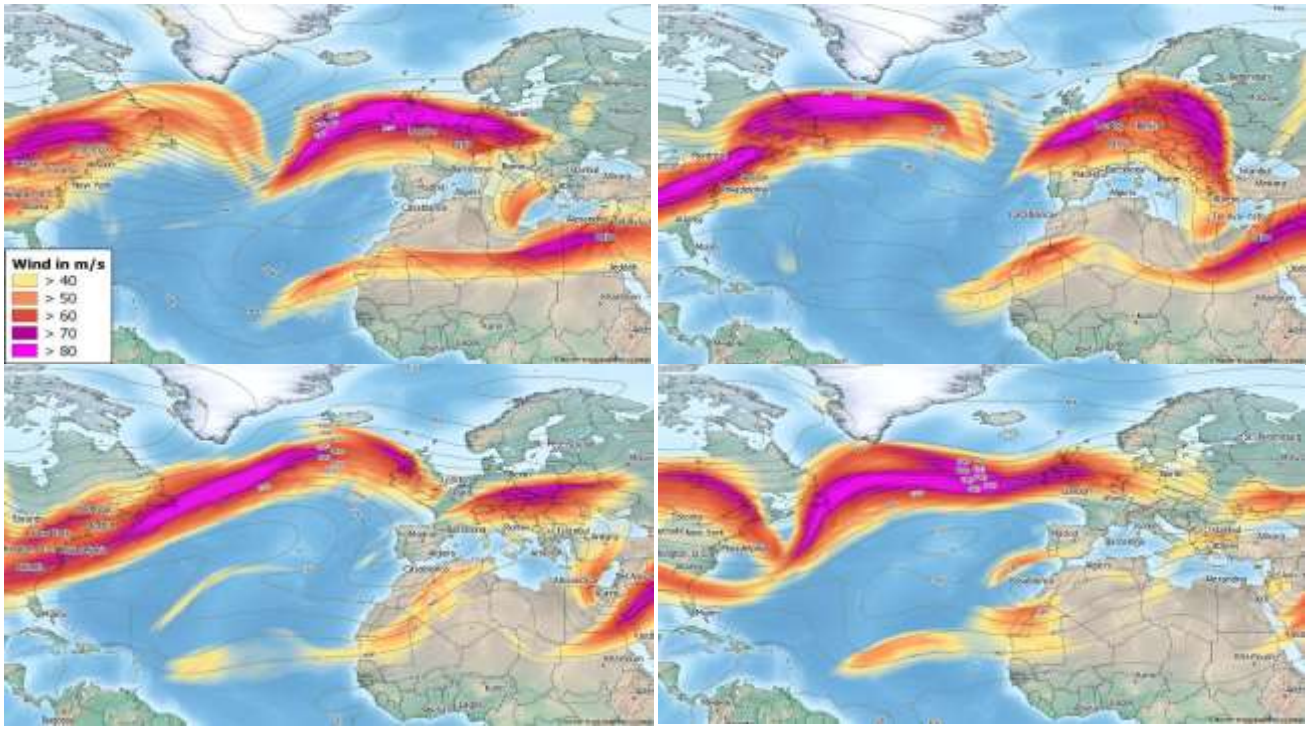


Figure 3: Analysis 300-hPa geopotential height (gpdam) and wind speed (m/s). Feb 17 2022, 12Z (upper left), Feb 18 2022, 12Z (upper right), Feb 19 2022, 12Z (bottom left), Feb 20 2022, 12Z (bottom right; Data: GEM).

A well-developed frontal zone is always characterized by high wind speeds in the upper troposphere, which become apparent, for example, in the 300 hPa level. The jet stream runs as a narrow, elongated and almost straight band of extreme wind speeds over the North Atlantic and extending towards Western Europe. While it sometimes meanders with considerable wave amplitude, the strong winds over the North Atlantic and Europe are recurrent during this period (Figure 3). It is not uncommon for wind speeds to exceed 300 kph at an altitude of about 9 kilometers and they can also be encountered over Central Europe on February 17 and 18, 2022, for example. Further explanations on this jet behavior can be found in section 3.1.

In the area of the frontal zone, a powerful cyclogenesis began, and culminated in several intense storms and hurricane-force depressions between 16 and 21 February 2022. Figure 4 provides information about the storm fields that formed with the low-pressure systems. It shows analyses of wind patterns at the 850 hPa level at four different times. On February 18, 2022, 12Z, the strongest wind speeds occurred at the southern edge of the low pressure area "Zeynep" (Figure 4, top left). Maximum wind speeds ranged from 150 to 200 kph over the southwestern and southern portions of England, in the vicinity of the English Channel, and over the southwestern North Sea. 12 hours later, the center of the low pressure system "Zeynep" had already shifted to the Kattegat. On its southern flank, the storm field covered areas from the Netherlands to northern Germany and the southwestern Baltic Sea with wind speeds remaining nearly unchanged (Figure 4, top right). With "Zeynep," the highest wind speeds were measured in England and northern Central Europe. In the wake of the southeastward propagating cold front, extreme wind gusts prevailed in very unstable stratified cold air in the vicinity of strong showers and also became prevalent near the ground. Wind gusts with wind speeds of more than 100 kph occurred almost everywhere in the northern two thirds of Germany during the night 18/19 February 2022. In England – subject to final confirmation – a new wind speed record of 196 kph could be set at the Needles station on the Isle of Wight on February 18, 2022. A so-called sting jet might have enhanced the wind speed at the surface in this region (see also Section 2.2.1.). A sting jet is an airstream originating from mid-levels within the

cloud head and descending to the boundary layer into the frontal-fracture region of a Shapiro-Keyser cyclone (Clark and Gray, 2018). From there, turbulence can bring the high momentum down to the surface.

The hurricane-force low pressure system "Zeynep", which is internationally known as "Eunice", appears as an impressive cloud vortex on satellite images (Figure 1). Around noon on February 18, 2022, the center of "Zeynep" lies over the east and southeast of England, the cloud spiral covers nearly entire Great Britain and parts of Central Europe, the elongated cold front runs over the Bay of Biscay and Galicia several thousand kilometers across the North Atlantic towards the southwest.

The analysis of surface pressure fields and station recordings on 18 February 2022, 00Z and 12Z, is shown in Figure 5. At midnight, the center of the low "Zeynep" (int: "Eunice") with a core pressure below 980 hPa is located about 300 kilometers southwest of Ireland (Figure 5, top). Surface fronts show a frontal fracture typical for a Shapiro-Keyser cyclone. 6 hours later, the center of the depression with less than 975 hPa could already be analyzed over Ireland (not shown), and by 12Z "Zeynep" had rapidly moved on to the western North Sea (Figure 5 bottom). In particular, an extreme air pressure gradient on the southern flank of the depression resulted in wind speeds of up to nearly 200 kph in the vicinity of the English Channel. With the passage of the cold front of "Zeynep", wind speeds of more than 100 kph were also measured in Central Europe on the evening of 18 February 2022 and in the night of 19 February 2022.

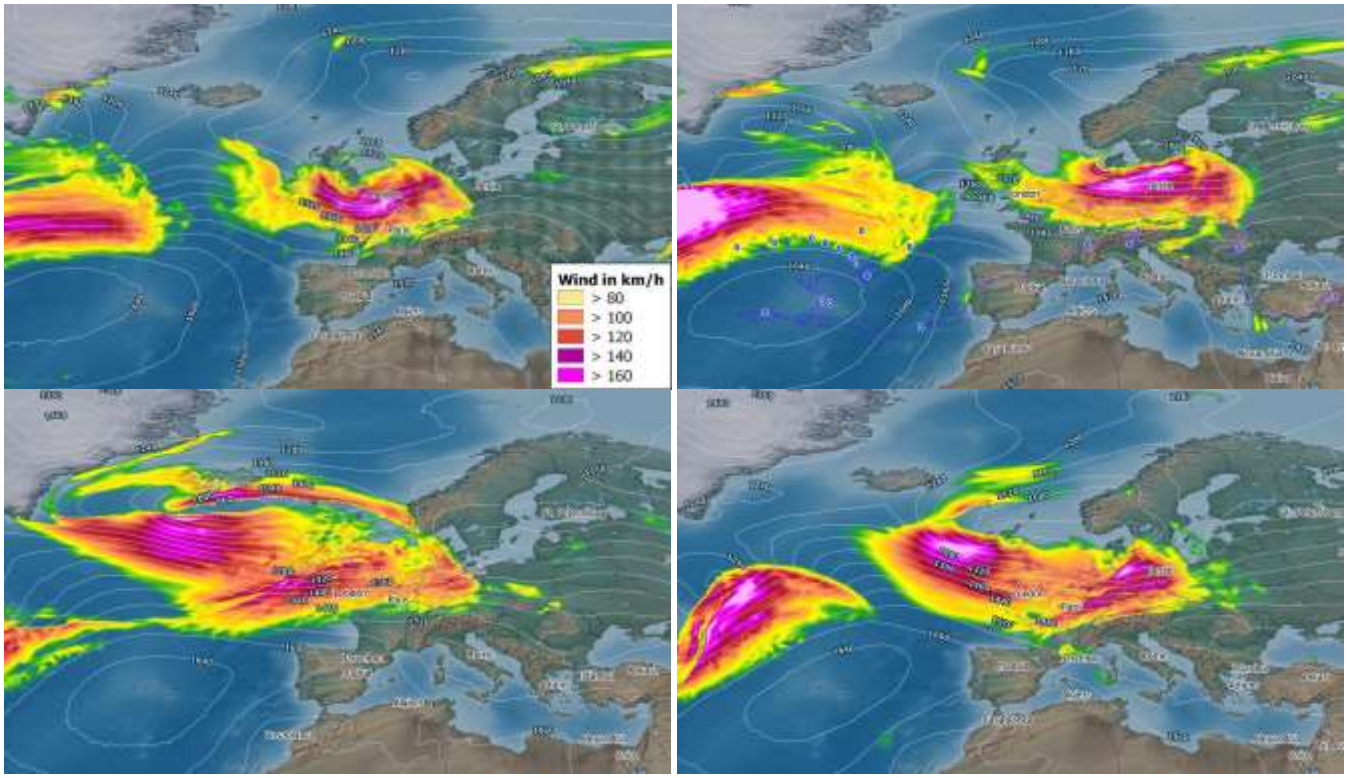
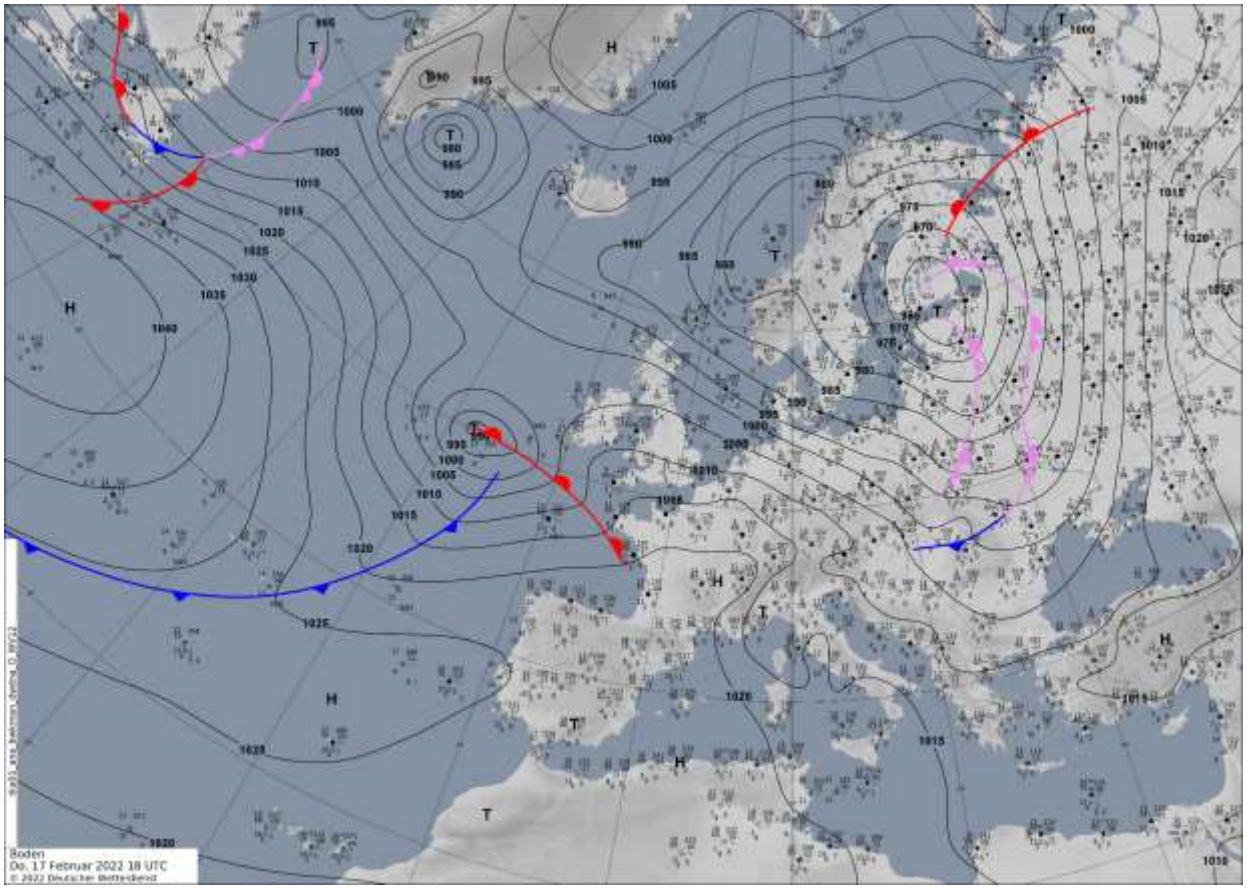


Figure 4: Analysis 850-hPa geopotential height (gpdam) and wind speed (m/s). Feb 18 2022, 12Z (upper left), Feb 19 2022, 00Z (upper right), Feb 20 2022, 12Z (bottom left), Feb 21 2022, 00Z (bottom right; Data: GEM).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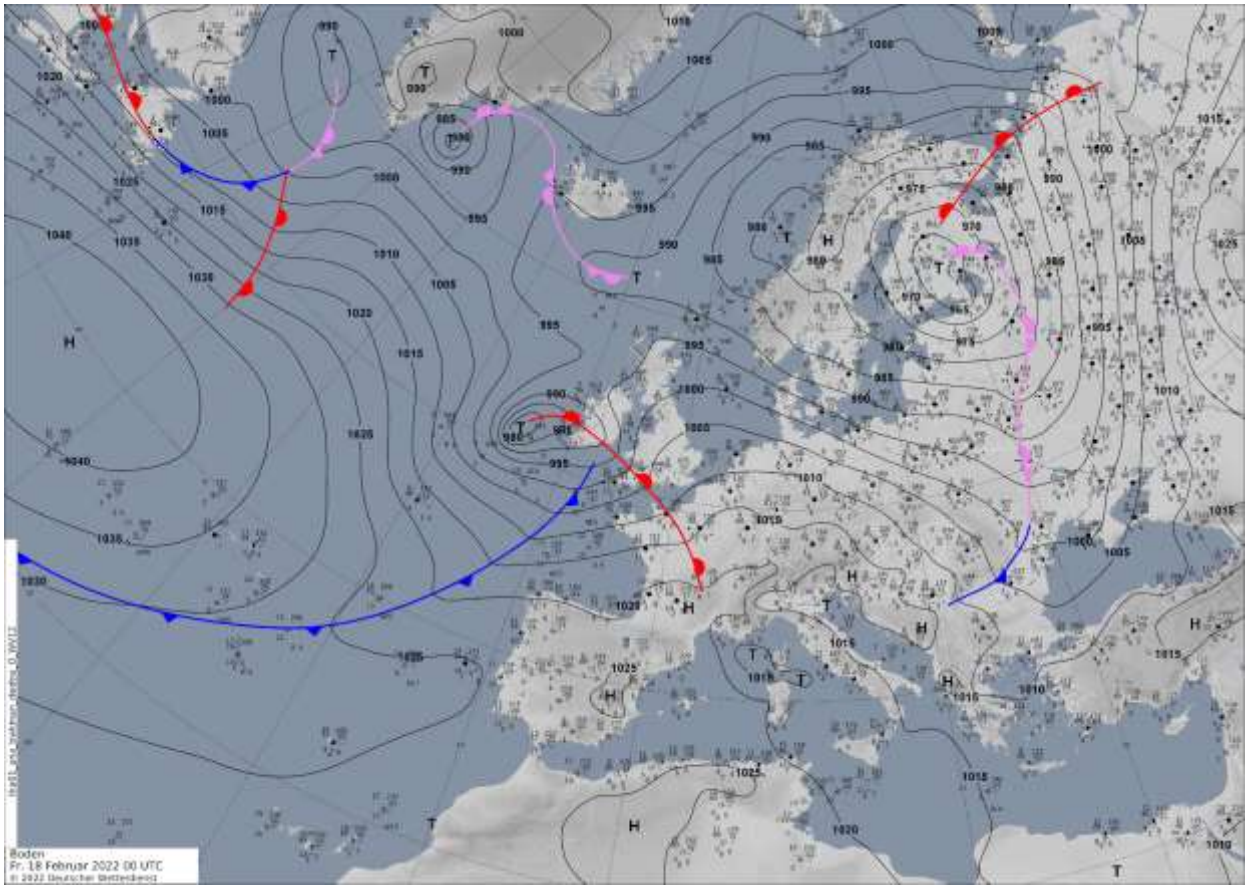
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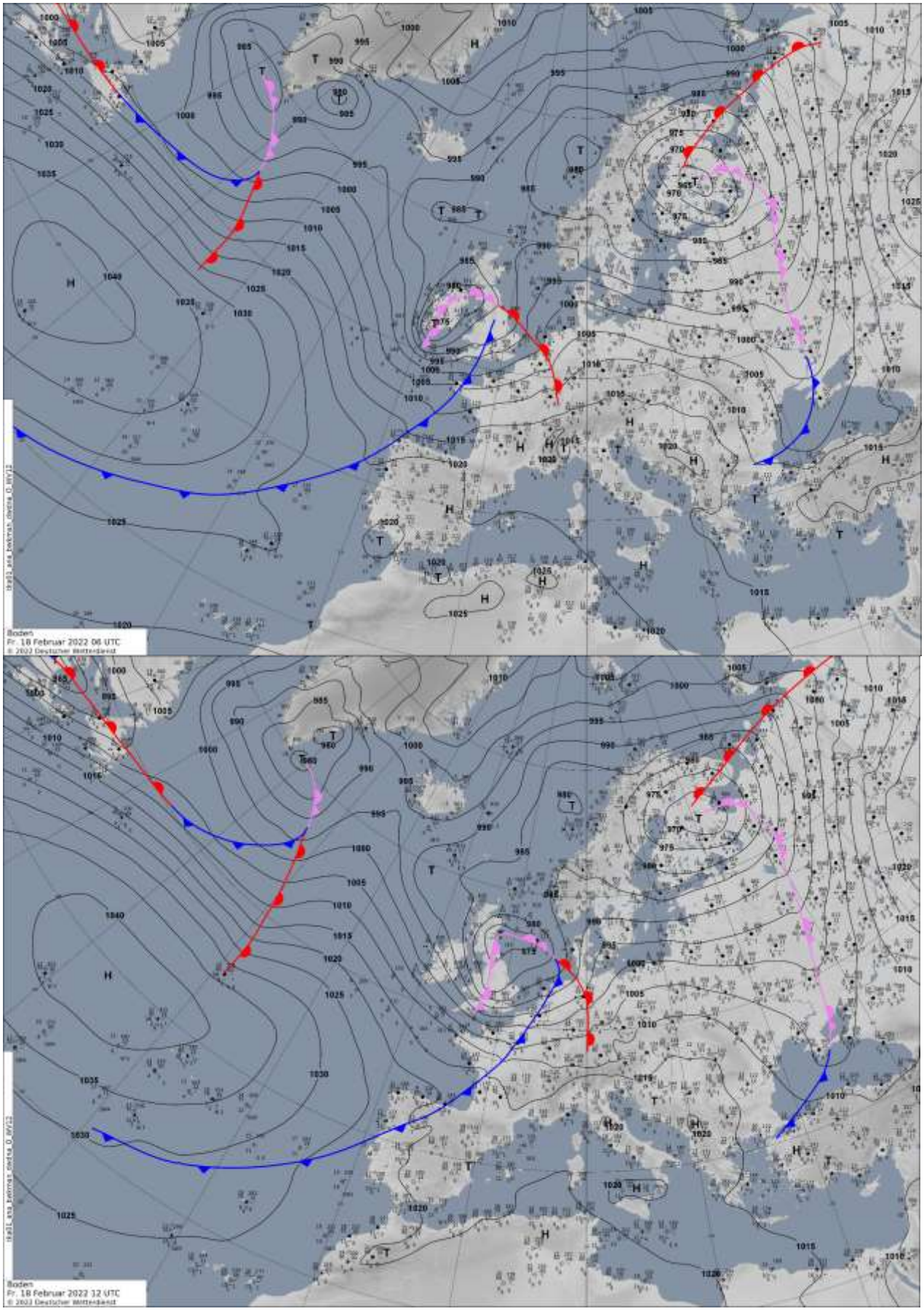
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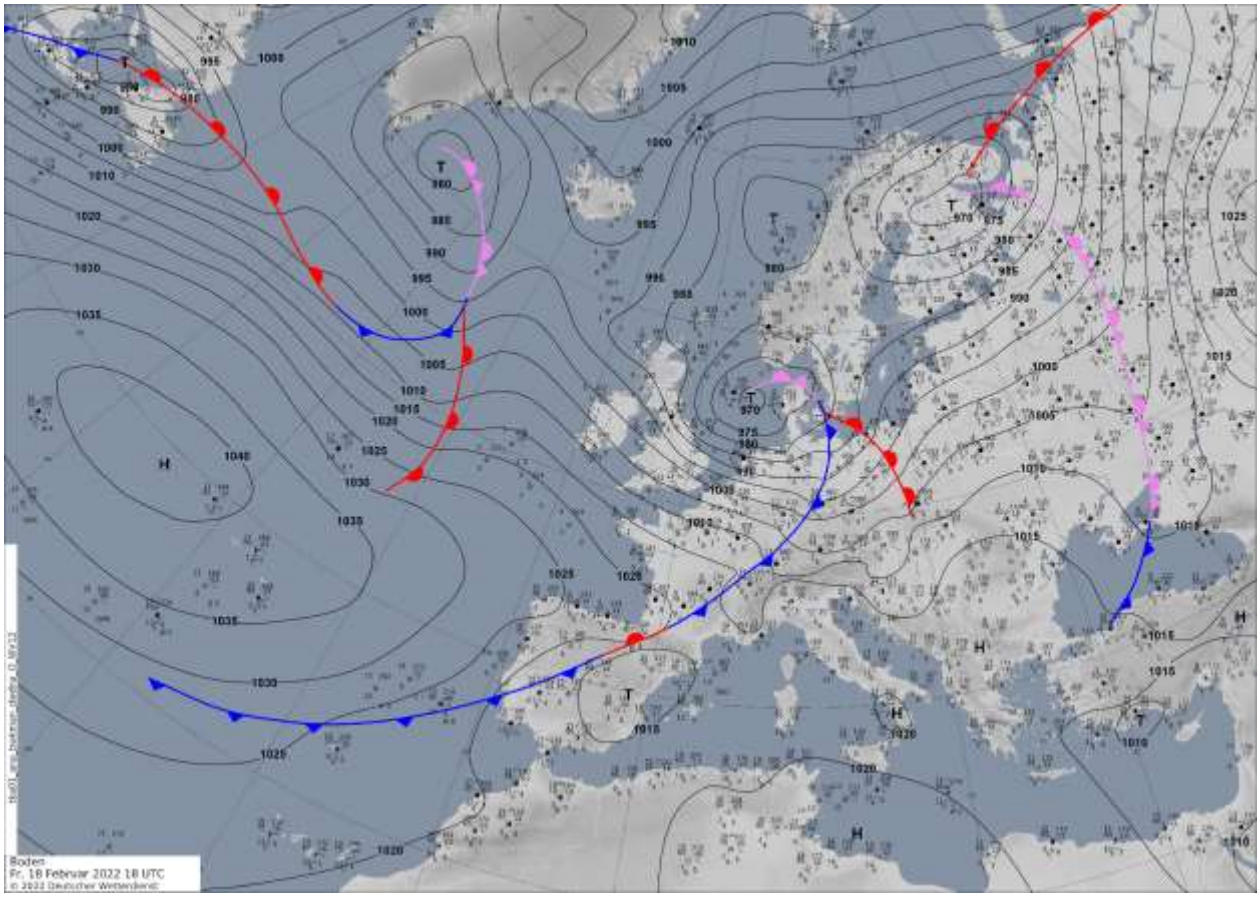

Figure 5: Surface pressure analysis, fronts and station recordings. From top to bottom: Feb 17 2022, 18Z, Feb 18 2022, 00Z, Feb 18 2022, 06Z, Feb 18 2022, 12Z, Feb 18 2022, 18Z Source: DWD).

2.2. Measurements of wind, temperature, and precipitation

2.2.1. Wind in Europe

The intense large-scale dynamics in the weather processes over the North Atlantic, as well as across northwestern and Central Europe is reflected in particular in the wind speeds. Figures 6a-c show the maximum wind speeds (gusts) as they occurred on the respective days in the period 15-20 February 2022. For Germany, data of the observational network of the German Weather Service are available, the other values are based on METAR data.

The 15 and 16 February 2022 were already windy in northern Central Europe (Figure 6a) with gusts often reaching gale force. On February 17, 2022, low pressure system "Ylenia" unleashed its strength mainly over Germany, when wind gusts of up to 100 kph occurred almost all over the country, even around 150 kph on the North Sea coast and in the mountains (Figure 6b above). And while "Ylenia" shifted its center far to the east to the Gulf of Finland until 17 February 2022, 18Z, low pressure system "Zeynep" (int: "Eunice") came closer to European waters. Gale-force winds of up to 140 kph occurred along the coasts of England and Wales, and near hurricane-force gusts of 113 kph were also recorded in London during the afternoon. The highest wind speed of the entire storm series, 196 kph, was recorded at Needles on the Isle of Wight, an island off the south coast of England. On the French side of the English Channel, the highest wind speeds were recorded at Boulogne, with 152 kph. In the afternoon, the hurricane force winds affected the Benelux countries. In Amsterdam, peak gusts of 126 kph occurred, in Vlissingen 137 kph (Figure 6b bottom).

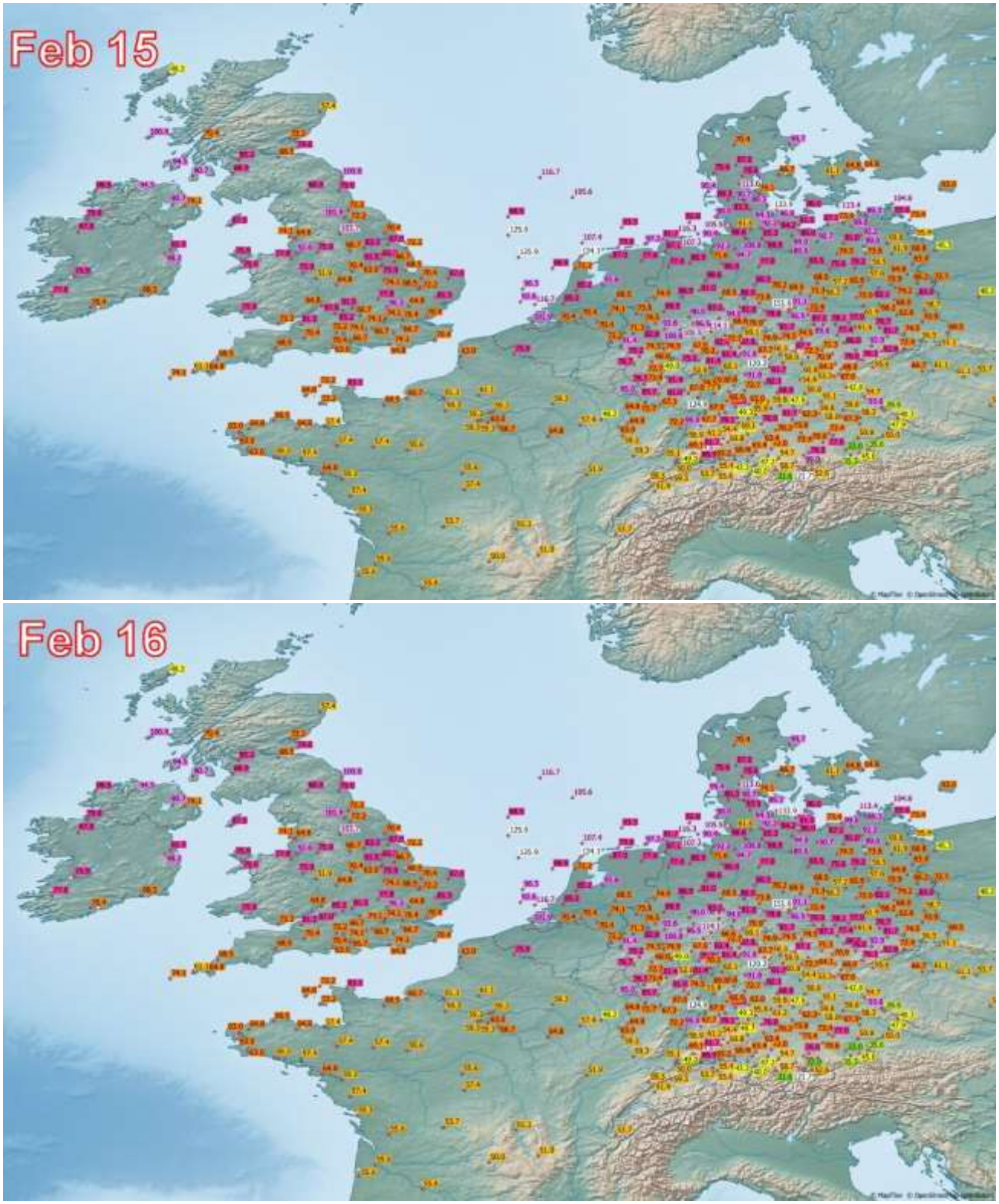

Figure 6a: Maximum wind gusts (German weather station network of DWD and METARS), Feb 15 2022 (top) and Feb 16 2022 (bottom; Data source: DWD and http://www.mesonet.agron.iastate.edu).

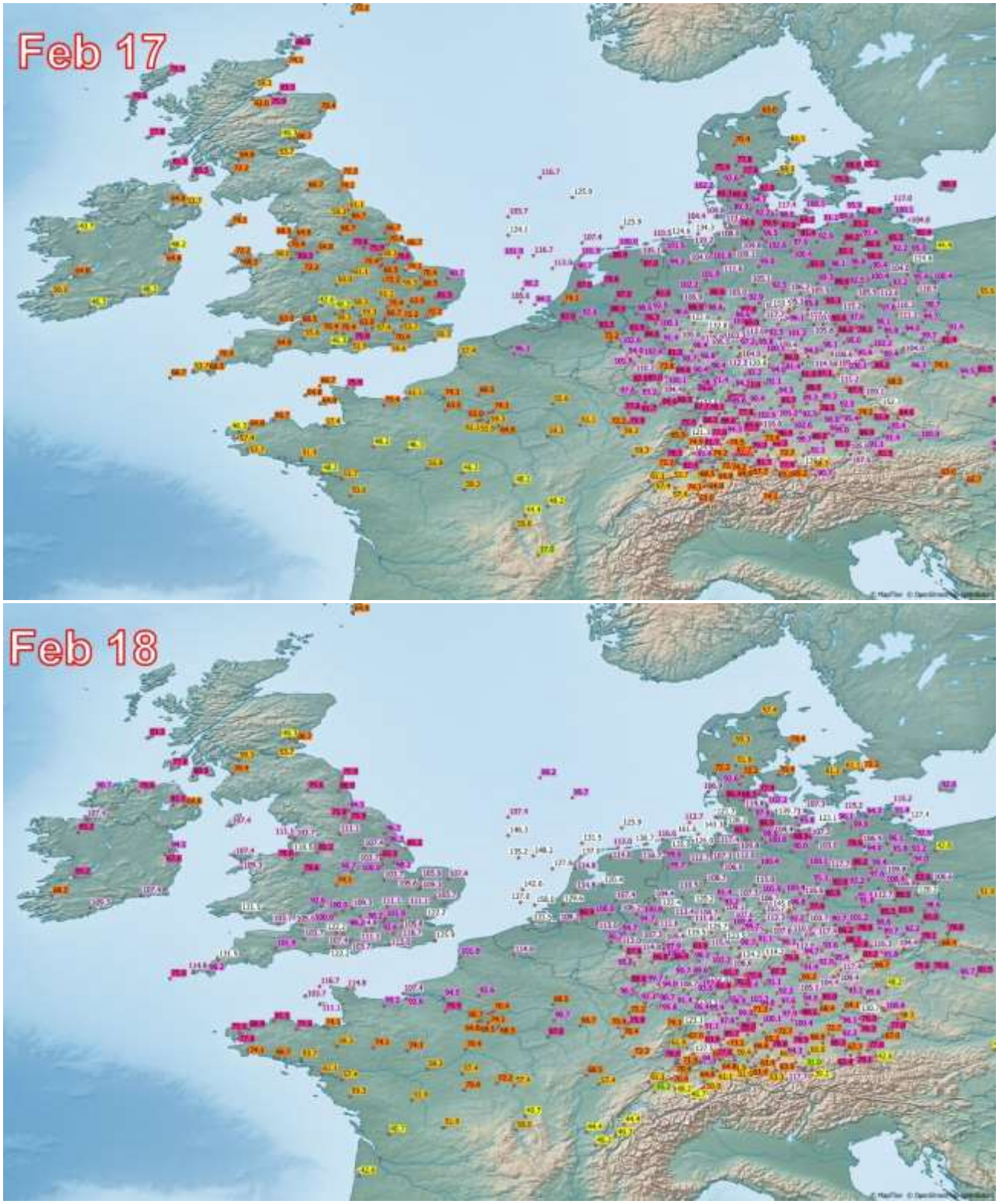

Figure 6b: Maximum wind gusts (German weather station network of DWD and METARS), Feb 17 2022 (top) and Feb 18 2022 (bottom; Data source: DWD and http://www.mesonet.agron.iastate.edu).

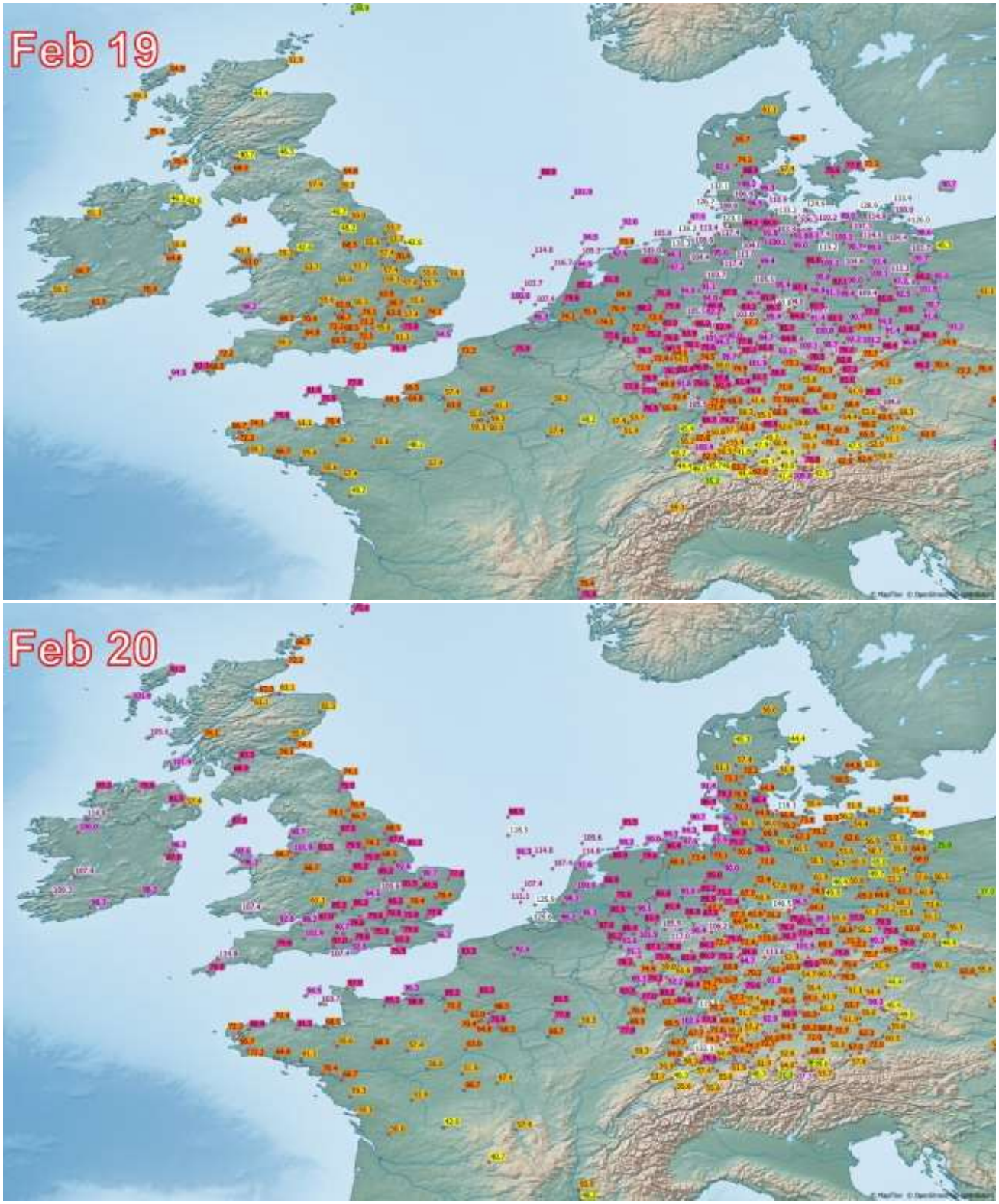

Figure 6c: Maximum wind gusts (German weather station network of DWD and METARS), Feb 19 2022 (top) and Feb 20 2022 (bottom; Data source: DWD and http://www.mesonet.agron.iastate.edu).

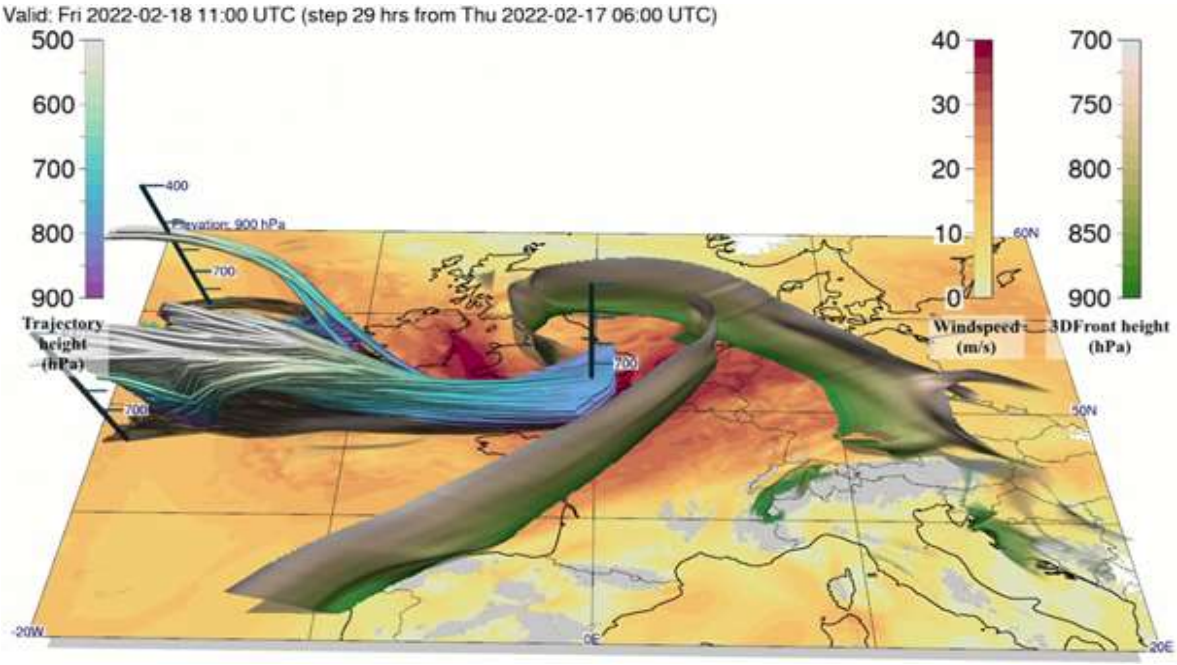

Figure 7: Wind speed at 850 hPa, 3D frontal structure and Lagrangian trajectories satisfying sting-jet criteria (200 hPa descent and wind speed above 35 ms-1) at 11Z on February 18, 2022. Data: ICON-LAM simulation (init: 06Z on February 17, 2022; Image produced by Andreas Beckert using Met.3D, met3d.wavestoweather.de).

ICON simulations run in limited area mode (ICON-LAM) allow the calculation of Lagrangian backwards trajectories analogous to Eisenstein et al. (2020). The output shows a large number of trajectories descending more than 200 hPa in 7 hours to the boundary layer and accelerating, hence confirming the presence of a sting jet between 05Z to 13Z on February 18, 2022 (see Figure 7 for 11Z). The descent happens on surfaces of constant wet-bulb potential temperature and shows drying when leaving the cloud head as seen in most sting-jet cases (not shown). The location of the trajectories coincide, among others, with the peak gust at the Needles suggesting an enhancement of surface gusts in that region. However, if and when the sting jet reached the surface cannot be certain on the basis of trajectories alone.

2.2.2. Wind speed in Germany

In Germany, gale-force winds and, in some cases, hurricane-force winds were recorded on all days during the period February 16 to 21, 2022. Even February 15, 2022, brought gale-force winds already, exceeding 150 kph on top of the Brocken mountain and near the sea. Table 1 provides information about the measured wind speeds at all stations in Germany where wind gusts reached hurricane force (118 kph). On February 17, 2022, it was the low pressure system "Ylenia" that was responsible for gale-force winds in many places; the front-runner was the Großer Arber in the Bavarian Forest with gusts of 152.3 kph. The storm field of depression "Zeynep" hit Germany in the afternoon of 18 February 2022 and was coupled to the cold front of the depression. The frontal passage produced gale-force winds in the lowlands and inland areas. Around 14Z, the station at Geilenkirchen in North Rhine-Westphalia put a first exclamation mark with 122 kph. A little later, 122 kph was also measured at the airport in Frankfurt/Main. A very unstable stratified air mass followed the cold front, allowing for further strong wind gusts during the night of February 19, 2022. The storm field covered most of Germany north of the Main River. In Germany, the highest wind speed of the entire storm was recorded at the station Leuchtturm Alte Weser with 163 kph, in Büsum it was 143 kph, in Bremerhaven 126 kph and in Schwerin 119 kph.

Table 1: List of stations with wind gusts exceeding 118 kph during the period Feb 16-20 2022 (Data source: DWD).

Station	msl	State	Lat	Lon	Max Gust	Days with gusts exceeding Bft 12 (118 kph)					
					kph	16.02.	17.02.	18.02.	19.02.	20.02.	21.02.
Leuchtturm_Alte_Weser	32	NI	53.86	8.13	**161.6**		134.3	161.6	138.2		119.9
Großer_Arber	1436	BY	49.11	13.13	**152.3**		152.3	130.7			
Brocken	1134	ST	51.80	10.62	**151.6**	151.6	150.5	145.8	140.8	146.5	145.1
Feldberg/Schwarzwald	1490	BW	47.88	8.00	**149.0**	124.6	124.6	137.5		132.1	149.0
Büsum	3	SH	54.12	8.86	**143.3**			143.3	123.1		
Leuchtturm_Kiel	31	SH	54.50	10.27	**139.7**	133.9		139.7	133.2	118.1	
Weinbiet	553	RP	49.38	8.12	**139.3**	124.9	132.5	139.3		119.5	135.0
Spiekeroog(SWN)	14	NI	53.77	7.67	**135.0**		124.6	135.0	130.3		
Arkona	42	MV	54.68	13.43	**133.9**				133.9		
Kahler_Asten	839	NW	51.18	8.49	**132.8**		132.8	126.7			
List_auf_Sylt	25	SH	55.01	8.41	**132.1**				132.1		
Borkum-Süderstraße	12	NI	53.58	6.67	**130.7**			130.7			
Hohenpeißenberg	977	BY	47.80	11.01	**130.0**		130.0				
Darßer_Ort(SWN)	4	MV	54.47	12.50	**128.9**				128.9		
Elpersbüttel	3	SH	54.07	9.01	**128.2**			128.2			
Greifswalder_Oie	12	MV	54.24	13.91	**127.4**			127.4	126.0		
Zugspitze	2965	BY	47.42	10.99	**127.4**	121.7					127.4
Hallig_Hooge	4	SH	54.57	8.51	**126.7**				126.7		
Wasserkuppe	921	HE	50.50	9.94	**126.4**	120.2	120.6	119.2			126.4
Bremerhaven	7	HB	53.53	8.58	**126.0**			126.0			
Angermünde	54	BB	53.03	13.99	**124.6**		124.6				
Fehmarn	3	SH	54.53	11.06	**124.6**				124.6		
Lautertal-Hörgenau	522	HE	50.58	9.29	**124.2**			124.2			
Hornisgrinde	1138	BW	48.61	8.20	**124.2**		121.3	123.1			124.2
Frankenberg-Geismar	392	HE	51.08	8.88	**123.5**			123.5			
Bastorf-Kägsdorf(SWN)	51	MV	54.13	11.67	**123.1**			123.1			
Arnsberg-Müschede	278	NW	51.41	8.01	**122.8**		122.8				
Münster/Osnabrück	48	NW	52.13	7.70	**122.4**			122.4			
Frankfurt/Main	100	HE	50.03	8.52	**122.0**			122.0			
Sankt_Peter-Ording	5	SH	54.33	8.60	**121.7**			121.7			
Gütersloh/Ems	70	NW	51.93	8.31	**120.2**			120.2			
Lindenberg	98	BB	52.21	14.12	**120.2**			120.2			
Birkelbach	541	NW	51.01	8.27	**119.5**			119.5			
Schwerin	59	MV	53.64	11.39	**119.2**				119.2		

Table 2: List of stations in Germany which set new records in wind speed for February (Data source: DWD).

Station	msl	State	Lat	Lon	Date			Max Gust		Years of recording
Berlin_Brandenburg	46	BB	52.38	13.53	18	2	2022	106.9	kph	49
Berlin_Brandenburg	46	BB	52.38	13.53	19	2	2022	106.9	kph	49
Lindenberg	98	BB	52.21	14.12	18	2	2022	120.2	kph	48
Angermünde	54	BB	53.03	13.99	17	2	2022	124.6	kph	44
Leinefelde	356	TH	51.39	10.31	18	2	2022	107.6	kph	43
Hallig_Hooge	4	SH	54.57	8.51	19	2	2022	126.7	kph	43
Harzgerode	404	ST	51.65	11.14	19	2	2022	108.7	kph	41
Cottbus	69	BB	51.78	14.32	18	2	2022	98.6	kph	39
Münster/Osnabrück	48	NW	52.13	7.70	18	2	2022	122.4	kph	33
Roth_bei_Prüm	593	RP	50.31	6.39	17	2	2022	101.9	kph	31

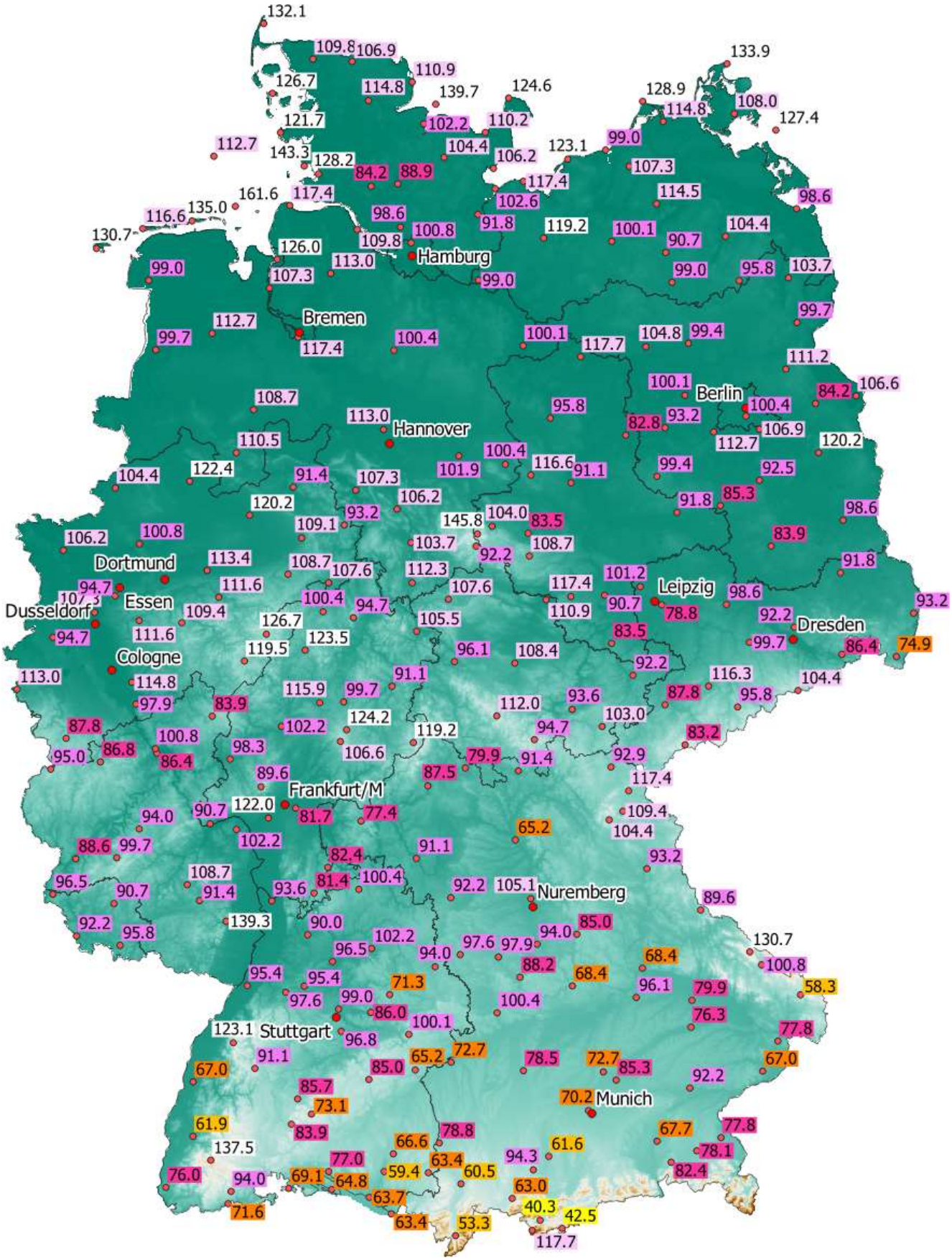

Figure 8: Maximum wind gusts in Germany, winter storm „Zeynep“, Feb 18-19 2022 (Data source: Weather station network of DWD).

Figure 8 illustrates the intensity of winter storm "Zeynep" based on the maximum wind speeds on February 18/19, 2022 in Germany. Almost everywhere, severe gale-force winds or hurricane-force gusts were on the agenda, with weaker winds only south of the Danube.

According to own analyses, some stations in Germany set new records for maximum wind speeds in February. Table 2 lists some stations where it has never been as windy as before on a day in February.

2.2.3. Temperature and precipitation in Germany

The most serious consequences and most damaging effects were mostly caused by extreme wind speeds. However, temperatures and precipitation also reached considerable levels and values in many places – and even new records for February were set.

The powerful storm depressions reached far south with their circulation and carried very warm and moist air masses of subtropical origin towards the northeast. Figure 9 shows the moisture fields at the 700 hPa level as they are streakily transported northeastward by the developing low pressure system "Zeynep" on 18 February 2022, 00 UTC. Where extended frontal precipitation areas became almost parallel to the stream flow, they were able to linger for a longer period of time and it rained profusely.

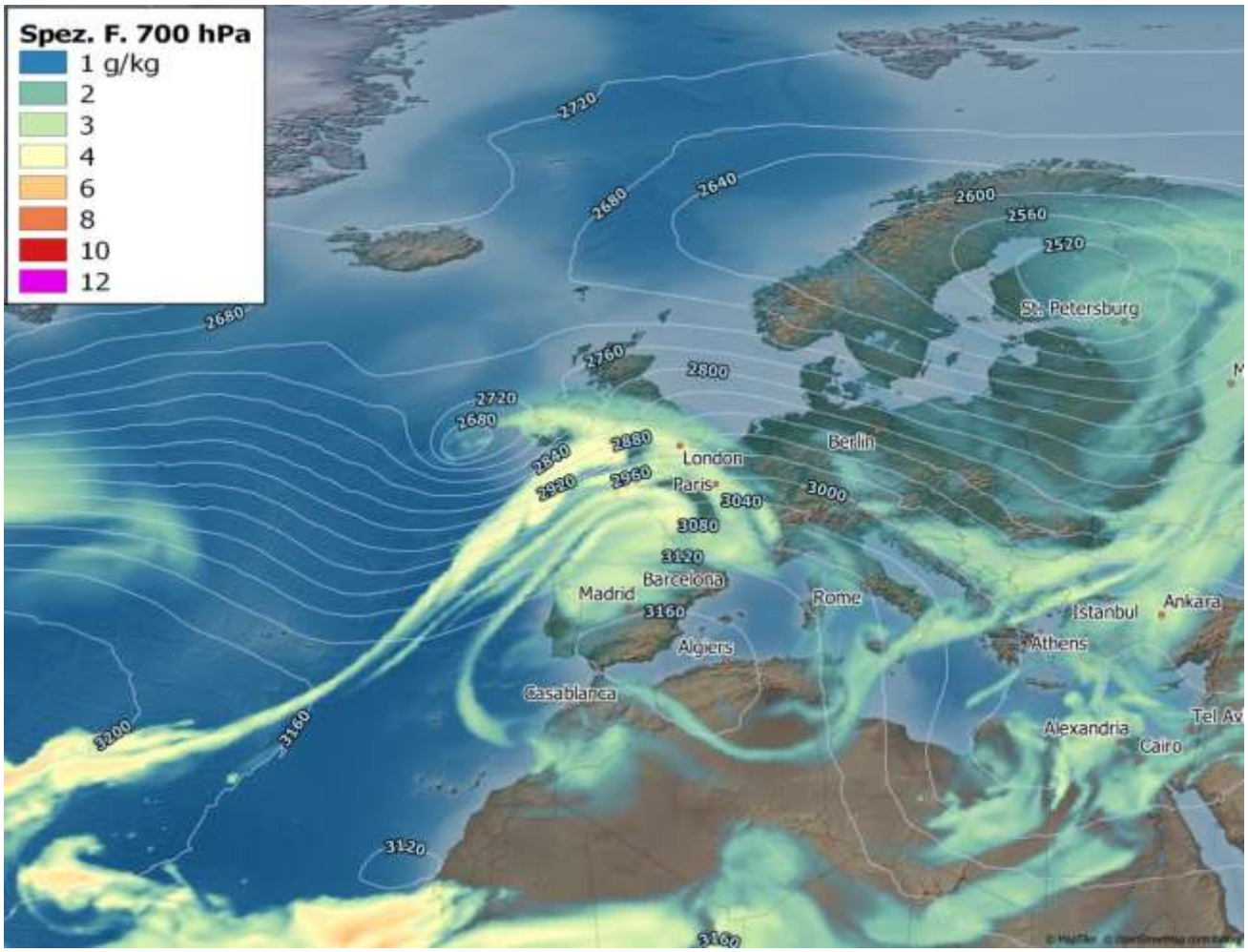

Figure 9: Analysis 700-hPa geopotential height (gpdam) and specific humidity (g/kg) on Feb 18 2022, 00Z (Data: GEM).

The frontal systems and their extensive precipitation areas dumped large amounts of rain and triggered flooding in some areas. Towards the end of the series of storms, for example, low pressure system "Antonia" (int: "Franklin") was responsible for 24-hour rainfall totals of more than 30 mm in England on 19/20 February 2022. Shap in northwest England accumulated 37.8 mm, Capel Curig 36.8 mm, Eskdalemuir in southern Scotland 34 mm, and Lough Fea in Northern Ireland 30.4 mm.

In Germany, too, precipitation added up to enormous amounts over a period of 6 days. Especially in the north and west of the country, more than 50 mm were recorded. In the western uplands, in parts of the Emsland region and in Schleswig-Holstein, more than 100 mm were recorded (Figure 10 left). In many places in the northern half of Germany, the 6-day precipitation already corresponded to the average amount of precipitation for the entire month of February. It was particularly wet from Emsland to the Baltic Sea, and parts of Schleswig-Holstein already received more than twice the usual February precipitation (Figure 10 right).

Table 3 shows a selection of stations from the observational network of the German Weather Service where new records of daily precipitation were set for the month of February. This was especially the case in Schleswig-Holstein, where, for example, the station in Schleswig recorded a 24-hour precipitation amount of 37.9 mm on February 20, 2022, more than on any previous day in February.

Very mild air masses made unusually high temperatures possible in the east and southeast of Germany. New decade records (February 11-20) were recorded here and there. The highest temperature was recorded in Piding in the Berchtesgadener Land county of Bavaria. Table 4 shows some stations in Germany where new records of daily maximum temperature were set.

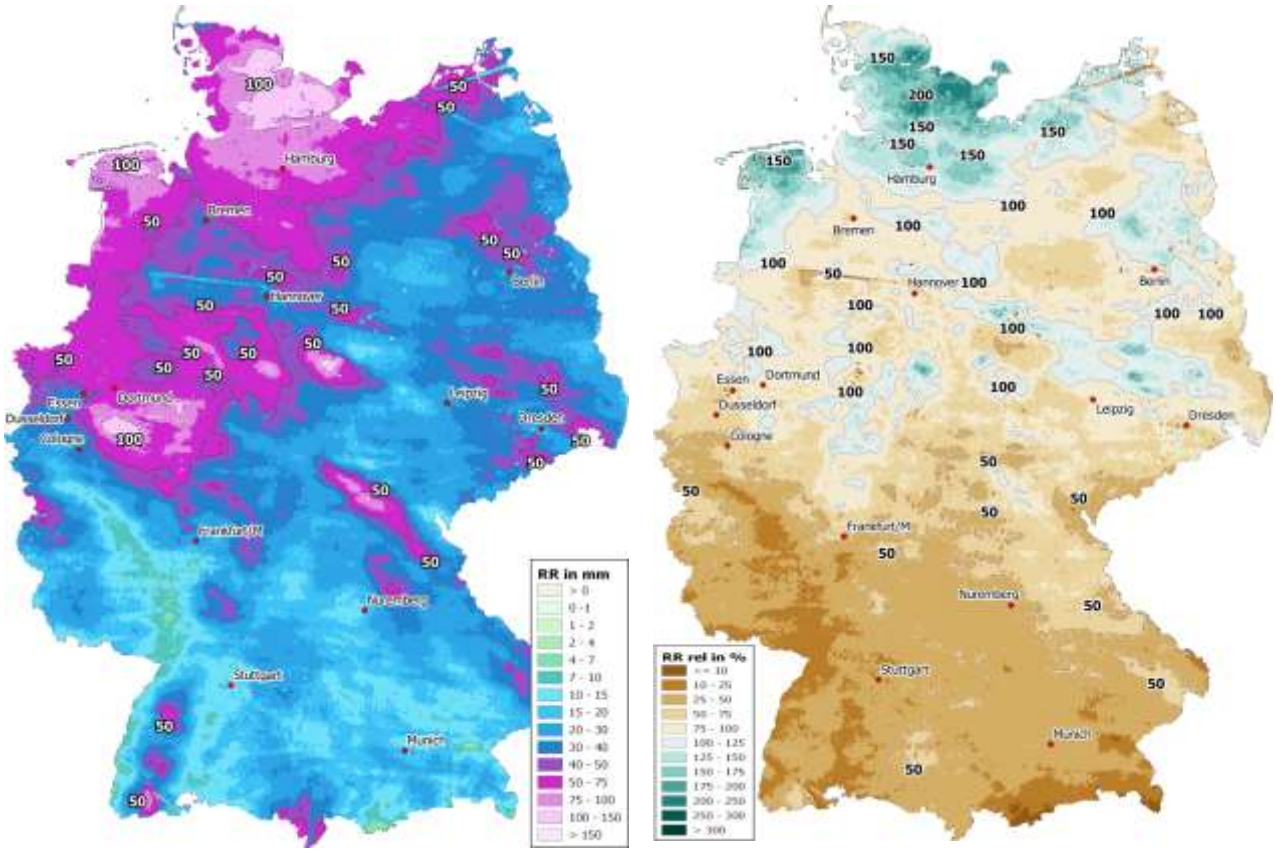

Figure 10: 6 day-accumulated rain amount in Germany, Feb 16 2022, 05:50Z – Feb 22 2022, 05:50Z, in mm. Based on radar data (REGNIE), left. Deviation of 6 day accumulated rain amount from monthly normal 1991 to 2020 in %, right (Data source: DWD).

Table 3: List of stations with new records for 24h-rain amount for February (Data source: DWD).

Station	msl	State	Lat	Lon	Date			RR 24h		Years of recording
Schleswig	43	SH	54.53	9.55	20	2	2022	37.9	mm	76
Dörpen	8	NI	52.95	7.32	20	2	2022	34.6	mm	63
Erfde	18	SH	54.30	9.32	20	2	2022	27.6	mm	58
Leck	7	SH	54.79	8.95	20	2	2022	22.9	mm	48
Wagersrott	40	SH	54.67	9.81	20	2	2022	33.2	mm	47
Hohn	10	SH	54.32	9.54	18	2	2022	28.6	mm	40
Kiel-Holtenau	28	SH	54.38	10.14	16	2	2022	31.9	mm	35
Moringen-Lutterbeck	240	NI	51.72	9.84	16	2	2022	36.5	mm	31
Glücksburg-Meierwik	12	SH	54.83	9.51	20	2	2022	28.0	mm	29
Lüdenscheid	387	NW	51.25	7.64	20	2	2022	42.1	mm	29

Table 4: List of stations with new daily maximum temperature records for the second decade of Februar (11-20; Data source: DWD).

Station	msl	State	Lat	Lon	Date			Tmax		Years of recording
Lichtenhain-Mittelndorf	321	SN	50.94	14.21	17	2	2022	14.4	°C	32
Piding	457	BY	47.77	12.91	17	2	2022	17.0	°C	16
Weidenbach-Weiherschneidbach	455	BY	49.23	10.61	18	2	2022	14.0	°C	23
Donauwörth-Osterweiler	435	BY	48.74	10.74	18	2	2022	14.3	°C	16

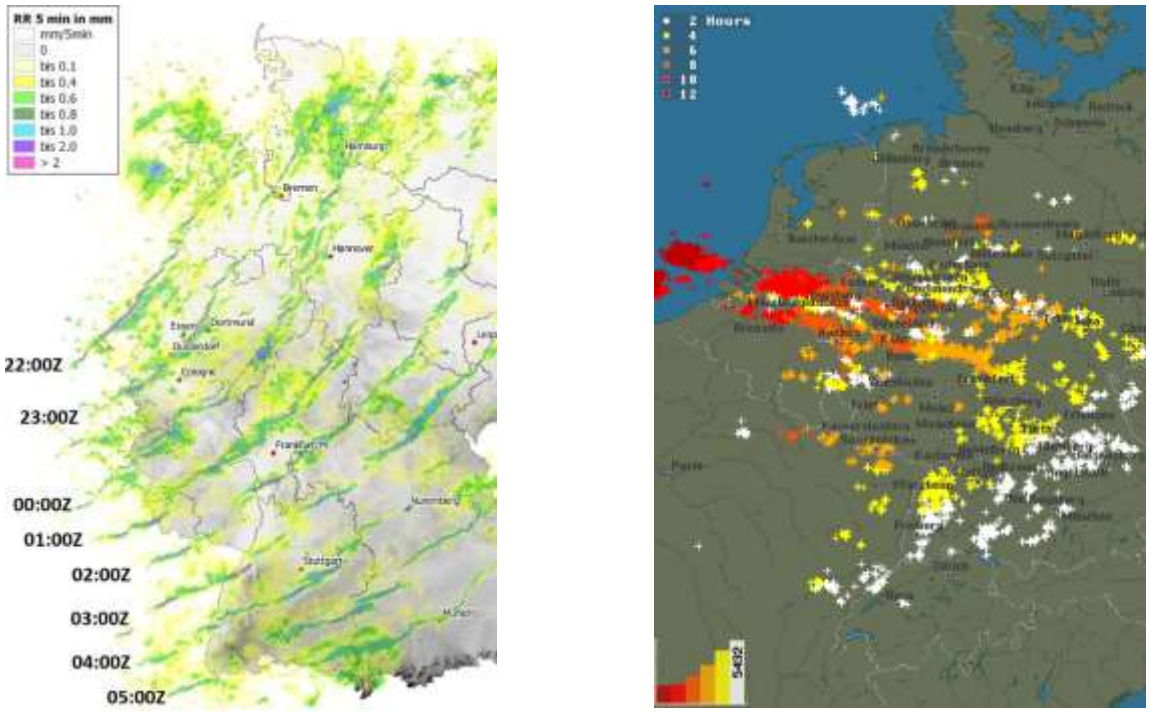

Figure 11: Propagation of the cold front of low pressure system "Antonia" on Feb 20-21 2022 in Germany based on hourly radar information (rain amount per 5 minutes, left). Lightning detection between Feb 20 2022, 18Z, and Feb 21 2022, 06Z (Data sources: DWD, www.blitzortung.org).

2.2.4. Cold front passage of low pressure system “Antonia” in central Europe

With its cold front passage during the night of 20/21 February 2022, the low pressure area "Antonia" brought a spectacular end to the series of storms. Over a period of about 10 hours the cold front made its way across Germany from northwest to southeast as a narrow band of precipitation. The frontal passage was associated with numerous lightning discharges; a total of several thousand lightning strikes could be recorded (Figure 11).

2.2.5. Weather recordings at Karlsruhe

Figure 12 shows the course of temperature, air pressure as well as mean wind and wind peaks at the station of the Institute for Meteorology and Climate Research (IMK-TRO) at an altitude of about 60 meters above ground. The institute is located in Karlsruhe, a city in the middle Upper Rhine region. In the period from February 15 to 22, 2022, the individual low-pressure systems and their passage can be read primarily from the air pressure curve. The low pressure system "Ylenia" became apparent shortly after midnight on February 17, 2022; after a pressure increase of about 15 hPa, the cold front passage of the next low pressure system "Zeynep" followed on the evening of February 18, 2022. And finally, the very well developed cold front of low pressure system "Antonia" passed the weather station shortly after midnight on February 21, 2022. The temperature curve reveals the abrupt air mass changes. On February 18, 2022, subtropical warm air quickly prevailed in the afternoon, and temperatures reached 15 °C. In the evening, the cold front led to a temperature drop of almost 6 K within minutes. Winds briefly reached 32 m/s (115 kph) in gusts. The cold front passage of low pressure "Antonia" was quite similar, with 6 K colder air pushing through within minutes.

3. Historical context and impact

3.1. The February 2022 storms compared with previous storms

The storm series of „Ylenia“, „Zeynep“ and „Antonia” were part of a so-called cyclone family. This denomination was first used by Bjerkness and colleagues (e.g. Bjerknes and Solberg, 1922) who recognized that sequences of cyclones were of great importance for weather prediction. A storm series indicates that multiple and related cyclones affect a particular area within a comparatively short period of time, potentially leading to severe cumulative losses (Mailier et al., 2006). Periods corresponding to important storm series affecting western Europe include late February 1990 (Vivian, Wiebke), Christmas 1999 (Lothar, Martin), and January 2007 (Franz, Gerhard, Hanno, Ikarus, Kyrill, Lancelot) are typical examples (Pinto et al. 2014). Many of these storms are mentioned in Table 5, which lists the strongest storms affecting Germany in the month of February since 1979.

In the literature, two physical reasons have been identified for the occurrence of cyclone clustering (Dacre and Pinto 2020): first, the steering through the large-scale flow, typically characterized by an intensified, quasi-stationary jet-stream extending towards Europe and second, the occurrence of secondary cyclogenesis, i.e. the development of new systems within the trailing cold front of a pre-existing (primary) cyclone. Both factors were given for the storm series of „Ylenia“, „Zeynep“ and Antonia: The jet stream over the North Atlantic was very intense over the North Atlantic over this period and extended towards Western Europe (Figure 3). While waviness and variability is often identified on a day-to-day basis, the jet stream was recurrent around 50°N over this time period. The jet stream was spatially constrained and accelerated by the breaking of atmospheric waves at the tropopause level on both sides of the jet stream, in so called Rossby Wave Breaking events

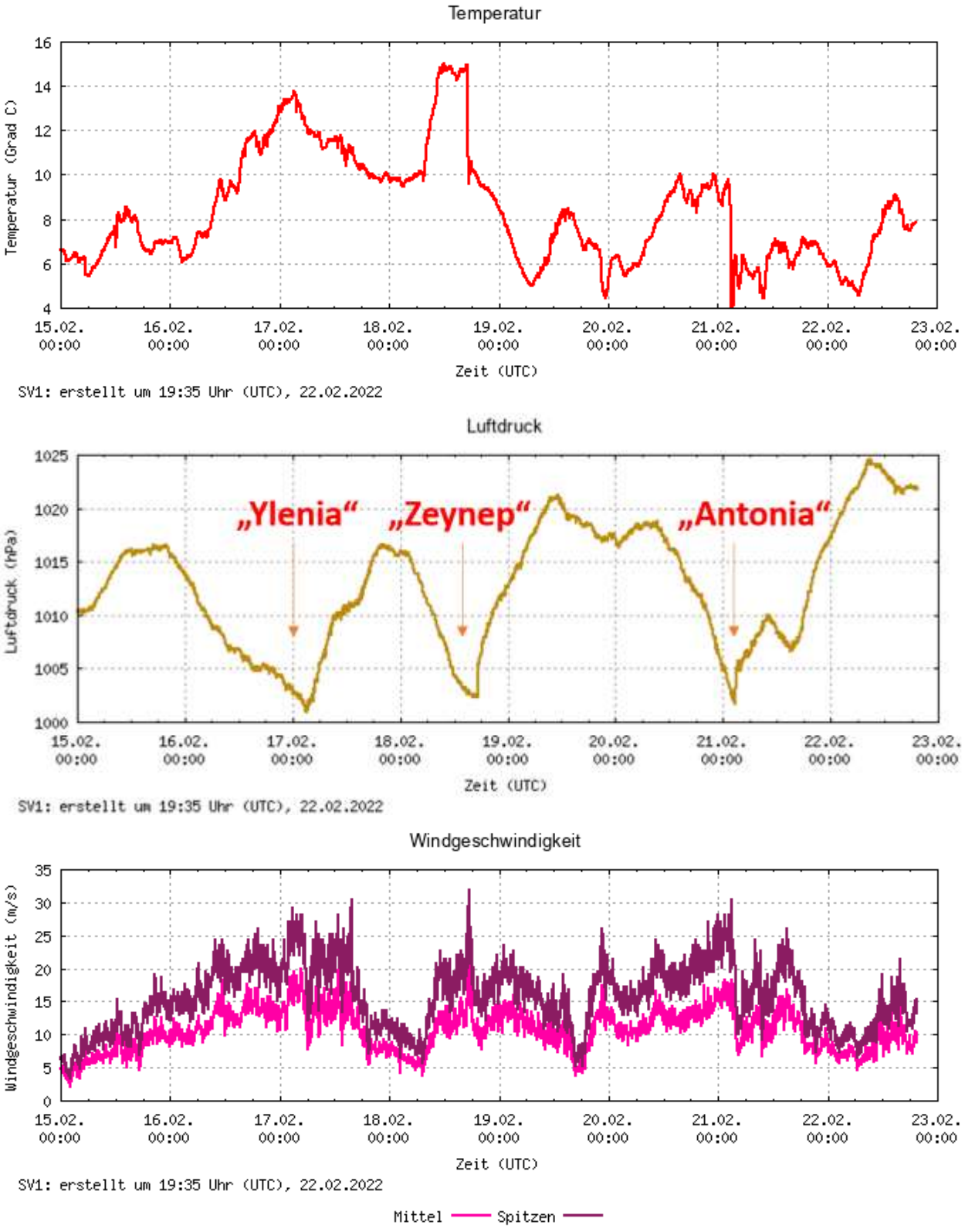

Figure 12: Temperature (top), air pressure (middle) and wind speed (mean wind and gusts, bottom) in Karlsruhe at the weather station of the Institute for Meteorology and Climate Research (IMK-TRO) at KIT. Continuous measurements in the period from Feb 15-22 2022 at a height of 60 m above ground (Data and graphics: IMK-TRO).

(see Box 1 in Priestley et al., 2017 for a schematic and concise explanation of this phenomena). Given this jet configuration, all three storms travelled into Europe following a similar path. Regarding the second mechanism, „Zeynep“ developed as a small perturbation on the trailing cold front of „Ylenia“ close to Western Europe and evolved to a full-on storm in its wake hitting Germany on the 18th.

Therefore, the occurrence of storm series like in the period from 15 to 20 February is not uncommon over Western and Central Europe. Moreover, we have added in the recent past both longer (e.g. 2007 and 2014) or more damaging storm series (e.g. 1990 or 1999). Nevertheless, the potential for large impacts given a storm series should not be underestimated. For example, if the first storm brings a lot of precipitation and warmer temperatures, it may facilitate forest damage by the following storms as the soils will be wetter and more unstable and then more prone to tree uprooting. A pertinent example of the cumulative effect of multiple storms bringing enhanced rainfall over a certain area occurred in February 2014 in the UK - a combination of cyclone clustering and stalling lead to widespread floods over Southern England (Huntingford et al., 2015; Priestley et al., 2017).

3.2. Brief overview of the effects of the storms "Ylenia", "Zeynep", "Antonia

- Total insured losses (Germany, all storms): > 1 billion Euro, probably most expensive winter storms since Kyrill in 2007
- 12.000 fire runs in Northrhine-Westphalia
- At least 12 fatalities (3 in DE, 2 in BE, 4 in PL, 3 in GB)
- In Europe, around 2 million households experienced power outage (FR, IE; GB, PL)
- Regional and long-distance rail services in northern Germany were discontinued
- Numerous traffic accidents due to broken branches / fallen trees
- Very severe storm surge Hamburg / St. Pauli: water level 375 cm above MHW (1088 cm)
- 90% of the bathing beach on Wangerooge washed away
- Highest post mill in Germany (438 m, Weimarer Land) destroyed

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Table 5: Compilation of some characteristics of the strongest storms in the period from 01 February 1979 to 22 February 2022 (selection). Ranking with respect to the 90% percentile of highest wind speeds recorded at stations. Own calculations (Data basis: DWD).

Date	Number stations	Mean kph	Median kph	Max. Gust kph	75% Percentile kph	90% Percentile kph	Name
19900226	188	115.9	112.5	230.4	129.6	146.2	Vivian
19900125	188	105.4	107.3	230.4	126.0	140.4	Daria
19900301	189	100.2	93.2	202.0	118.8	135.4	Wiebke
20070118	194	113.4	110.7	202.7	120.6	135.0	Kyrill
19940128	196	107.7	105.1	192.2	118.8	134.3	Lore
19841124	187	107.6	105.5	262.8	118.8	133.2	Yra
19900126	184	95.8	93.6	194.4	109.4	131.8	Daria
19930124	194	105.4	107.3	192.2	118.4	131.4	
19930113	196	83.4	83.2	181.4	105.5	131.4	Verena
19921126	196	96.7	98.7	172.1	113.0	131.4	Ismene
19991226	184	79.0	64.8	258.8	102.6	127.8	Lothar
19841123	189	93.3	90.0	216.0	105.5	127.8	Yra
19830201	184	101.2	100.1	187.2	111.6	127.8	
19930114	196	90.0	90.3	190.4	109.1	127.1	Verena
20020226	185	92.2	87.8	164.2	107.3	126.0	Anna
19840114	183	95.8	93.6	216.0	106.9	126.0	
20021027	193	105.4	104.4	182.9	113.4	123.5	Anna
19830118	183	90.9	88.2	216.0	111.6	123.5	
19931209	185	101.0	101.5	181.4	110.9	122.8	
19991203	184	90.4	88.0	183.6	105.5	122.4	Anatol
19900227	190	98.4	93.6	265.0	109.1	122.4	Vivian
19821216	184	93.7	90.7	180.0	105.5	122.4	
19851206	184	87.5	86.4	208.8	103.7	122.0	
19900203	197	84.1	83.2	183.6	101.2	121.0	Hertha
20050108	192	84.3	84.6	166.3	99.0	120.6	Erwin
20220218/19	**260**	**98.0**	**98.8**	**161.6**	**109.0**	**120.2**	**Zeynep**
20080301	202	100.6	97.8	223.2	108.0	119.9	Emma
19950123	188	94.1	94.2	162.4	107.3	119.9	
19860119	184	91.2	91.2	216.0	105.5	119.2	
19900228	191	92.1	89.6	176.0	100.8	118.8	Wiebke
19900208	198	97.3	97.4	230.4	108.0	118.8	Judith
20200210	199	96.0	93.6	176.8	104.8	116.3	Sabine
20220218/19	**260**	**94.4**	**94.3**	**152.3**	**103.0**	**111.2**	**Ylenia**

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