A reconstruction of the August 1st 1674 thunderstorms over the Low Countries

Gerard van der Schrier[1] and Rob Groenland[1]

[1]Royal Netherlands Meteorological Institute, De Bilt, the Netherlands

Correspondence to: G. van der Schrier (schrier@knmi.nl)

Abstract. On August 1st 1674 an active cold front moved over the Low Countries. The accompanying thunderstorms along the squall line were abnormally active, leading to large-scale damage in Europe, from northern France to the northern parts of Holland where damages were particularly severe. Using reported and pictured observations of damages and modern meteorological concepts, the reconstruction of the storm points to an exceptionally severe squall line. The orientation and the velocity of the squall line are reconstructed and shows a developed bow-echo structure. An estimate of the strength of the strongest wind gusts is $\approx$ 55-90m/s and is based on an assessment of the damages caused by this event. A rough estimate of the of the return time of this event, based on observed hail size, is between 1000 and 10.000 years. This storm is compared to a more recent storm which was similar in dynamics but much less devastating. Special attention is given to the city of Utrecht which was hit hardest, and where the impact of this storm is still recognizable in the cityscape.

1 Introduction

Wednesday August 1st 1674 (new/Gregorian calendar) ended in thunder and lightning over the Netherlands, which is not uncommon for a typical warm and humid Dutch summer day. Different from other days was that the meteorological conditions of this day lead to the formation of a line of thunderstorms along the cold front which developed to extremely severe levels. During the passage of this line, wind gusts caused severe damages over an area from northern France, into (what was called in the 17th century) the Spanish Netherlands and the Dutch Republic. The passage of the front was noted as far east as Hamburg (Northern Germany, see Fig. 1 for the location of mentioned places). The damage was overwhelming in the Netherlands and this storm was referred to in the time (in Dutch) as 'het Schrickelik Tempeest', or The Terrible Tempest.

Using modern insights in mesoscale meteorology and by gathering impact-related evidence and accounts from various sources, we take a fresh look at this day, analyse the event and make an estimate of its severity in terms the strength of the wind gusts and its return period. Here we argue that this event is characterized by strong straight line winds resulting from downbursts. This contrasts with the popular view that a single tornado caused this damage. However, we argue in this study that vortices, embedded within the frontal structure, are likely to have been present. In addition to a description of a historic event, the reconstruction and analysis of this summer storm event illustrates the impact of a storm of this ferocity that is rare enough not to be captured by the modern weather radar archives (which are a few decades long) but apparently not unlikely to

occur. The quantification of the strength of the windgust associated with this event may provide a perspective on the disruption to society in case such a rare event would occur again.

A summary of the storm event is given by the newspaper 'The Dutch Mercurius' of August 1674:

> On the first day of this month, in the evening around 8 o'clock nearly throughout all of Holland a terrible thunderstorm passes, mixed with Thunder and Lightning, Winds, rain and hail. Severe damage in Amsterdam occurred, where the powerful winds overturned most of the trees, many ships broke adrift from the quay of which 9 sunk and several houses lost their facades. Hardly any house was found that had no damage to its tiles, windows or something else. Several windmills were overturned by the wind (...) As it was all prayers day, many men were outside, many of them were never found again. Several other towns in Holland suffered damage as well, though not as much as Amsterdam. On the island of Texel, the furious winds drove many ships on the beach or were sunk. The largest damage happened in Utrecht because in a quarter of an hour most of the houses lost their facades and roofs. (...) These thunderstorms were not only in Holland but also in other provinces. In Brussels, hail stones fell which were as large as marbles, many trees were removed from the Earth, but also many house facades were overthrown. The bridge in Antwerp, which lay over the river Scheld, was destroyed by the strong winds, and the ships drifted away on the river. In Hamburg and in the area of the river Elbe this thunderstorm was felt as well. In Strassbourg, hailstones fell as large as baby's heads.

The storm causes an enormous amount of damage in the Dutch provinces of Holland and Utrecht (located in the west and central parts of the Netherlands). Especially Utrecht city and surrounding villages are hit hard, where church towers from five surrounding villages were partly or completely destroyed based on newspaper accounts (Haerlemsche Courant).

The Dom cathedral in Utrecht has probably suffered most from the storm. Although the church has seen storm damages from earlier storms, this time the nave of the church, between tower and the transept, collapsed (Fig. 2).

2 Accounts and descriptions of the storm

2.1 Used sources

There are several newspapers and a pamphlet which provide descriptions of this storm and its damage (Sweerts, 1674; Haerlemsche Courant; Hollandsche Mercurius; Amsterdamse Courant). Although details in these accounts differ, the general structure and a considerable amount of the wording in these articles are similar. This indicates that the three newspapers and the pamphlet should be regarded as one source rather than four independent sources.

The exact circumstances during and after the storm are well known due to the publication of Gerrit Jansz. Kooch (1674), skipper and merchant (1597/98-1683). Kooch painted a picture of the damage in the Netherlands in a poem of 138 couplets. He has also collected some information about the damage in Flanders (Belgium). Its sources include official publications on the storm (likely including the newspaper articles mentioned above), but he also writes to people and used his network of friends and family to gather damage reports. Furthermore, he asked carpenters and roofers to the extent of the damage and he

investigated himself the extent of the damage by interviewing people which he then introduces in his poem. The rhyme begins with Kooch's personal account of the impact of the storm on his surroundings in Amsterdam and then gives descriptions of damages from Flanders, following the path of the storm northward until it leaves Holland over the North Sea. Some additional information on Kooch is provided by Pfeifer (2015).

5   The drawings of the landscape painter Herman Saftleven (1609-1685) was commissioned by the Utrecht city council to record the damage in and around the city in great detail. The sheer amount of drawings depicting the damage of the storm in the vicinity of Utrecht, over 25 are available in the Utrecht city archives[1] while some 60 drawings are known to exist (A.F.E. Kipp, personal communication), indicate the widespread character of the damage this storm produced. An inventory of Saftleven's known drawings of the ruins in and around the city is provided by Kipp (1974) and reproduced by Graafhuis and

10 Snoep (1974). Some of these drawings depict damages within the city walls (18 focusing on the Dom Cathedral, 5 of others subjects) but most (45 in total) depict damages in the vicinity of the city, outside the walls.

    In the summaries of local histories of all Dutch cities and villages compiled by Van der Aa (1839) , damages due to the events surrounding the 1674 storm are frequently mentioned.

    In a historical description of events by Joh. Lodew. Gottfrieds , published in 1700, the storm of 1674 and the damages it

15 caused is described to some detail.

    Finally, Buisman (2000), in his impressively detailed description of each single season in 1000 years of weather in the Low Countries, has collected a vast amount of descriptions of this storm from city archives, official records and diaries. A similar collection of sources for descriptions of the storm and its damages is provided by Graafhuis and Snoep (1974) and Graafhuis (1974).

20 ## 2.2   Summary of contemporary descriptions of the storm and its damage

The short duration of the storm is made clear in Kooch's account of the damage in Amsterdam. His personal experience was that the storm passed in a short half hour (strophe 10). Later, one of his sources claims that the storm passed over Amsterdam in a quarter of an hour (strophe 80 and 81) and that no house would have been undamaged if the storm would have lasted a full hour. Sweerts (1674) writes that in less than half an hour the whole town of Utrecht was turned to ruins.

25   The passing of this system saw unusually strong gusts which are described in Kooch's report, accounting of numerous cases of people, small boats and carriages taken up into the air. The impact of the storm on the landscape is also made clear by Kooch (1674, strophe 42-44) in which a farmer fails to recognize the surroundings of his grass land after the passage of the storm, with not only the haystacks blown away, but the trees along the borders of his land and church towers of a nearby towns as well.

30   The destructive force of the gusts was illustrated by the nature of the damage: churches collapsed, church choirs and spires were damaged or destroyed, wind mills were overturned, pieces of lead used as roofing (some of them 150 pounds in weight) were blown off completely and roofs of houses were ripped off. One account from the city of Hilversum (Kooch, 1674, strophe

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[1]http://www.hetutrechtsarchief.nl/

45,46) is indicative of the enormous damage which affected this town where 50 homes were leveled and others badly damaged, causing many deaths (van der Aa, 1839).

There are several reports from the water-rich province of North Holland about boats that did not survive the storm. An example from the area near Ilpendam (north of Amsterdam), where two farmers were first blown out of the boat and then the boat was taken up by the winds, flying 'over several fields'. The boat was shattered to pieces when the farmers found it again (Kooch, 1674, strophe 119,120).

The amounts of rain (Kooch, 1674, strophe 91-95) must have been exceptional, described by qualifications as: "the rain was overwhelming", "as if buckets were emptied", "it came streaming down the streets" and "the rain, which came like the Deluge, flooded the houses, ruined the walls and spoiled the grain that was left on the fields". Kooch also reports on he remarkable size of the hail stones. Other reports of large hail stones come from northern France, Belgium and the Netherlands (Hollandsche Mercurius; Buisman, 2000).

A compilation of all damage reports is shown in fig. 3. Multiple reports for one city or village are shown as one report. The figure clearly shows the path, from north France over Flanders into the western part of the Netherlands. Gottfried (1700) notes that the storm was violent in north France, with the hail and winds causing severe damages to grain fields, grapes and orchards. The Royal Palace of Fontainebleau was 'severely damaged' as well. The figure shows hardly any damages in the eastern parts of the Netherlands. Although these parts were relatively sparsely populated, no damage reports for some larger cities have been found which could be related to this storm.

Interesting is that in the westernmost parts of North and South Holland almost no damage was seen (Figure 3). This remarkable feature is also noted by Kooch (1674, strophe 114), mentioning Alkmaar and Haarlem. Inquiries with the historical societies of the cities Leiden and Delft, close to the North Sea coast but more south than Haarlem, show that no damage is known that is related to this storm (personal communication).

At smaller spatial scales, the contrasts in damage are also striking. Kooch (1674, strophe 110) notes that in the Amsterdam harbour the moorings of the ships broke and made them drift away, while empty barrels on the quay were unaffected. What is striking about the drawings of Saftleven (Fig. 4), is that the houses around the cathedral square, visible in the background of the drawing, still appear to be intact. Even the facades are intact and the pinnacles on the facades appear undamaged. A tree apparently survived the storm. Kooch notes some of these contrasts (strophe 77) when describing a poorly maintained little house, weakened to the point that it could be brought down 'with bare hands' was undamaged by the storm.

The thunderstorms produced a long track of massive destruction through the province of North-Holland, without losing strength. Up to the northern part of Holland at the island Texel damage is found.

3 Meteorological interpretation

3.1 Reconstruction

The widespread damage in east-west direction and the rapid passing of the storm point to a narrow frontal structure passing over the Low Countries. Such cold fronts are common in the summer season, replacing warm humid air with cooler air.

A few sources match the passage of the front to the time of day. Between 18.00 and 19.00 local time the storm passes Antwerp (Kooch, 1674, strophe 12) to arrive between 19.00 and 19.30 LT (local time) in Utrecht (Sweerts, 1674) and just before 20.00 LT (Kooch, 1674, strophe 80) or around 20.00 LT the front passed Amsterdam (Hollandsche Mercurius). The front passed Koog aan de Zaan between 20.00 and 21.00 LT (Buisman, 2000), which is northwest of Amsterdam. The direction in which the front moved is estimated to be parallel to the line on the west side of the damage reports over the province Holland (north of $\sim52°$N). Note that even in the small Dutch Republic there were different time zones; these timings are adjusted. When using the distances between the centres of Antwerp, Utrecht and Amsterdam, and the uncertainties in the timing of the passage of the front, lower and upper bounds of the average speed can be calculated between these cities. For Antwerp – Utrecht and Antwerp – Amsterdam, the lower bounds are 70 km/h and 60 km/h respectively (upper bounds are unrealistic at > 150 km/h). Between Utrecht – Amsterdam, the upper bound is 78 km/h (lower bound is unrealistic at 26 km/h).

A decomposition of these estimates in the direction parallel to the movement of the squall line and one perpendicular to it, the average speed of the frontal system on the west side of the front (passing through Antwerp) is about 60 km/h. More to the east, passing trough Utrecht, the speed is about 65 km/h. These estimates can only be made consistent with each other using speeds close to the lower bounds for the Antwerp - Amsterdam and Antwerp - Utrecht sections, and close to the upper bound for the Utrecht - Amsterdam section. These diverging estimates of the average speed of the frontal system are consistent with a situation that an accelerating part of the squall line passed Utrecht while the western part of the squall line, traveling at smaller speeds passed through the area west of Amsterdam.

The distance between Amsterdam and Koog a/d Zaan is too small ($\approx$ 4 km) and the timing estimates have too large uncertainties to be of much use.

An accelerating central part of the squall line and an area west of the squall line without significant damage point to the existence of a bow echo. A bow echo is formed when the band of convective thunderstorms is combined with a rear-inflow jet. When this rain-cooled downdraft of a thunderstorm reaches the earth's surface, it spreads horizontally and most rapidly in the direction in which the front progresses, producing straight-line winds. The rear-inflow jet advects high-momentum winds from aloft, further enhancing the wind speeds at the surface. Within these areas of convective downdraft, or downbursts, smaller pockets of intense winds exist which are referred to as microbursts. Microbursts are characterized by spatial scales of approximately 4 km. Still smaller areas of extreme wind within microbursts are called burst swaths, which range from 40 to 140 m. The strong heterogeneity at small spatial scales of the storm damages are in line with this concept.

When the rear inflow jet bends the frontal system, bookend vortices develop on either side of the jet which are advected along with the front. The cyclonic vortex on the west will be strong due to the interaction with the Coriolis force, making the winds on west side of the vortex much weaker, explaining the absence of damage in towns like Haarlem and Alkmaar (which are to the west-northwest of Amsterdam close the the coastline with the North Sea). The stronger winds due to the bookend vortex at the west end of the squall line could have contributed to the vast damages in Holland. The bookend vortex at the eastern side lacks the interaction with the Coriolis force and is much weaker, making the distinction between areas with or without damages more inland less clear than at the west side of the bow-echo.

3.2 Is there evidence of embedded vortices?

Apart from the bookend vortex of the squall line, the straight line wind associated with the bow echo may have embedded vortices which are produced by horizontal shear. There are no observations of a whirlwind in the accounts of Kooch (or elsewhere). However, the direction in which church spires fell in the city of Utrecht may indicate embedded vortices. While the nave of the Dom cathedral and the towers of the Nicolaaskerk fell in northerly direction (in the same direction as the movement of the front), the drawings of Saftleven show that the two towers of the Pieterskerk (200m to the ENE) were blown down in the direction of the nave and choir of the church (left panel fig. 5). One account (Haerlemsche Courant) confirms that the church spires fell through the roof of the Pieterskerk. The nave and choir of the Pieterskerk are facing east, indicating that the winds were perpendicular to the direction in which the squall line moved and to the direction of the straight line winds.

The Jacobikerk, about 680 m northwest of the Dom cathedral, had a spire reaching up to nearly 80 m height in 1674. Gottfried (1700) writes that the spire fell down between the church and the surrounding houses without damaging any of these houses. The most likely place for the spire to fall is then west or even southwest of the Jacobikerk where a large square was present. Joint to the spire of the Jacobikerk, at the east side, was a (much) smaller tower containing the carillon. The bells of this tower fell trough the church roof, destroying the arches. The position of the bells after the collapse of the spire has been documented (Kipp, 1974) and the damaged arches have never been repaired. A view of the direction in which the spire of the Jacobikerk fell is given in the right panel of fig. 5. This evidence indicates a southwesterly fall direction. The damages in Utrecht and the direction in which these towers fell is indicated in fig. 6.

Embedded vortices are also observed in the damage analysed by Fujita and Wakimoto (1981). In a study of a series of destructive windstorms on 16 July 1980 in the American Midwest, the damage of downbursts on a forest is analysed, including the direction in which the trees have fallen. The pattern of damage reflects the burst swaths associated with these downbursts where most trees fell in the direction of the movement of the front. At the sides of the burst swaths some trees fell sideways or (nearly) against the direction of the movement of the front.

4 Estimate of the strength of the storm

There are no direct measurements of the strength of the mean winds and wind gusts at the surface generated by the downbursts of this storm. In order to make an assessment of the strength of this storm and a provisional estimate of its return period, two approaches are tried. One relates the observed damage to a wind strength via the Fujita scale (Fujita, 1958; Fujita and Wakimoto, 1981). The other attempts to make a return period analysis using a modern climatology of hail and observed hail size.

4.1 Wind strength estimate

The accounts of the storm from the newspaper reports, the drawings of Saftleven and especially Kooch's rhyme are detailed to the point that a Fujita damage scale[2] can be attached to the storm. Below are some of the descriptions of damages related to this storm.

In Kooch's rhyme are several accounts, mostly from the water-rich northern parts of Holland, of prams being taken up into the air to be transported (in one account) 'over several fields'. A pram is a light tender with a flat bottom and a bow formed from the ends of the side and bottom planks meeting in a small raised transom. The common size of these barges in the province of North Holland was typically 6.6m x 1.4m x 0.4 m (Schutten, 2004). By making an estimate of the water displacement, the weight of a loaded pram is estimated at 2000 kg (personal communication, Dutch National Maritime Museum), while ≈ 600 kg is the estimate for an empty pram. There are also numerous accounts of carriages with horses, taken up in the air (Kooch, 1674, strophe 35) and other heavy objects being displaced, like the lead from the roof of Amsterdam's orphans house (with a weight of more than 1500 kg) which was ripped off, fell to the ground and was transported through three streets (Gottfried, 1700).

There are numerous accounts of uprooted or snapped trees from Utrecht (like from the St. Jans churchyard) and Amsterdam where on the Nieuwe Markt (New Market) a heavy tree ('too large to embrace') was uprooted and transported across the market for 180 feet (≈ 50m) (Kooch, 1674, strophe 97).

Of the 7 windmills on the city wall of Utrecht, perhaps one survived the storm (Perks, 1974). Two other windmills, just outside the city, survived the storm as well. These windmills were post mills, which consists of a large square box, constructed to turn about a heavy wooden pillar (the post). The post is supported by a system of double quarterbars and heavy crosstrees resting on brick piers (Stockhyzen, 1963). This construction makes them vulnerable to strong winds, lifting the square box off the post. Kooch accounts (strophe 124) also of the destruction of the wind-powered powder mill in Monnikendam, north of Amsterdam, and the displacement of its six edge runner millstones (vertical millstones which revolve on a circular base), attached pair-wise by a wooden axle.

In Kooch's rhyme we find two accounts of objects which are propelled at high speed. One is in Amsterdam, where the lead roofing of the corn exchange was stripped off (estimated to weigh nearly 2000 kg (Kooch, 1674, strophe 85)), broken into 27 pieces and one of these parts was propelled at high speed into the window-frame of the nearby cheese merchant's warehouse. The other account is from Diemermeer (southwest of Amsterdam) where three planks from a shed made a large opening in the thatched roof of a farmstead.

The drawings made by Herman Saftleven of the destruction in and around the city (fig. 7) show removals of thatched roofs from a farm just outside the city and many brick houses and buildings with collapsed walls. Note that it may be that houses, roofs and chimneys have been repaired by the time Saftleven made these drawings (some of these drawings were made a considerable time later), although Kooch reports (strophe 89) that the waiting time for reparations to houses could be as long

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[2] http://www.spc.noaa.gov/faq/tornado/f-scale.html

as 2 months because of the shortage of bricklayers, carpenters and glaziers. A similar word of caution applies to the trees seen in the drawings, uprooted trees were strutted after the storm if they could be salvaged.

The description of the Fujita scale for F2 includes 'roofs torn off frame houses', 'large trees snapped or uprooted', 'light-object missiles generated' and 'cars lifted off ground'. With the lighter carriages and prams replacing the description of cars, these descriptions match the accounts of the 1674 storm damage. The F3 scale for 'severe damage' describes 'roofs and some walls torn off well-constructed houses', 'most trees in forest uprooted' and 'heavy cars lifted off the ground and thrown'. In the heavier-hit areas, like the city of Utrecht, such damage to roofs and walls is evident in the drawings of Saftleven. The provinces of Holland and Utrecht were almost completely deforested in the 17th century, probably explaining the lack of accounts of large-scale damage to forests, but the account of uprooting of all trees in the St. Jans church yard and elsewhere in- and outside Utrecht resonate with this description.

Wurman and Alexander (2005, their fig. 8) relate observed damage of a F4 tornado to observed 5 second wind gusts using Doppler measurements and theoretical estimates. Although they warn that damage may not be a simple function of peak wind gust and structural integrity, but that other factors like the duration of intense winds may be critical factors as well, we use their estimates to relate the observed velocity data to damage survey F-scale estimates. Their analysis suggests that damages scaled between the F2 and F3 scale relates to 5 second wind gusts of approx. 85-90m/s.

There are insufficient grounds from the damage reports of the 1674 storm to related wide-spread damages to the stronger F4 and F5 ratings. The damage descriptions relating to the F4 rating are 'well-constructed houses leveled', 'structures with weak foundations blown away some distance' and 'cars thrown and large missiles generated'. Although many houses have been severely damaged in the 1674 storm, the qualification above is too strong. Similarly, there is evidence that missiles were generated, but all these relate to planks or a piece of lead roofing which do not qualify as 'large missiles'.

The Enhanced Fujita scale[3] is difficult to apply to the European situation of 1674 since most of the damage descriptions relate to the typical American 20th century situation (like automobile showrooms). However, there are some elements in this scale which are more general. The uprooted deciduous trees scale 3 in the degree of damage rating, with associated estimates of 91 mph ($\approx$40m/s) 3-second wind gust. The large-scale destruction of wooden houses, the many accounts of damages to roofs and walls and the drawings of Saftleven of destructed stone houses scale 6 to 10 in the degree of damage rating for 'one and two family residences', giving an estimate of 122 - 200 mph ($\approx$ 55-90m/s) wind gusts. With this estimate, the assumption is made that 17th century houses, of which many still exist in Dutch cities, were of comparable quality as the residences alluded to in the Enhanced Fujita scale.

Note that the Fujita scale relates to rotational winds and may not be directly applicable to straight-line winds.

4.2 return period estimate

The severest damages caused by this storm are from the wind gusts and a return period estimate should be based on the strength of the wind gusts. However, a climatology of wind gusts related to downdrafts is not available in the Netherlands or surrounding countries. As an alternative, we turn to hail stones for an estimate of the return period.

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[3]http://www.spc.noaa.gov/faq/tornado/ef-scale.html

There are frequent observations of severe hail and massive hail stones. Gottfried (1700) notes that the weight of the hail stones observed near Paris were 'three and a half pound'. In Strassbourg (NE France) the size of the hail stones were as large as 'a baby's head' and weighted as much as 2, 3, 4 or even 7 pounds. The damage to the glass windows in this city amounted to 16.000 Dutch guilders (Gottfried, 1700), the equivalent of $\approx$ 163000 euro (Luiten van Zanden, 2010). Damage to windows in churches is also noted by Kooch (1674, strophe 3). The amount of hail in Frankfurt am Main was knee-deep (Gottfried, 1700).

The modern equivalent of the 'pound' mentioned in these reports is difficult, and the weight of a pound varied from region to region and depended on the goods to be weighted (butter having for instance a special 'butter pound')[4]. This makes the translation from these observations into modern metrics difficult. The size ($\sim$diameter) is a more useful, although Knight and Knight (2005) comment on the issues of quantifying hail size by a diameter (given that severe hail is usually not very symmetric).

The largest hail observed during the 1674 event is the hail in northern France, estimated to be somewhere between 15 and 20 cm. This account seems to be single observation and one source has reported this. However, reports of extreme hail (both size and quantities) are mentioned by several sources for many other places, making the possibility to observe extremely large hail stones less unlikely. Nevertheless, the uncertainty on this observation is considerable. Hail of this size (20 cm) has earlier been observed in South Dakota (USA)[5], and weighted about 0.9 kg. During a hail storm in southwestern Germany on 6 August 2013, hail of up to 14 cm in diameter was observed (Punge and Kunz, 2016).

The Netherlands has no climatology of hail, so the accounts of the size of hail stones cannot be compared to modern measurements. A climatology of severe hail, covering the period 1930-2006 is available in Finland (Tuovinen et al., 2009). Although southern Finland is at a much more northerly latitude than the Netherlands, the summer climates are remarkably similar. The average daily maximum temperatures for Southern Finland and the Netherlands are 20.1°C and 21.9°C respectively and the number of summer days (days where the daily maximum temperature is $\geq$25°C) are 17.0 and 20.5 respectively, calculated over the 1981-2010 climatological period[6]. Tuovinen et al. (2009) have collected accounts of severe hail (diameter of 2 cm or more) by newspaper report, storm spotters and eyewitness reports. Most of their cases (84%) occurred from late June to early August, with the most sever hail occurring late afternoon-early evening (14.00 - 20.00 LT). These severe cases occurred most often in western and southern Finland.

An estimate of the return times of severe hail can be obtained by fitting a Gumbel distribution to the maximum observed hail size per year (one value each year). Fig. 8 shows the plot of these data. The observations with the largest diameter (three observations of 8.0 cm) appear to deviate a little from the straight-line fit in this Gumbel plot. This may be due to the perhaps somewhat approximate character with which severe hail is quantified. People often refer large hail to objects of similar size (like baseballs), making that these sizes appear more often in observational records (Knight and Knight, 2005).

Using the Finnish data as a proxy for the circumstances in the Low Countries, the return time of hail with a diameter between 15 and 20 cm is estimated to be more frequent than once every 10^3 years and less frequent than once every 10^4 years. Note that

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[4]http://www.meertens.knaw.nl/
[5]http://www.weather.gov/media/abr/vivian/073010RecordHailVibianSD.pdf
[6]http://www.ecad.eu

the uncertainty in these estimates, due to the extrapolation of the hail size is large. These return periods should be regarded as carefull estimates only.

5 Comparison against a recently observed bow-echo

A modern - but much less devastating - equivalent to the summer storm of Aug. 1 1674 is the squall line with an embedded
bow echo that occurred on July 14 2010 and passed over Belgium, the westernmost part of Germany and the southeast of the
Netherlands. This squall line caused severe wind damage in

The most active part of this frontal system was part of a long squall line which extended into Switzerland and it caused
severe wind damage in the Netherlands, particularly near the villages of Vethuizen, 85 km ESE of Utrecht, and Neerkant (60
km SSW of Vethuizen). The storm caused two casualties in Vethuizen.

The Vethuizen storm is described in some detail in this section based on an earlier technical report (Groenland et al., 2010),
in terms of damage and meteorological interpretation, and the similarities between the 1674 storm and this modern equivalent
are pointed out.

5.1 Damage survey

The progression of the squall line is shown in fig. 11 with 30 minute time steps. The first report of strong windgusts was at
15.32 UTC at Maastricht Aachen airport (southernmost part of the Netherlands) with 31 m/s. Somewhat later, a gust of 34.2
m/s was measured at the Volkel airbase after which the anemometer broke down due to a lightning strike.

An on site survey was carried out by a team of the Royal Netherlands Meteorological Institute (Groenland et al., 2010)
shortly after the event. This showed a destroyed farm with its tiles removed from the roof, the chimney broken off and part
of the facade of the farm destroyed. The farmer reported heavy rains, obstructing his view through the windows, and a very
short period (half a minute) in which the damage occurred. Near the farm poplar trees, aged between 40 and 70 years, were
snapped-off or uprooted. Further down the road, a hotel lost its thatched roof but the tiles on a neighbouring building were not
damaged. The two casualties died on the nearby camping site, where their caravans rolled over and were transported to the
lake on the camping site (a distance of a few 10s of meters). Large damage occurred to five power pylons in this area which
were blown down. An analysis of the power company indicates that these pylons were blown down simultaneously and that a
'domino' effect, where one falling pylon pulls down a second, was not present. The direction of the fall of all these pylons was
in the direction of the movement of the frontal system.

In the village of Neerkant, the damage consisted mostly of snapped or uprooted trees. It was estimated that about 75% of
the trees in this area have been damaged, mostly oak with an approximate age of well over 50 years. Greenhouses in this area
have been destroyed; one greenhouse lost al its glazing while another was detached from its foundations and moved for about
8 m. Observations of trees falling in other directions than the direction of the movement of the frontal system were made.

5.2 Synoptical analysis

European weather maps (fig. 9) show a low pressure area, of just below 990 hPa, south of Ireland and in combination with a powerful ridge of high pressure, a southern flow over the Low Countries is generated. This replaced the warm continental air, with temperature above 30°C, with cooler air from the Bay of Biscay. The enhancement of thermal contrasts over western Europe fueled the development a thermal low.

The centre of this heat low was present in Belgium at 1500 UTC (Coordinated Universal Time, fig. 10), with a pressure of 998 hPa. The strong air pressure gradient southwest of the centre is remarkable, just as the observed pressure drops of 7 hPa/3 h prior to the arrival of the cyclone and pressure increases of nearly 6 hPa/ 3 h after the passage of the centre in the area of the city of Reims (northern France). Less than 30 minutes later, the cyclone arrives in the Netherlands, passing in six hours towards the eastern parts of the Netherlands. Fig. 10 shows the synoptical observations of wind direction, wind speed, cloud cover, pressure and pressure change.

The track of the frontal system was in the NNE direction and its speed decreased gradually. At 1400 UTC, the speed was about 85 km/h while at 1700 UTC is was moving at 78 km/h.

The radar image of 1630 UTC (fig. 11) coincides with the passage over the village of Vethuizen. The strongly developed squall line is seen in this image. The red values relate to precipitation with an intensity of over 30 mm/h. On the squall line, a bow-echo structure is recognizable, with a 'notch', a zone with less intense radar echos. This is a sign for the presence of a band with strong winds close to the surface at the back-end of the bow echo, the rear inflow jet. The combination of strong precipitation and the rear inflow jet cause downdrafts and wind gusts which are held responsible for the observed damage.

The horizontal shear causes rotations which are sometimes referred to as gustnado's.

A theoretical estimate of the maximum possible windgust, under the most ideal circumstances, gives a value of 50 to 55 m/s (about 180-200 km/u). The characteristic spatial scales at which such high values occur are too small for the density of the observing network to be measured.

5.3 Similarities and differences between the 1674 and the 2010 events

From the meteorological perspective, many similarities can be observed between the 1674 and the 2010 situation. The direction of the movement of the squall line, from SSW to NNE, is similar between the 1674 and the 2010 events and matches the direction of movement of the strongest squall lines in the modern climatology of the Netherlands. The velocity of the squall line in the 1674 situation is perhaps a little slower ($\approx$ 60 km/h) compared to the 2010 event ($\approx$ 85 km/h). Witness reports of the modern event indicate that the strongest winds passed in a time of 5-10 minutes, while it took 15-20 mins. before the rains stopped. The time of passage of the squall line seems shorter in the 2010 event than the 1674 event. The similarity in the direction of movement of the squall line between the 1674 and modern climatology makes it very likely that the 1674 case was associated with the passage of a cold front.

Fig. 10 shows the thermal low preceding the squall line. With the rapid approach of the frontal system, a dark band of clouds was observed (Groenland et al., 2010), similar to what was reported in 1674 by a source (Buisman, 2000) form the town of

Medemblik (44 km NNE of Amsterdam). He reports seeing 'a black dark sky' approaching with thunder and lightning. This source mentions that the winds, appeared to come from all four directions. The rapid changing of the wind direction may relate to the passage of a thermal low over Medemblik, similarly as what happened in the 2010 situation.

The theoretical maximum of wind gusts strength in the 2010 event ($\approx$ 50 - 55 m/s) is somewhat smaller than the maximum wind gust estimated during the 1674 event (max. 90 m/s).

While both the difference in max wind gusts and the speed at which the squall line passed will have contributed to the less extensive damages in the 2010 case compared to the 1674 situation, the possible development of multiple segments with a bow-echo structure along the squall line in the 1674 case will have made the area over which violent wind gusts develop much larger. However, the lack of sufficient detail in the observations prevents a confirmation or reconstruction of these structures.

6 Discussion and Conclusions

Estimates of the number of people severely injured of dead due to this storm are lacking. There are anecdotes mentioning people getting injured, like hail stones bruising people caught in the fields (Kooch, 1674, strophe 72), or people getting hit by falling trees or other debris. Gottfried (1700) mentions the death of more than 1000 people blown in the water and drowned within a distance of less than 'half a mile' from Amsterdam. A lacking estimate of the loss of live makes that the impact of this storm seems to have been most profound in terms of material loss, but the human cost must have been extensive.

A cultural-historical perspective of this storm is provided by Hauer and Pfeifer (2011) and their study on the human dimension gives some clues how contemporaries dealt with such calamities. In this study, the damage is related to a single tornado rather than straight line winds on a squal line associated with an active cold front. Although the evidence from the Pieterskerk and the Jacobikerk points to the presence of vortices embedded in the straight line winds, the straight-line winds account for the largest part of the wide-spread damages in the city of Utrecht and in the Low Countries in general. A single tornado causing the collapse of the Dom cathedral is unlikely since this would produce a damage trail in the city that is much more confined that what is observed.

It has been argued that the nave of the Dom cathedral might have been more vulnerable because of the lack of flying buttresses and because of having a roof supported by a wooden structure rather than an overarching stone structure (den Tonkelaar, 1980). However, de Kam et al. (2014) observe that in the Netherlands many churches still exist without an arched roof and apparently survived the centuries, like the St. Bavo in Haarlem. Although the city of Haarlem was just west of the western bookend vortex, making that the wind gusts there were not as strong as elsewhere, the more active part of the front passed over the St.-Jan in Gouda and the New Church in Amsterdam which have similar roofs as the nave of the Dom cathedral. The windows of these churches were damaged due to hail and, in the case of the New Church in Amsterdam, the hail damaged the roof as well, but these structures remained largely intact during the storm. Similar to the Dom cathedral, the orientation of these churches have their choirs facing eastward (de Kam et al., 2014, p.269-270), which makes that the wind gusts hit these churches from the side as well.

A comparison with a modern bow-echo event from 2010 shows many similarities in terms of the meteorology. The severest of summer storm events in the past century in the Netherlands occurred the early evening of August 10 1925 in the town of Borculo (van Everdingen, 1925). Similar to the 1674 event, this event was initially related to a single tornado. The damage caused by the 1925 event can be traced from the southeastern part of the Netherlands in NNE direction to the eastern parts of the Netherlands over an interupted path several 10s of km wide. Areas with additional damage were found north and south of this path. Although at several places the characteristic cone associated with a tornado has been spotted, most of the damage of this event is related to downdrafts (Wessels, 1968). Interesting is that the confusion on the cause of the damage (tornado vs. straight-line winds) is commented on by Fujita and Wakimoto (1981) who indicate that 'this type of damage has often been reported as tornado damage' rather than to straight-line winds from a downdraft.

Although direct meteorological measurements of the events of August 1st 1674 lack (the earliest instrumental weather observations were made in 1697), the meteorological interpretation of the contemporary reports indicate that the wide-spread damages from northern France into Holland were caused by an exceptionally active cold front. Strong downbursts generate straight-line winds where the strongest wind gusts are estimated to have a speed of possibly up to 90 m/s. While the damages to the Dom cathedral and the Nicholaaskerk are in the direction of the movement of the front, embedded vortices in this front, due to horizontal shear, explain the direction of the fall of the towers of the Pieterskerk and the tower of the Jacobikerk which is not aligned with the direction of movement of this front. Estimates of the return period of this cold front, based on the size of the hail, indicate that this event is a very rare event with a return period much larger than once every thousand years.

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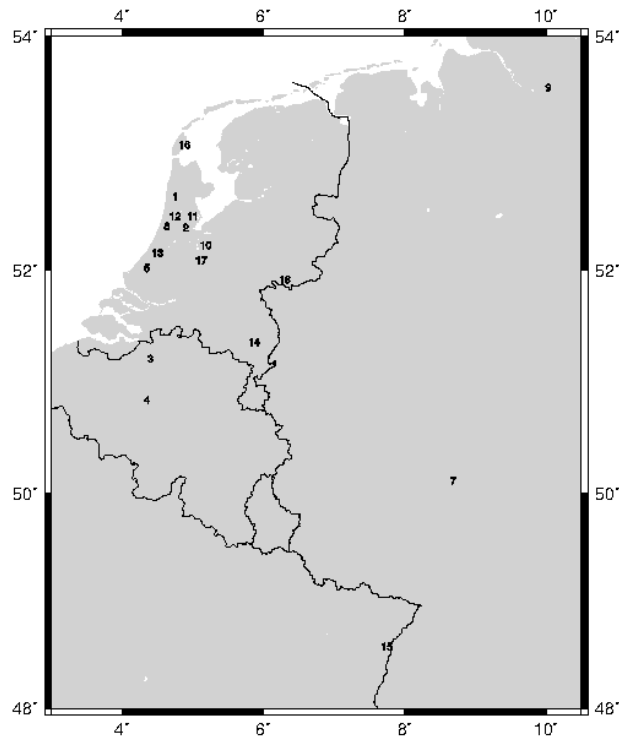
Figure 1. Cities, towns and villages mentioned in the text. The numbers in the map refer to 1) Alkmaar, 2) Amsterdam, 3) Antwerpen, 4) Brussel, 5) Delft, 6) Fontainebleu, 7) Frankfurt am Main, 8) Haarlem, 9) Hamburg, 10) Hilversum, 11) Ilpendam, 12) Koog aan de Zaan, 13) Leiden, 14) Neerkant, 15) Straatsburg, 16) Texel, 17) Utrecht, 18) Vethuizen

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Figure 2. Drawing of the ruin of the Dom cathedral following the 1674 storm by Herman Saftleven (Utrecht City Archive no. 28635). The viewpoint of the artist is from the undamaged part of the Cathedral overlooking the area with the collapsed nave towards the Dom tower.
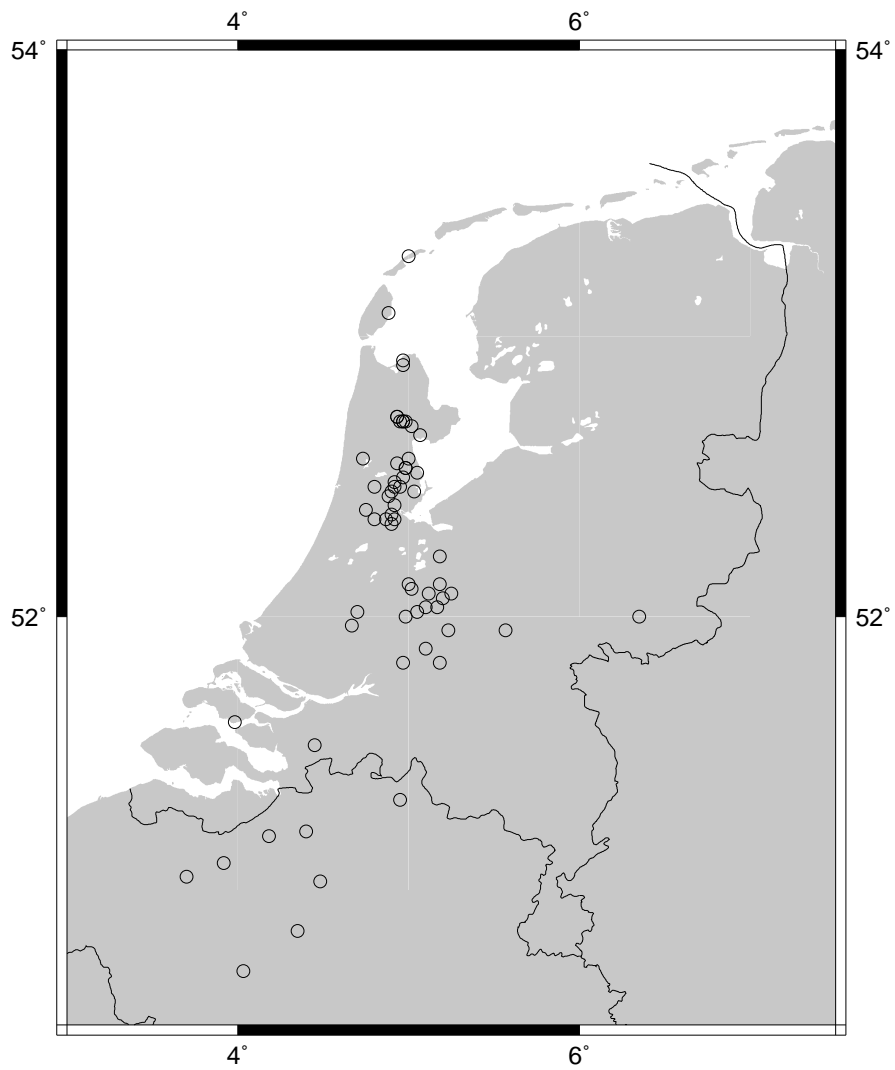
Figure 3. Damage reports compiled from various sources related to the August 4 1674 storm.

Figure 4. Drawing of the ruin of the Dom cathedral following the 1674 storm by Herman Saftleven (Utrecht City Archive no. 28629 and no. 28630, both views from the southeast).
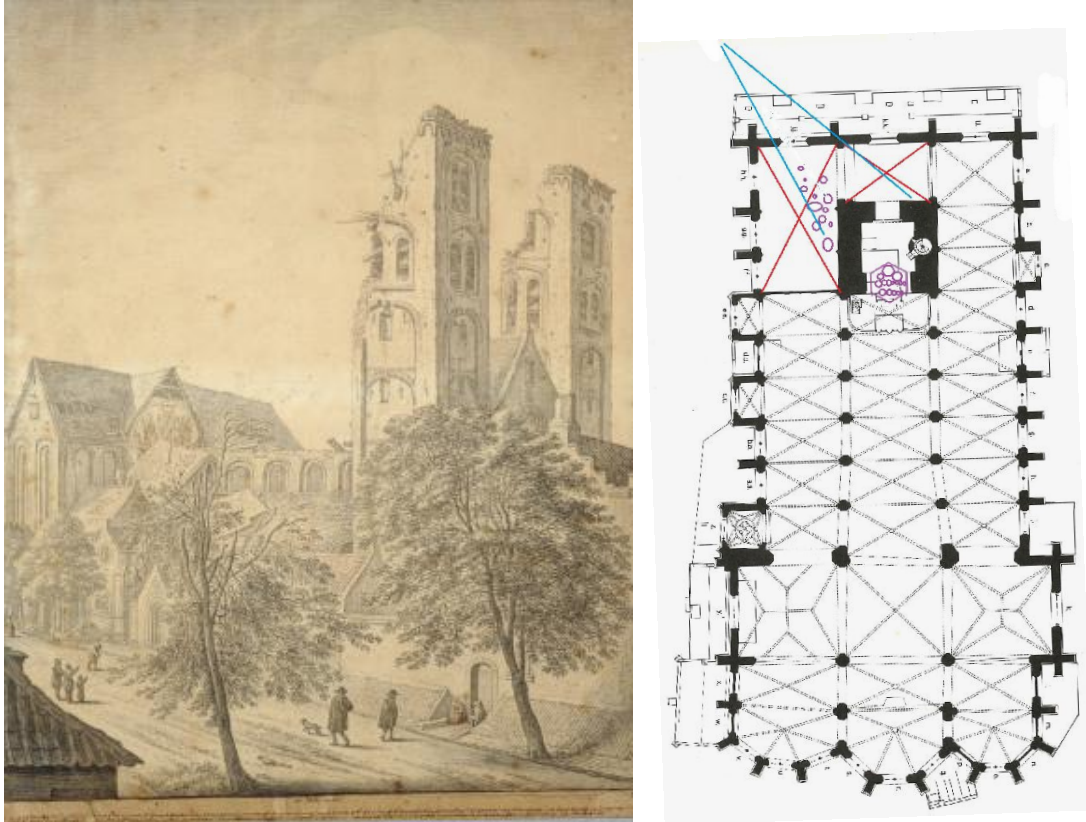
Figure 5. (left) Drawing of the ruin of the Pieterskerk with the spires and part of the church towers removed by the storm. The direction of the fall is into the church. Drawing by Herman Saftleven (Utrecht City Archive no. 28644). (right) Plan view of the Jacobikerk, showing in blue the reconstruction of the direction in which the spire fell in the 1674 storm. In purple, the carillon is shown in its separate spire east of the main spire, with the position of the bells on the church floor after the collapse of the spire. In red, the the destroyed arches are shown (which have never been repaired). Figure from Kipp (1974).
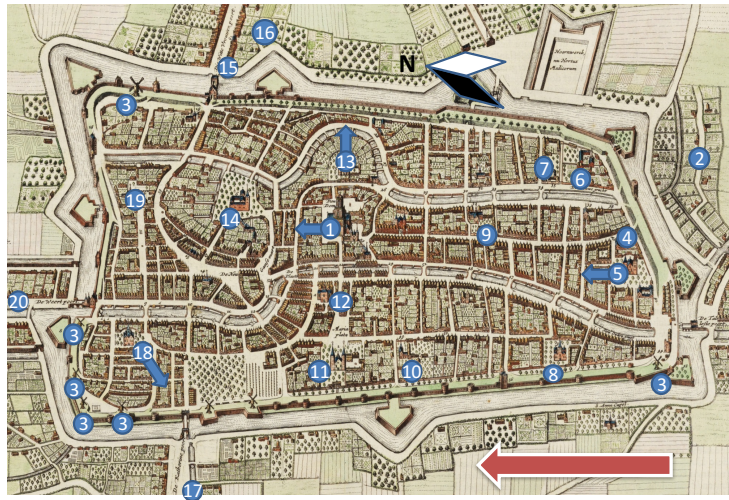
Figure 6. Compiled damages to larger structure in the city of Utrecht. The number is in blue circles refer to table 1, the blue arrows refer to the direction in which the structure collapsed (details in sect. 3.2). The large red arrow denotes the direction in which the front moved over Utrecht. Map from J. Bleau (1649), Utrecht City Archive no. 214022.

Figure 7. Selection of drawings of Herman Saftleven following the storm of 1674. a) view on Gildbridge near the Biltsche Grift (30817), b) Ruined house at the 'Nieuwe Weerd' (38525), c) farm Abstede (26155), d) outside the Catharijne gateway (38638), e) just outside Wittevrouwen (38526), f) Ruin of St. Bethlehem, just outside the Catharijne gateway (37718). Numbers between brackets refer to the Utrecht City Archive catalog number.
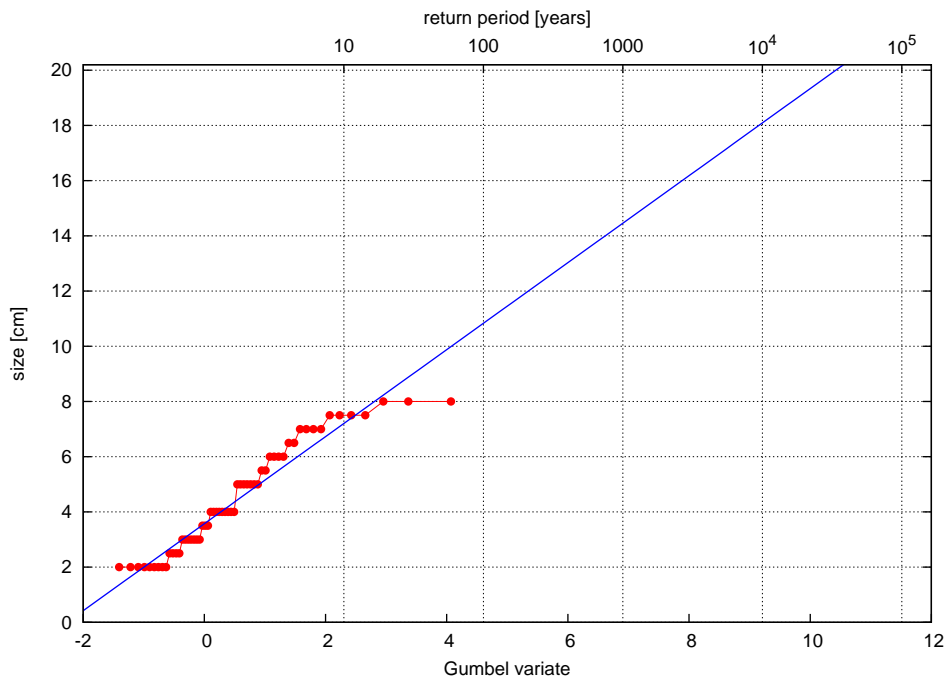
Figure 8. Maximum observed hail size (one value per year, minimum value 2 cm) from Finland (Tuovinen et al., 2009) in relation to return times, using a Gumbel distribution.
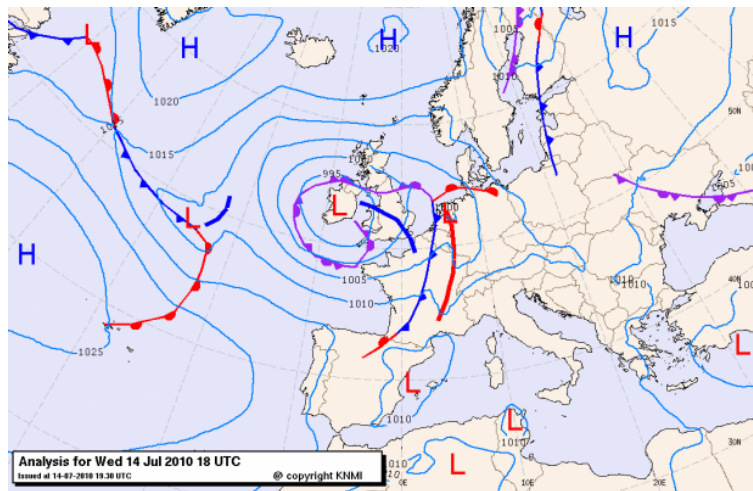
Figure 9. Weather chart of July 14, 1800 UTC. The chart shows the low pressure system south of Ireland and the cold front, displacing the warm continental air with cooler air from the Bay of Biscay, as the blue line with closed triangles.
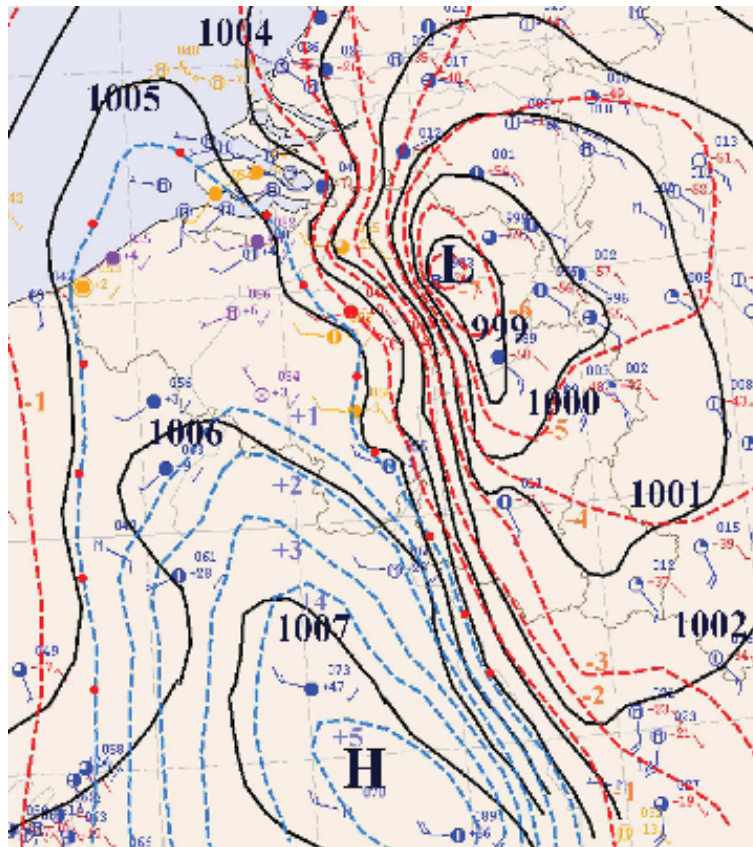
Figure 10. Synoptic analysis of 14 July 2010 1500 UTC. Isobars are solid black lines, dashed red and blue lines are isallobars, showing pressure drops and pressure increase respectively. Station observations indicate wind direction and strength and the (partly) filled circle show the cloudiness.
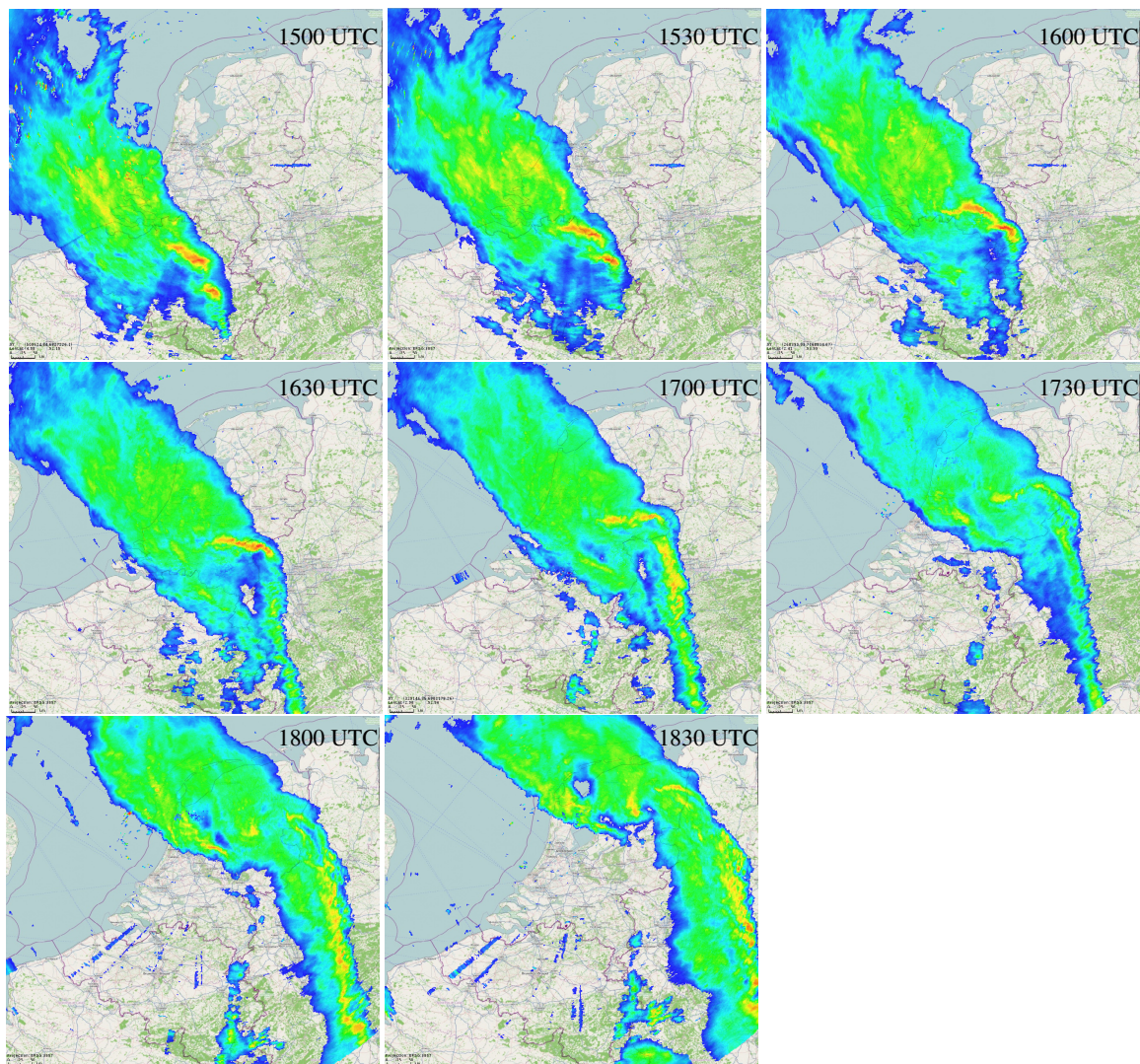
Figure 11. Rainfall intensity from radar images on July 14 2010, from 1500 UTC to 1830 UTC. The red colors denote precipitation intensities of over 30 mm/h.

Table 1. Detailed damage reports within the city of Utrecht and its immediate surroundings. Numbers refer to the locations on the map of Fig. 6.

1	Dom Cathedral
2	Abstede
3	7 windmills on the city wall
4	towers of Agnieten monastery
5	towers of St. Nicholaaskerk
6	St. Servaaskerk
7	Magdalenakerk
8	Geertekerk
9	St. Catherinakerk
10	Duitse Huis kerk
11	Mariakerk
12	roof of the Buurkerk
13	the two towers of the Pieterskerk
14	nearly all trees on St. Jans churchyard
15	inn just outside Wittevrouwen
16	Gasthuissteeg
17	St. Jobs hospital on the way to Vleuten
18	tower of St Jacobikerk
19	Begijnhof
20	gate of Bemuurde Weerd

Gottfried (1700) claims that of the 8 windmills on the city walls, only 3 were not severely damaged.