Reconstruction of Storm Frequency in the North Sea Area of the Pre-industrial Period, 1400-1625 and the Connection with Reconstructed Time Series of Temperatures

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Introduction

This paper shows how the reconstructed time series of storm frequency of the polder area west of Antwerp is extended back in time as early as 1400. It also shows how this time series[1] is verified by giving it a wider reach, including the entire Belgian and Zeeland Flanders coast. This area is of specific interest for the study of storminess, because it is very vulnerable to northern and western storms and gales, and apart from that tides rise higher in this southern part of the North Sea, especially in the estuary of the Westerschelde. Knowledge of storm frequency throughout the period 1400-1625 is of interest in order to understand the forcing of the North Atlantic Oscillation which very strongly affects weather patterns in Western and Central Europe. At the same time a reconstruction of storm frequency over a longer period enables us to have an insight in weather extremes then and how this weather pattern compares to our present climate. Although there is a connection between the variability of storminess and rainfall in specific areas, no reconstructed time series of rainfall of that period are available yet. Only several time series of temperature reconstruction enable us to find connections with our reconstructed time series of storm frequency.

In order to have high quality data that is representative for both a long period and a wider area, mainly written sources have been studied that deal with the impact of stormy weather. First these specific sources will be discussed within their historical context, then the kinds of proxy data they yield will be dealt with and after that the method that was initially developed will be explained. Finally, the main results will be highlighted and recommendations for future research will be made.

Data and their historical background

For the period 1400-1625 no instrumental weather data exists. In The Netherlands[2] instrumental measuring started in the early 18th century and in Belgium later.[3] This leaves us with only written sources that give either direct or indirect information about weather events, a kind of information that is called proxy data.[4]

Using proxy data from written sources to reconstruct climates of the past only makes sense if they meet three quality demands. Time series of proxy data need to be long, continuous and uniform.[5] In order to have knowledge of long term climate variability and to have a useful comparison with the present day climate, time series of at least half a century are needed. The kinds of series of written sources that are studied here start about 1400 and continue far into the 17th century. Secondly, the proxy data they provide is continuous for most of that period. Because several parallel time series of storm data have been studied, quality control of our data has been carried out and small gaps could be filled in order to have complete weather information of storms and high tides for the entire period. Thirdly, written sources need to give the same weather signal throughout the period in the same way. This implies for instance that storm events need to be observed and registered in the same way and at the same location. Sometimes time series give high quality climate signals, but after some decades a change in the way events and expenses were administered may render the written source useless for further climate research. In such cases this gap in the quality could be solved by using substitute written sources.

The written sources used have been carefully selected from a region in the south eastern North Sea. The area consists of the 65 km long Belgian coastal strip and the Zeeland-Flanders polders as far as Antwerp. This area is located at 51º 05´ - 51º 25´ N and at 3º 00´ - 4º 15´ E and it is a flat landscape which makes it very vulnerable to storms and gales. North westerlies blow perpendicular to the coast and tides rise higher during these events. Moreover in the Westerschelde estuary tides are funnelled and during storms and gales this results in dangerously higher water levels in easterly direction. This makes the south eastern part of the North Sea a perfect location to reconstruct the impact of high tides and storms in the present and during the past (Figs. 1 and 2.)

Fig. 1. Southern part of the North Sea and the Belgian coastal area.

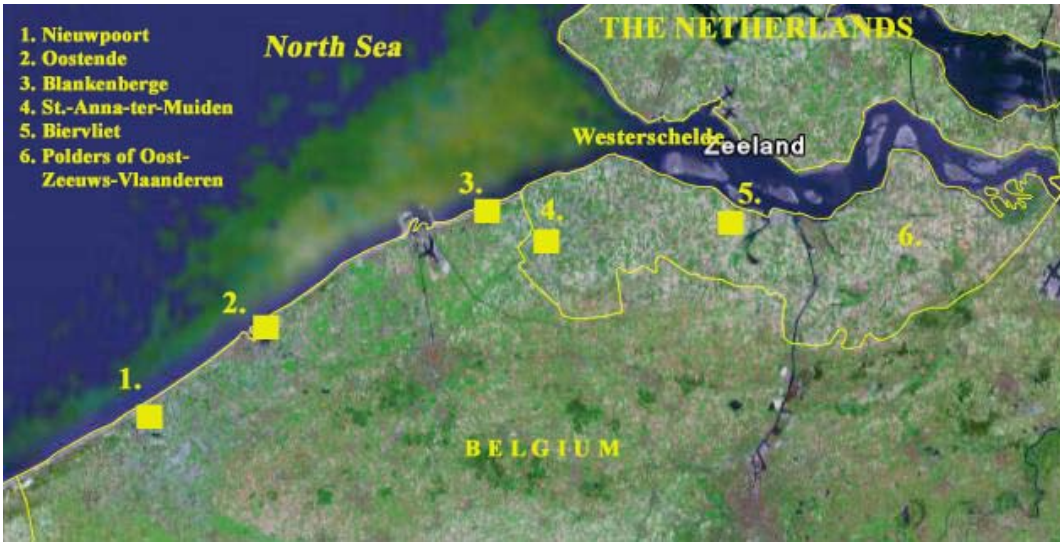

Fig. 2. Study area and its coastal towns with Biervliet and Zeeland Flanders in the Westerschelde estuary. (From Google Earth).

The kinds of sources that give information about storms and high tides of the past are the annual accounts of coastal towns and series of accounts of dyke and dune maintenance. Town accounts give special information about the maintenance of quays and wharfs and all kinds of public buildings that are vulnerable to storm events. The accounts contain information about storm and high tide events that have had a damaging impact which ranges from an indirect mentioning of damage to a precise storm date, the amount of damage it caused and its geographical reach. Consequently the same vicious storms and gales are not only mentioned in each time series of town accounts, they also occur in the dyke accounts.

Table 1. Time series of town accounts, 1400-1625. High quality town accounts in bold and marked with * partly studied.

Name	*characteristics*	*climate*
Biervliet	**seaport town (fisheries and salt)**	**storms**
Blankenberge*	village on dune coast (fisheries)	storms
Bruges	international market town	storms
Damme	small commercial town	storms
Diksmuiden	small town behind the dunes	storms
Veurne	small town behind the dunes	storms
Monnikerede	small town on the Damme canal	storms
St.-Anna-ter-Muiden*	village on the Zwin	storms
Nieuwpoort	**seaport town (fisheries)**	**storms**
Oostende	**seaport town (fisheries)**	**storms**
Oudenburg	village behind the dunes	storms

Because area no. 6 has already been studied, accounts of towns located on the Belgian coast were added along with additional dyke accounts that go further back in time than 1488. After having adapted the three quality criteria, eight out of eleven initially selected series of town accounts had to be left out.

Nieuwpoort is an old seaport town, which economy was based on herring fishery.[6] It flourished during the late 15th and the 16th century and shared many common interests with its neighbours (Dunkirk and Oostende). The Nieuwpoort town accounts are very important, because they give information about the maintenance of the dunes, the cities harbour, dams, quays, groins, sluices and some large buildings such as lighthouses, which very often results in a description of the impact of high tides and storms in terms of damage.[7] Until the 1520s the town account gives very detailed information on a weekly (sometimes even daily) basis in terms of a full report of maintenance work carried out and expenses made by officials travelling to neighbouring cities or to the government to report damage events. Some of the information even covered several pages of the town account rendering it an excellent source for proxy data on high tides, storms and gales. Unfortunately this changed during the 1520s when detailed reports were left out and replaced by summarized entries. From then on detailed reports were exclusively used as receipts at the time the account was checked and eventually they got lost and only the huge gales and storm surges were recorded in the Nieuwpoort accounts.

The Oostende and Nieuwpoort accounts are very similar in terms of content and layout.[8] During the 1450s Oostende built its first harbour which resulted in a lot of information about high tides and storms in the town account. Moreover this information could also be verified by comparing it to the information coming from the Nieuwpoort accounts. Again during the first quarter of the 16th century the administration of the Oostende account changed; detailed entries were replaced by summarized entries which resulted in a huge loss of weather information. The remaining accounts of the 16th and 17th centuries only provided information about a few huge storm surges.

The village of Blankenberge (no. 3) is located further north along the Belgian coast. During the period under consideration this was a small fishery village. It did not even have a harbour but it had to maintain parts of the dunes that could be damaged during high tides and storms. Unfortunately the rather thin accounts of this place eventually proved to have little or no use for the reconstruction of high tides and storm events.[9]

Still further north along the coast and located on the tidal inlet of the Zwin was the small town of St.-Anna-ter-Muiden (no. 4). This town was part of the harbour of Bruges-Damme-Sluis. Although this small port had to maintain different kinds of dykes and dams and also harboured a modest fishery fleet, the thin annual accounts proved to have hardly any interest to our subject.[10]

Biervliet (no. 5) was also a small seaport town that made a living from herring fishery and from salt production.[11] Moreover, the town was completely surrounded by the sea and Biervliet had to maintain dykes that suffered from damage during high tides and storm events which was recorded in the annual accounts.[12] The town's salt production is a very special source of weather information. Salt was extracted from peat that was dug out in the vicinity of the town. After it had been dried the peat was burned and the ashes were put in large pans with boiling water. These pans were placed in small wooden sheds that were covered with reed roofs. The evaporation of the water produced a kind of salt compound at the bottom of the pans. This process was repeated several times by using water from the estuary of the Westerschelde. About 1400 only French salt was being refined in the sheds in the same way.

As a result in Biervliet numerous fires were continuously burning. Such a situation could easily get out of control during windy and very dry or hot weather. Because of this risk, people were hired on windy and stormy days and during long spells of drought to keep a close watch on the sheds. The town account has registered all of these stormy days and in most cases it was registered whether it was stormy or just warm or dry weather. Data control through verification of the Biervliet data with those of Nieuwpoort and Oostende enables us to establish the exact weather event that occurred on a particular date.

As the town of Biervliet was also located on a small island consisting of several small polders it had to protect itself by dykes, that were vulnerable to high tides and storms. The information about dyke maintenance was split from the town account in 1516/7 and included in a separated series of dyke accounts.[13]

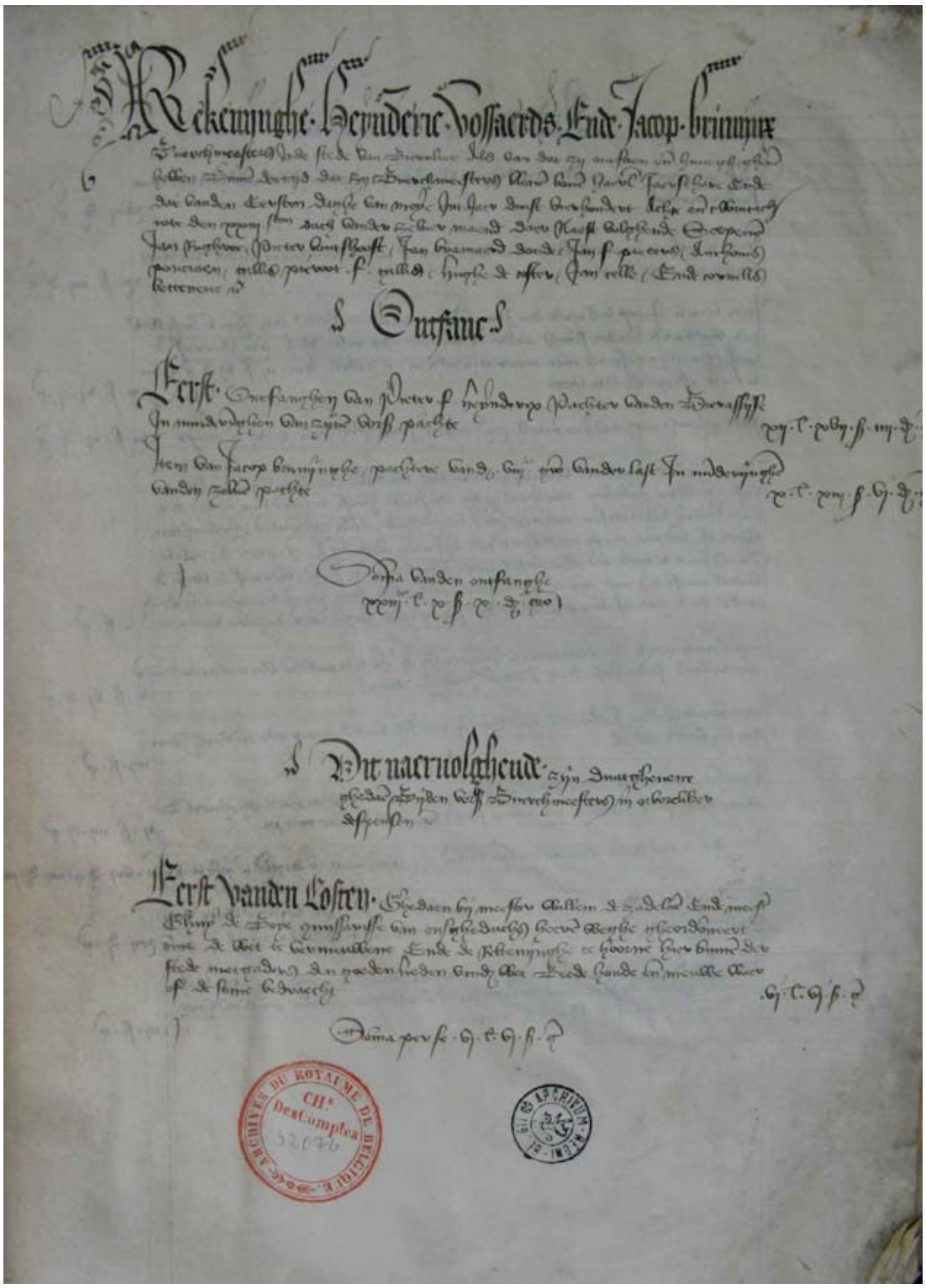

Fig. 3. First page of the Biervliet town account 1438-1439 (AGR CdC, no. 32,076)

Increasingly so the polders east of Biervliet (no. 6) faced higher rising tides and during storms the tides were funnelled up resulting in more damage to the dykes. Whereas the many dyke accounts and reports of damage during storm events and storm surges for the period 1488 to1609 have already been studied, only some additional series of dyke accounts prior to 1488 have been studied further.[14]

Finally all of the information of the written sources has been compared to two major studies about past weather conditions in the Netherlands in general and storm surges in particular. The first one is a study of storm surges and river floods in the Netherlands, which is a kind of compilation work that was carried out by Gottschalk[15] in order to distinguish fact from fiction. The second major study has been carried out by Buisman and Van Engelen, this work contains all kinds of weather events in the Low Countries and is in fact a kind of published of weather data base.[16]

Discussion of Data

First some general features of the data will be discussed, then specific data from the written sources will be discussed in more detail.

After having applied the historical criticism and additional quality checks to the written sources and the proxy data they yield, only three major time series of town accounts qualified as useful sources of information about high tides, storms, gales and storm surges: Nieuwpoort, Oostende and Biervliet. Although some information could be extracted from the Blankenberge and St. Anna-ter-Muiden accounts, most important information about high tides and storm events came from several series of dyke accounts and similar sources from the polder area east of Antwerp.

The series of written sources cover the 15th and 16th century well, except for the Biervliet location where the salt production stopped in 1544. This series was replaced by a series of dyke accounts of the island of Biervliet. Considering the number of accounts the written sources of Nieuwpoort, Oostende, Blankenberghe, St.-Anna-ter-Muiden and Biervliet, the coverage for the 15th century is 81.5%, for the 16th century 87.6% and for the 17th century 76.0%.

Because high tide and storm events are presented largely uniformly in the accounts, gaps in the Oostende accounts could be solved by using the Nieuwpoort accounts, etc. In this way even the minor high tides and storm events could be discovered and checked. Cross checking of time series proved to be of particular interest for the period that the Nieuwpoort and Oostende accounts did not any longer include detailed reports on damage and public works carried out anymore. The sudden change in including only summarized entries caused the loss of a lot of vital information on storm and high tides.

In order to know which storms and high tides occurred between 1400 and 1625 and how many, the written sources inform us in two ways. First, there is a mention of the storm events. Secondly, the accounts inform us about the money spent on damage and the type and the amounts of material used to fix it. Let us first look at the type and the amounts of material used in cases of damage.

The Nieuwpoort accounts give information about the damage caused by storm events to public buildings, its quays, wharfs, sluices and groins. Fig. 4. shows the number of weeks spent on the construction and repairs of reed and straw roofs in the city. Most significantly roof fixing increased between 1520 and 1565, while the earlier period does not show any conspicuous roof fixing. Although it is temping to look for a direct link between an increase in storminess and roof repairs caused by storms, we should keep in mind that because of it's booming herring fisheries during the 16th century Nieuwpoort was a fast developing city which resulted in an increase of the number of buildings. On the other hand, if we focus only on the 16th century there is a direct link between increasing damage to reed and straw roofs during the 1530s and the occurrence of two major storm surges in 1530/2 and 1552 (Fig. 5.). Evidence to support this direct link comes from the Biervliet accounts. The town was severely hit by the storm surges of 13th of January and 15th of February 1552. Two thatchers worked for 28 days to repair the roofs of the town hall and the market which were partly destroyed by the two tempests.[17] In addition to this kind of information it also becomes clear that the two tempests must have reached Beaufort 10 or even more.

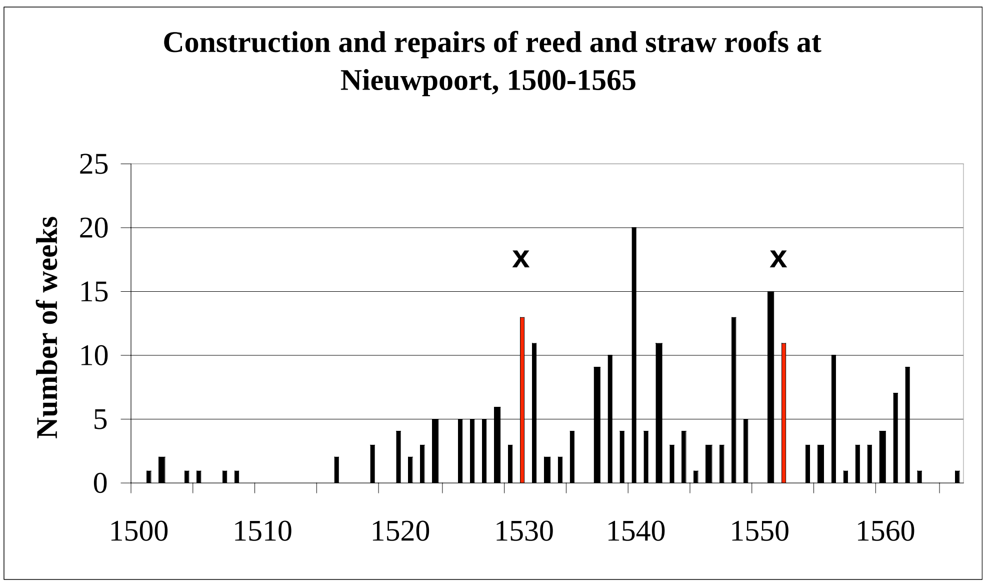

Fig. 4. Number of weeks working on repairing reed and straw roofs at Nieuwpoort, 1500-1565 with the marked (x) storm surge years 1530/2 and 1552.

The correlation between increasing damage to reed and straw roofs and storminess is only noticeable in two instances of major storm surges and therefore it is too weak a connection to be able to measure storminess throughout the entire period. Therefore we also need to look at the damage caused by high tides and storms to dunes, dykes, wharfs and quays. Because annually huge amounts of bundles of reed and sheaves of straw were used to protect the weakest parts of dykes, dunes and groins, we were able to quantify these amounts. Fig. 5. represents the number of bundles reed, straw and wicker used for annual maintenance of dunes and groins of the Nieuwpoort (Ni) and Oostende (Oo) harbours. This graph shows a variability in time including years of a strong increase in the amounts needed for maintenance that coincides both with storm events and extra repairs that had to be carried out after years of 'neglect'. In some cases the town's clerk had forgotten to register last years amounts. Some of the peaks are simply explained by a fast development of one of the harbours.

Looking at the annual numbers of reed, straw and the amounts of sods used at Oostende to fix damage caused by high tide and storm events even less peaks can be distinguished. Moreover it seems that severe damage caused by major storm events, such as major storm surges is answered for in separate accounts of which most have been lost by now.

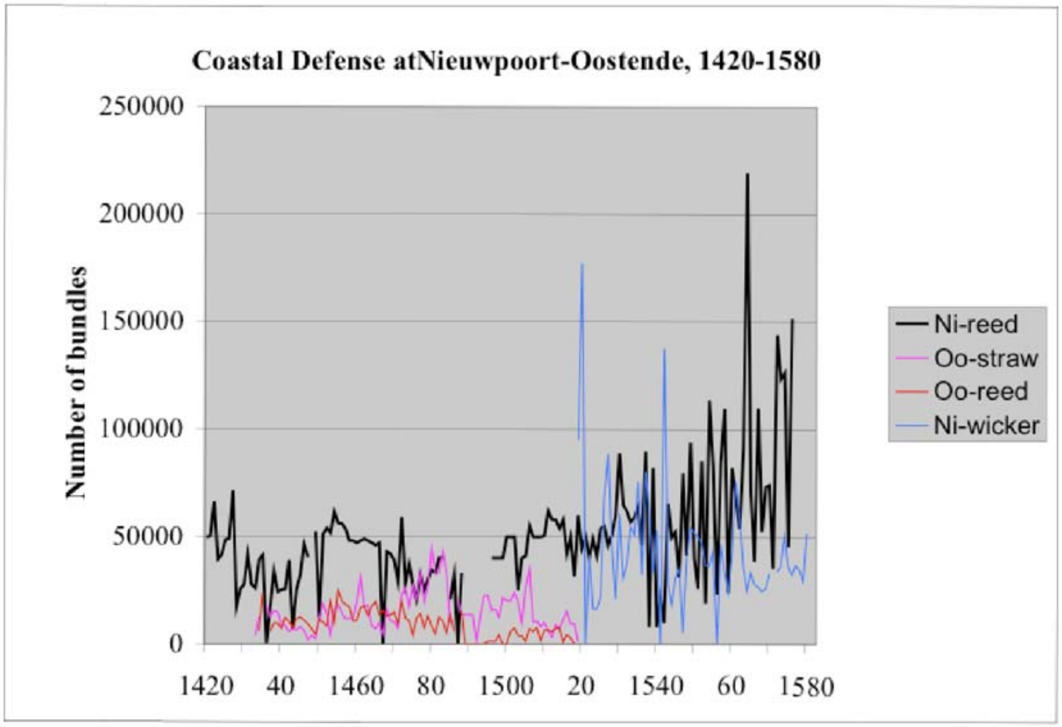

Fig. 5. Use of reed and straw for coastal protection and annual maintenance at Nieuwpoort and Oostende, 1420-1580.

Because of the inflation during the period and because of the fast development of the city and probably also its harbour it is hard to distinguish the part that high tides and storms may have played. Although the amounts of reed and straw used for dyke and dune maintenance can be indicative for high tides and storm events, this kind of information cannot be used exclusively for reconstruction of storminess throughout the period.

This in fact mainly leaves us the mentioning of storm and high tide events, the precise year or date and the amount of damage as far as Nieuwpoort and Oostende are concerned. For instance a group of workers was employed on 17th of November 1404 on the dunes of Nieuwpoort during the "great flood". Work continued for several weeks and also included fixing the large holes that were caused by the flood.[18] And at Oostende on the 3rd of January 1496 a gale had knocked out the doors of the lock of the harbour.[19]

Fig. 6. Paragraph of the Biervliet town account of 1428-1429 about the fire prevention (AGR CdC, no. 32076).

The Biervliet town accounts provide information about damage caused to dykes by high tides and storms and also give the number of stormy, hot and dry days during which the salt pan fires had to be guarded. On 20th of December 1407 there was a risk of fire in salt sheds, because of a long period of freezing drought.[20] Another period of long drought occurred in March-April 1451 during which sharp winds also raised a fire hazard.[21] In 1410/11, 1417/18 and 1468/69 fires got out of control at Biervliet. In nearly all cases of dates of fire prevention mentioned in the Biervliet town account the combination of hot, sometimes even cold and dry weather along with sharp winds is vital for causing large scale fires. Unfortunately about a quarter of the accounts is missing (blank bars in Fig. 7) and that the 16th century ones are less informative about fire prevention, nevertheless the annual number of stormy, hot and dry days during which a fire guard was needed, can be shown.

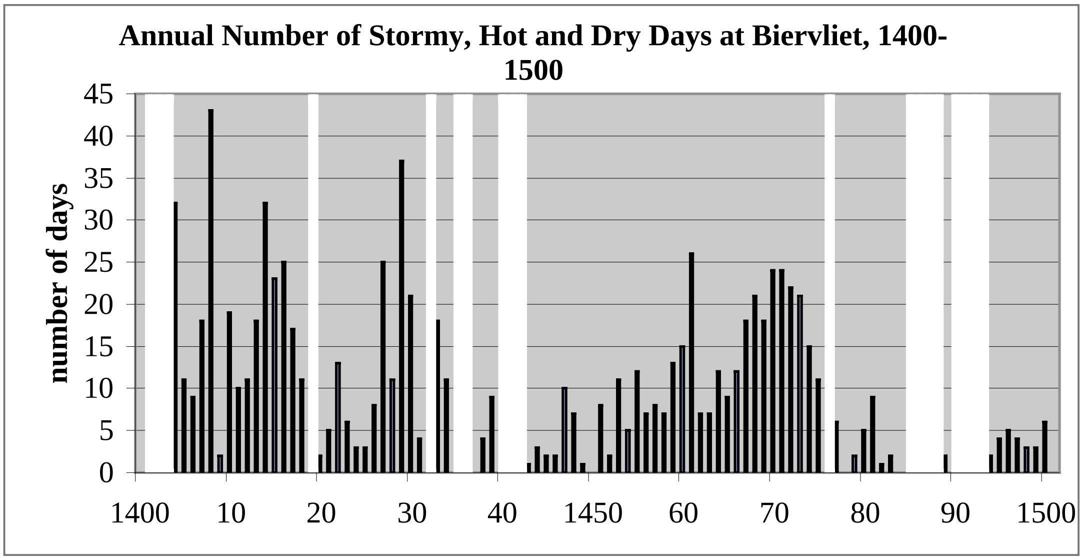

Fig. 7. Graph showing the annual number of days of fire prevention at Biervliet, 15th century. White bars represent missing years.

Fig 8 also shows a variability of storminess throughout the 15th century with three peaks of storminess. The first lasted from 1400-1418, the second 1423-1431 and a third period started about 1452 and continued until the beginning of the 1470s. It is hardly possible to assess the wind force during the days that fire prevention was needed. Considering the large stocks of dry peat and reed and the straw covered wooden sheds that could very easily catch fire, wind force could range from Beaufort 5, 6 or even higher. Experimental archaeology could possibly supply an answer, but so far it has not.

Method

In spite of the fact that most of the weather data discussed so far can be indirectly or directly connected to storms and similar weather events, it remains impossible to obtain an overview of storms of or even to have a storm frequency throughout the period. Therefore direct and precise information about storms and high tides needs to be used that comes from the town account's entries that deal with dyke and other kinds of maintenance mentioning the date of the storm event, the extent of the damage and other specific information. Similar information is provided by the numerous dyke accounts from the polder area located between Biervliet and Antwerp.[22] In order to get an insight into the variability of storms throughout the period 1400–1625 first an annual inventory of high tide and storm events needs to be made. Such an inventory already exists (1488-1609), but also needs to includes the new high quality data coming from the written sources discussed so far earlier on. This data base can then be extrapolated back into time.

Basically, there are two ways of reconstruction storminess. The first and by far the easiest way is by just counting the number of weather events.

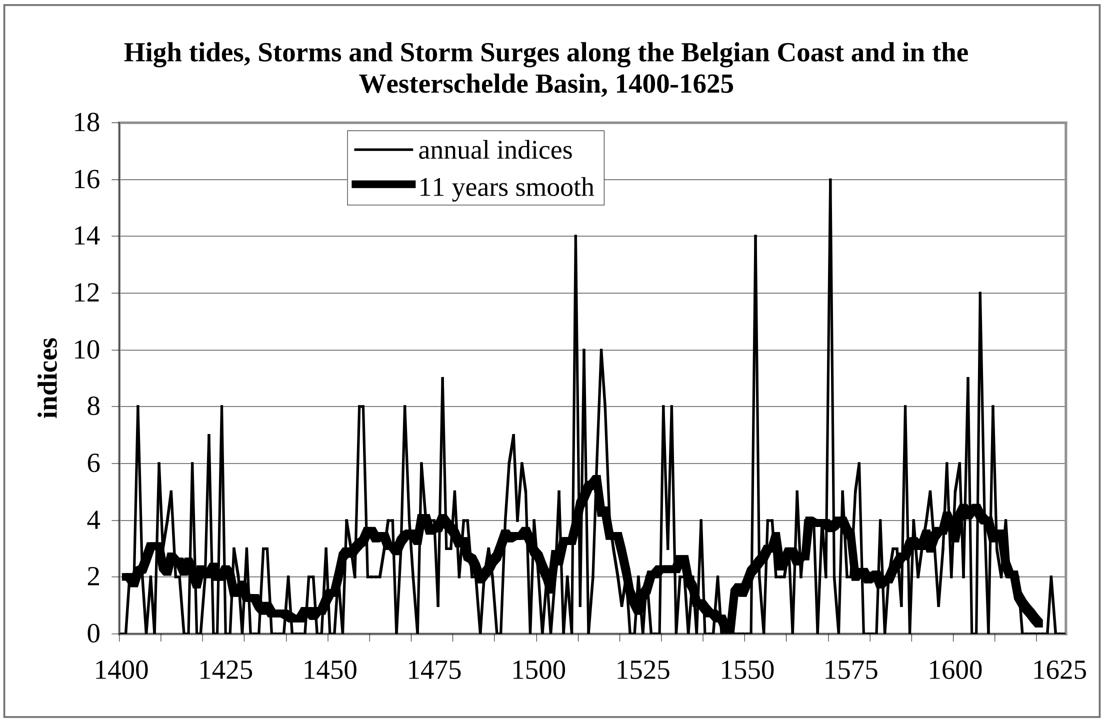

Fig. 8. Annual number of high tides, storms and storm surges on the Belgian coast and in the Westerschelde estuary, 1400-1626.

However, this does not justify the impact individual storm events may have had. An event may occur at one place, while it is not mentioned at another place. A storm event may have caused huge damage all over the coastal area, such as flooding and it may be mentioned in numerous entries in all accounts. Therefore additional criteria are needed. These criteria can be summarized in four categories.

- Wording system or vocabulary which takes into account the way the events is described, such as high tide, flood, storm or tempest, sharp wind, etc.[23] For instance a 'high tide' should be assessed differently from a 'severe flood.'
- Size of the damage in terms of the number of acres flooded, the amounts of reed, straw and sods used for repairs.[24] Several breaches in a dyke should be assessed differently from sand being blown off the dunes near Nieuwpoort.
- Locally, regionally determined or having a much wider range. High tide and storm events that occur at several locations, for instance Nieuwpoort, Oostende, Biervliet and in terms of serious damage to dykes in the polders east of this town need to be assessed differently from the mention in terms of a storm that only occurred at St.-Anna-ter-Muiden.
- Duration of the event: one high tide or three spring tides during a severe storm surge. Especially storm surges may last for more than just one day. 'Long' lasting storm events cause the second or third high tide (spring tide) to rise even higher than the first and is therefore to be much more damaging.

These four criteria and their variables have been included in eight categories resulting in the method that has been established earlier. This method is still valid and only needs to be adjusted in some detail.

Table 2. The eight categories used in this study with a short characterisation of the high tide or storm event and description of specific features.

Value	Phenomenon	Consequences, spatial scale, duration……
1.	High tides	no damage, only mentioned once
2.	High tides	coinciding with storms, causing damage
3.	Storms	causing damage at several places at the same time
4.	Heavy storms	causing damage at several places
5.	Heavy gales	causing severe damage, even flooding
6.	Heavy gale winds	heavy and large scale damage and flooding
7.	Storm surges	general and large scale damage restricted to certain areas
8.	Storm surges	general and large scale damage in wide areas

Results and calibration

Before the final result is obtained an additional check is needed. This check is the storm frequency of the 15th century and its 11 years smooth compared to, for instance, the annual number of storms and the dry and hot weather at Biervliet (Fig. 7).

From Figs. 7 and 8. a significant connection is shown between the overall picture of storm frequency and the storm events at Biervliet. Again the three peak periods of storm events emerge. This ensures us that our method is valid to reconstruct storminess throughout the period 1400 to 1625.

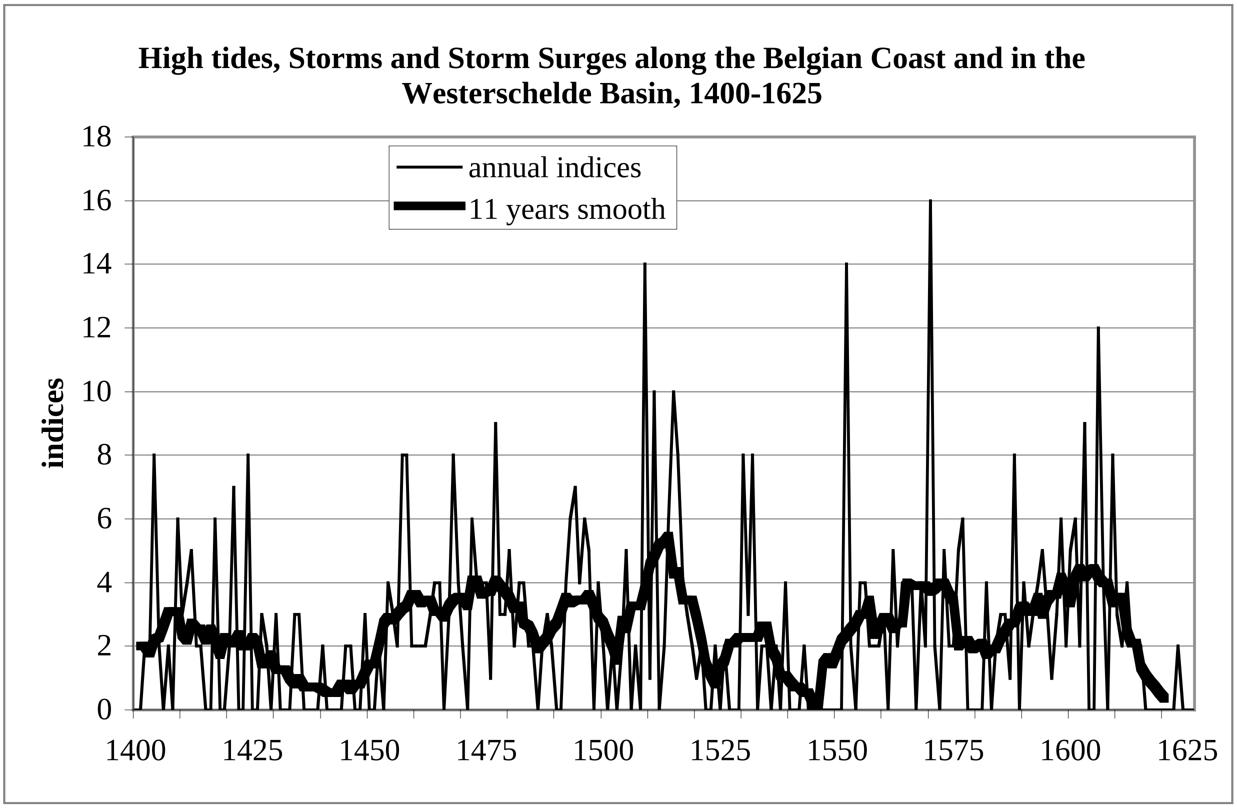

Fig. 9. Storm frequency 1400-1625 on the Belgian coast and in the Westerschelde estuary.

Surveying the storm frequency of the period 1400 to 1625, roughly five periods of increasing storminess can be distinguished:

- first quarter 15th century
- about 1460 to 1495
- 1510 to 1530s
- 1560 – 1590s
- 1610s

The next step is to look for connections with contemporary time series of weather events. There are only a few time series of reconstructed temperature and there is hardly any connection between the Mann et al[25] temperature reconstruction which represents an annual but global temperature reconstruction and our reconstructed storminess 1400-1625. The Jones et al[26] and Briffa[27] temperatures reconstruction both representing summer temperature show rather similar results, however, they cannot automatically be used. In spite of their extra-tropical nature they remain far too general and besides disagree amongst themselves.[28]

This brings us to use the temperatures reconstruction of the Netherlands developed by Van Engelen of which we have used the time series of indices.[29] There only seems to be a fair connection between the increase of storminess and summer warming on one hand and the decrease of storminess and summer cooling during the 15th century on the other hand (Fig. 10). A comparison of both features for the entire period 1400-1625 hardly shows a distinctive connection between storminess and winter temperature (Fig. 12).

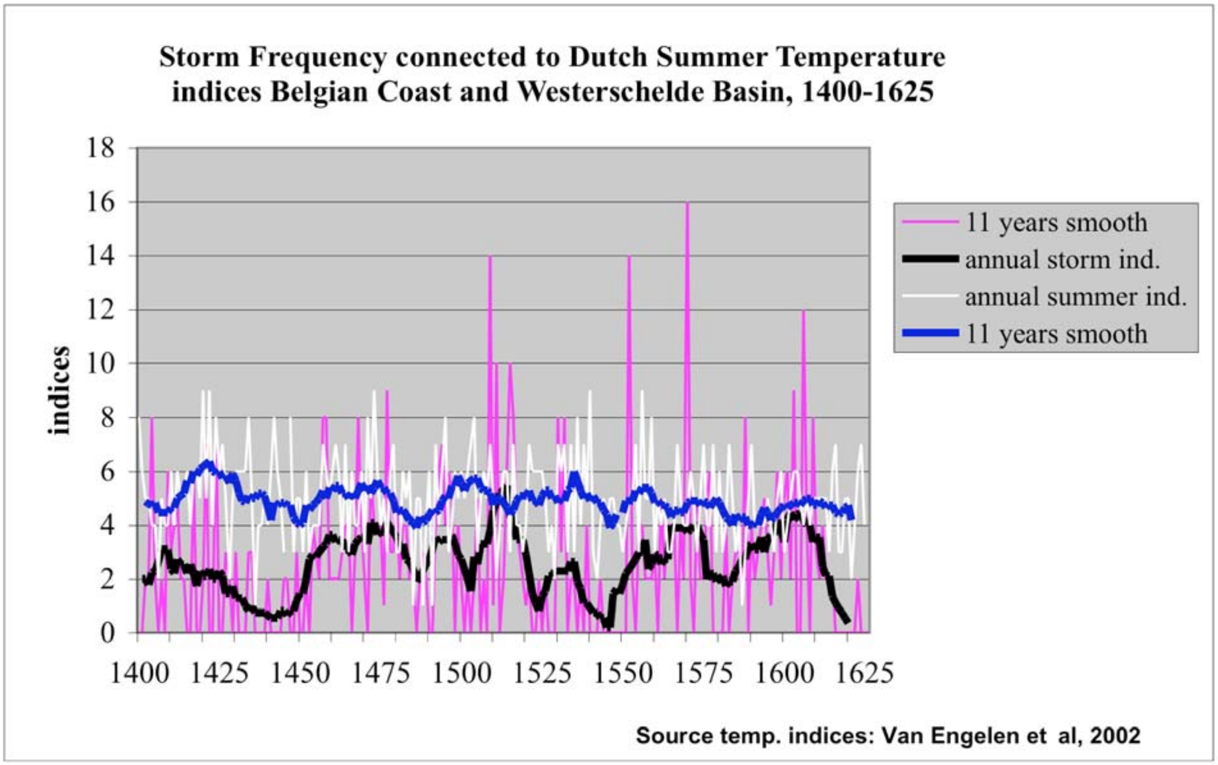

Fig. 10. Connection between storm frequency and annual summer temperature, 1400-1625 on the Belgian coast and in the Westerschelde estuary.

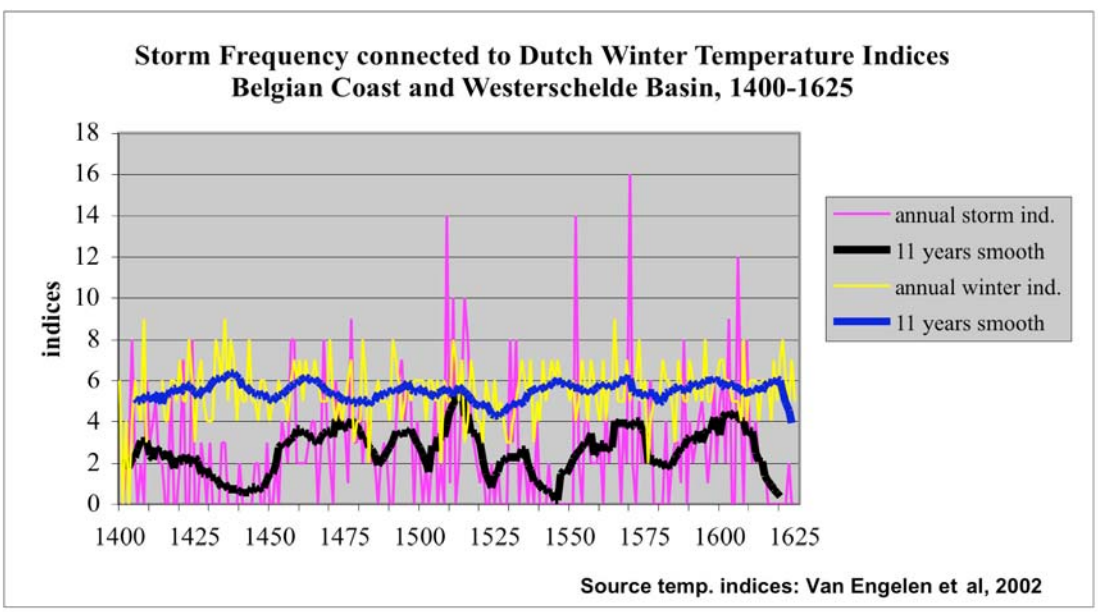

Fig. 11. Connection between storm frequency and annual winter temperature, 1400-1625 on the Belgian coast and in the Westerschelde estuary.

From the comparison of storm frequency with both summer and winter indices of temperatures there appears to be a much more significant variability in storminess than in temperature throughout the period. In order to assess whether this stronger variability is exceptional a comparison with storm frequency over the past 150 years from the Westerschelde area has been made (Fig. 12).

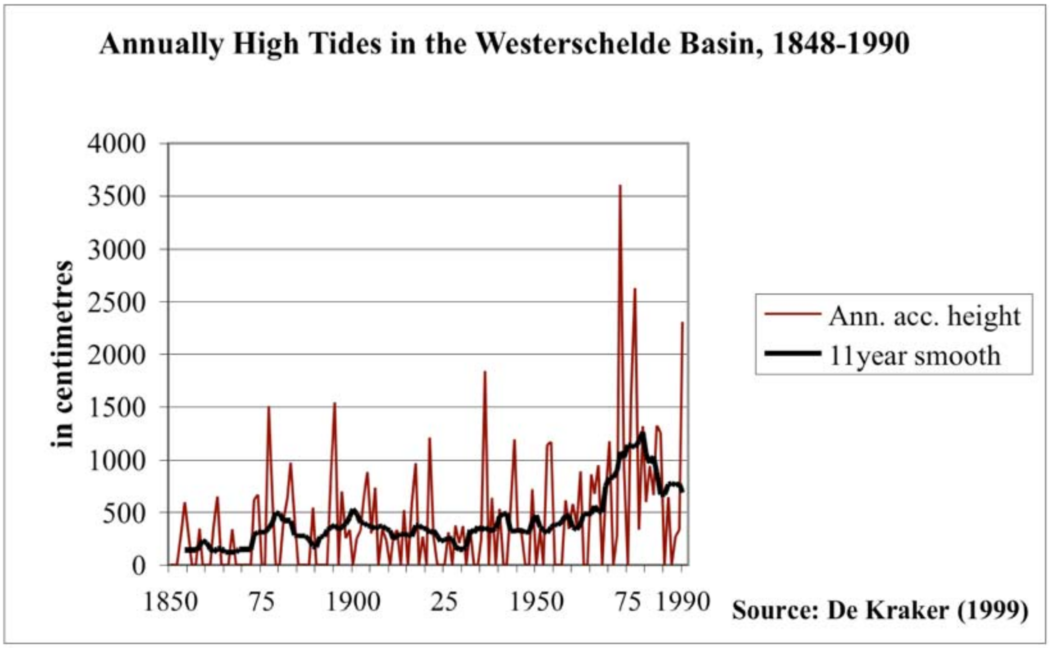

Fig. 12. Storm frequency 1850-1990 in the Westerschelde estuary.

Fig. 12. represents the accumulated annually height in centimetres of high tides reached in the Westerschelde basin. Each year shows the total number of the maximum height reached by each spring tide and during each storm surge. Therefore the graph not only shows the annual fluctuation but also the general sea level rise in this area. In particular the 1970s and 80s show a strong increase in storminess which then decreases, but still remains at a higher level during the 1990s. If we plot the number of gales Beaufort 10 to 12 that occurred between 1910 and 2000 in a graph an increase in storminess which starts during the 1970s is shown. For instance in 1977 there were four days of Beaufort. 10.

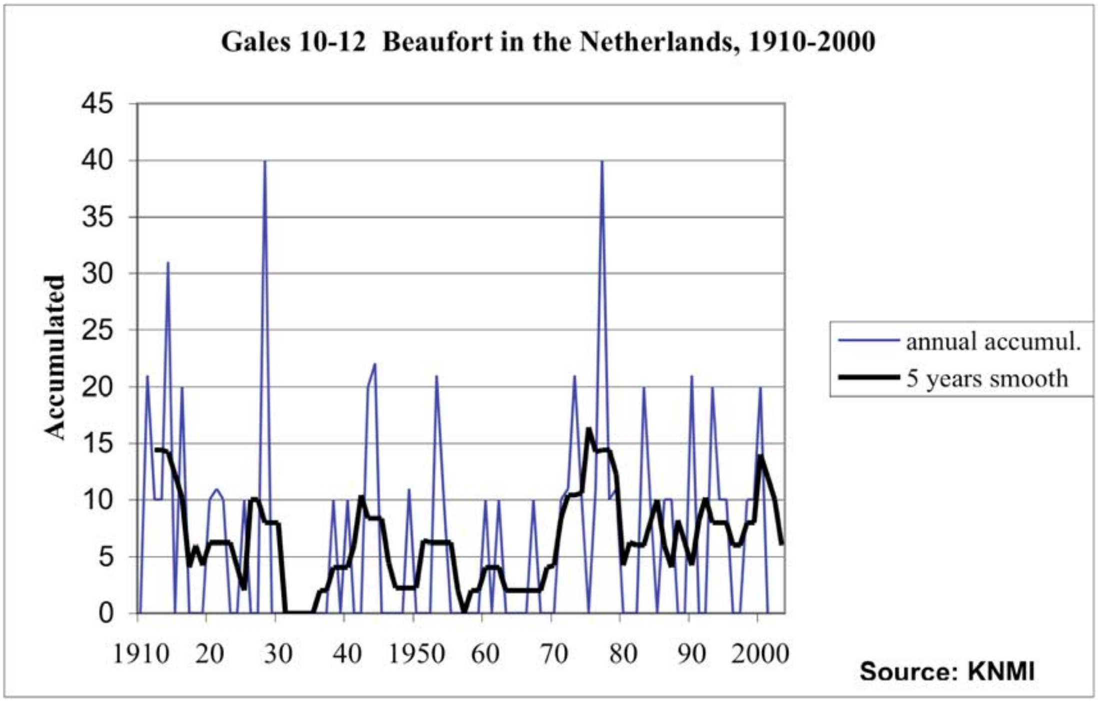

Fig. 13. Storm frequency in The Netherlands, 1910-2000

A final comparison could be made with patterns of rainfall of the period under consideration and the North Atlantic Oscillation. Whereas Atlantic storms travelling into Europe very strongly control rainfall, a direct link could be made between increasing storminess and increasing rainfall throughout for instance Central Europe. Unfortunately, there are no rainfall data sets of the period 1400-1625 available.[30] A high NAO during winter time coincides with a north-eastward orientation during which depressions push deeply into NW-Europe and should, therefore be corresponding with an increasing storminess in the North Sea area. Although it is tempting to connect the periods of increasing storminess between 1400 and 1625 to a high NAO during winter time, far more research is needed to have additional information about high tides and storm events per year and to specify these per season as well, not only for the southern part of the North Sea but also for the northern part in order to be able to assess the track of single storm events more precisely.

Conclusion

The study of proxy data from Belgian and Dutch series of written sources of the period 1400 to 1625 has provided information about high tides, gales and storm surges in the south eastern part of the North Sea. The information is of high quality because the obtained proxy data is continuous over a long period and uniform. Moreover the proxy data comes from a large area that is very vulnerable to high tides and storms and consists of the entire Belgian coastal plain and the estuary Westerschelde. Studying a larger area and using new and additional time series of written accounts has enabled us to not only verify our data but also to draw more fundamental conclusions.

First, the data base of high tides, storms and storm surges has been extended back to 1400 by adding many previously unknown events. Most of these could be dated with great precision.

Secondly, by using a method that reckons with the terminology, damage-size, geographical distribution and the duration of high tides and storm events by assessing each single event, it has become possible to reconstruct storminess throughout the entire period. From the storm frequency over 2.25 centuries five distinctive periods of increasing storminess emerge of which the second half of the 16th century stands out most strongly.

Thirdly, comparison with mean annual temperature reconstruction carried out by Man, Jones and Briffa showed a weak connection between a drop in temperature and increasing storminess. But comparisons with three that largely disagree amongst themselves proved to be very difficult.

Fourthly, the comparison with summer and winter temperature reconstruction from the period under consideration that was only carried out for the Netherlands showed a significant connection between storminess and annual summer temperature, especially for the 15th century.

Fifthly, a comparison with the sea level change of the past 1.5 centuries in the Westerschelde estuary again shows a connection between increasing storminess and accelerated sea level rise.

Sixthly, a comparison between the gales Beaufort 10 –12 of the 20st century and our reconstructed storm frequency also show a significant variability

Looking at future research on storminess this can be summarized as follows.
It is possible to push the storm frequency further back into time by a few decades by studying additional time series of Belgian accounts from the coastal area. Some decades of the period 1400 to 1625 still need some additional proxy data in order to verify the reconstructed storm frequency time series as it is now. More importantly still, is to bridge the period from 1626 to the 18th century in order to have a comparison with some of the early instrumental time series and to connect with the NAO time series and additional temperature and rainfall reconstructions. Bridging this gap can be achieved by studying the huge number of dyke accounts that date from the 17th century.

Acknowledgements

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Endnotes

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