Historic Storms in the North Sea Area, an Assessment of the Storm Data, the Present Position of Research and the Prospects for Future Research

Adriaan M.J. de Kraker

Department of Human Geography, University of Amsterdam,
Nieuwe Prinsengracht 130, NL-1018 VZ Amsterdam, The Netherlands
e-mail: Krakeram@zeelandnet.nl

Abstract: A survey of historic storms, storm surges and sea floods in the North Sea area from about 1000 to the present day reveals that there is a rather complete and reliable time series of storm surges from the period of 1400 to 1700 for the Netherlands only. However, this time series does not include storms and high floods. Such a series has only become recently available for a small polder area near Antwerp from the period of 1488 to 1609. British, Danish and German time series of storm surges, storms and sea floods are very incomplete for the period earlier than the second quarter of the 18th century. Records from the Low Countries, owing to their special documentary sources starting as early as the 16th century in combination with additional data from Britain, Denmark and northern Germany, seem to offer the best opportunity of completing a useful time series of storms, storm surges and high floods for the period of AD 1500 to 2000.

Introduction

'A great, severe and tempest flood ..., never seen the like during our life time' an official of the Chapter of Our Lady at Kortrijk in Flanders told a government committee in 1513, when he was asked what he remembered of the storm surge of 14th of December 1511 (De Kraker 1997). Large scale flood on the coasts of the North Sea on Christmas Day of 1717, more than 11.500 casualties, 100,000 cattle drowned, 5000 buildings destroyed and about 6,000 square kilometres inundated (Gram-Jensen 1985).

These are just reports of two historic storms which battered the North Sea coast and which in turn led to large scale flooding. Two extreme weather events that hit a densely populated area that may be considered to be an economically very important region, with major harbours, such as Rotterdam, Hamburg, Antwerp, Le Havre and London. Moreover the coastal zone of the North Sea (from Dunkirk to Denmark) is very vulnerable with its broad estuaries and range of Wadden isles enabling floods to penetrate deeply into the hinterland of which parts are even far below sea level. Two examples of extreme weather events quite different in time and space, which set the scene for the North Sea region at a time of storm, storm surges and sea floods. This raises the first question in this paper, whether we have a complete overview of the history of storms of the recent onethousand years. And if the answer is no, is this due to the fact that there are no sufficient documentary sources left, or was there no tradition of observing wind in the coastal zone and no attention was paid to studying extreme weather events as mentioned before? Furthermore, this paper focuses on the prospects for future research on the subject of extreme weather events, e.g. historic storms and floods in order to be able to reconstruct wind force and to discover patterns in storms and storm frequency in historical times. Finally, it must be stressed that a complete overview of the historical storms on a time scale and a geographical scale can substantially

From WEFER G, BERGER W, BEHRE K-E, JANSEN E (eds), 2002, *Climate Development and History of the North Atlantic Realm.* Springer-Verlag Berlin Heidelberg, pp 415-434

contribute to our understanding of the transportation of air masses of a different moisture and temperature over Central Europe. Consequently this might also contribute to our knowledge of the boundaries of the Medieval Warm Epoch and the Little Ice Age, of the periodicity of fisheries and even of the changing shape of the Wadden isles.

Climate and Wind Patterns in the North Sea Area

In order to understand the pattern of wind, storms and storm surges in the North Sea region and its surrounding countries or parts of these countries, it is necessary to know how air masses flow within the climate system of the North Sea region.

The movement of air masses in the region of interest is largely determined by a general high pressure over Greenland with cold air masses and a low pressure region around Iceland, fed by warm air masses from the south. The front along which the warm and cold air masses collide is dominated by bad weather, rain and wind development of cyclonic storms. As wind speeds increase, such a system can develop into a severe gale, causing storm surges and sea floods, especially during winter seasons, when they have a far greater intensity than during summers.

The movement of a strong cyclonic storm from Iceland into the North Sea may be followed by means of the pressure charts of 29th January to 2nd February 1953 (Bijvoet et al. 1960). At 12.00 h on 29th of January (Fig. 1) there was a low pressure centre south-west of Iceland (1005 mb) which moved slowly south-east. At the same time there was a low at about 40°N in the middle of the Atlantic which hardly moved at all. Over France, a strong high is seen which moved slowly towards the north-west. At 12.00 h on 30th January the Icelandic low was now south-east of Iceland and greatly strengthened, while the high pressure area moved from southern France to the western Alps. The next day, on the 31st of January, a strong low lodged between Scotland and Norway, while a weak high south west of Iceland had strengthened and extended from south of Iceland over Iceland into Spain. The pressure gradients between this high pressure ridge and the low over the North Sea became extremely strong, generating forceful northerly winds. Finally a most severe storm surge developed at the place of the low, causing perhaps the largest natural disaster in Western Europe during the 20th century.

Air masses can flow from very different directions and these directions generally determine whether these air masses are relatively cold or warm, stable or unstable. Accordingly, Lamb (1972) made a classification of wind types. His classification of winds contains eight directional types: north (N), north-east (NE), east (E), south-east (SE), south (S), south-west (SW), west (W) and north-west (NW). There are two other categories: anticyclonic (A) and cyclonic (C) and still a third when no direction or distinctive type can be defined (Kelly et al. 1997). This additional unclassifiable type is called (U).

So whenever there is an air mass passing over from the north-west which is very unstable and consequently brings much rain, this type is called CNW. Travelling at a high speed this air mass can develop into a storm or storm surge overnight. An ANE type causes a stable air mass to be travelling from Scandinavia or northern Russia towards the North Sea. During winter such a high pressure system causes a drop in temperature below 0° Celsius. During summer the same pressure system causes warm and sunny weather.

However, there is more to it than only distinguishing wind directions and this is caused by the funnel shaped character of the shallow North Sea. Consequently north-westerly winds are piling up water into the southern funnel causing severe damage on the south-west Dutch coast, while westerly winds cause waters to be piled up in the German Bight. So in this respect the Lamb classification is not only useful in reconstructing wind direction and weather types as such, but his method enables us to determine a distribution of wind types on a longer time scale, especially the westerly and north-westerly winds.

Analysis of the variability of air pressure in the Atlantic has shown significant patterns on a geographical scale as well as on interannual and interdecadal time scales. In order to quantify this kind of variability the North Atlantic Oscillation index was introduced. The NAO-index shows how the Azores

Fig. 1. W
the Nort
G.M.T. a

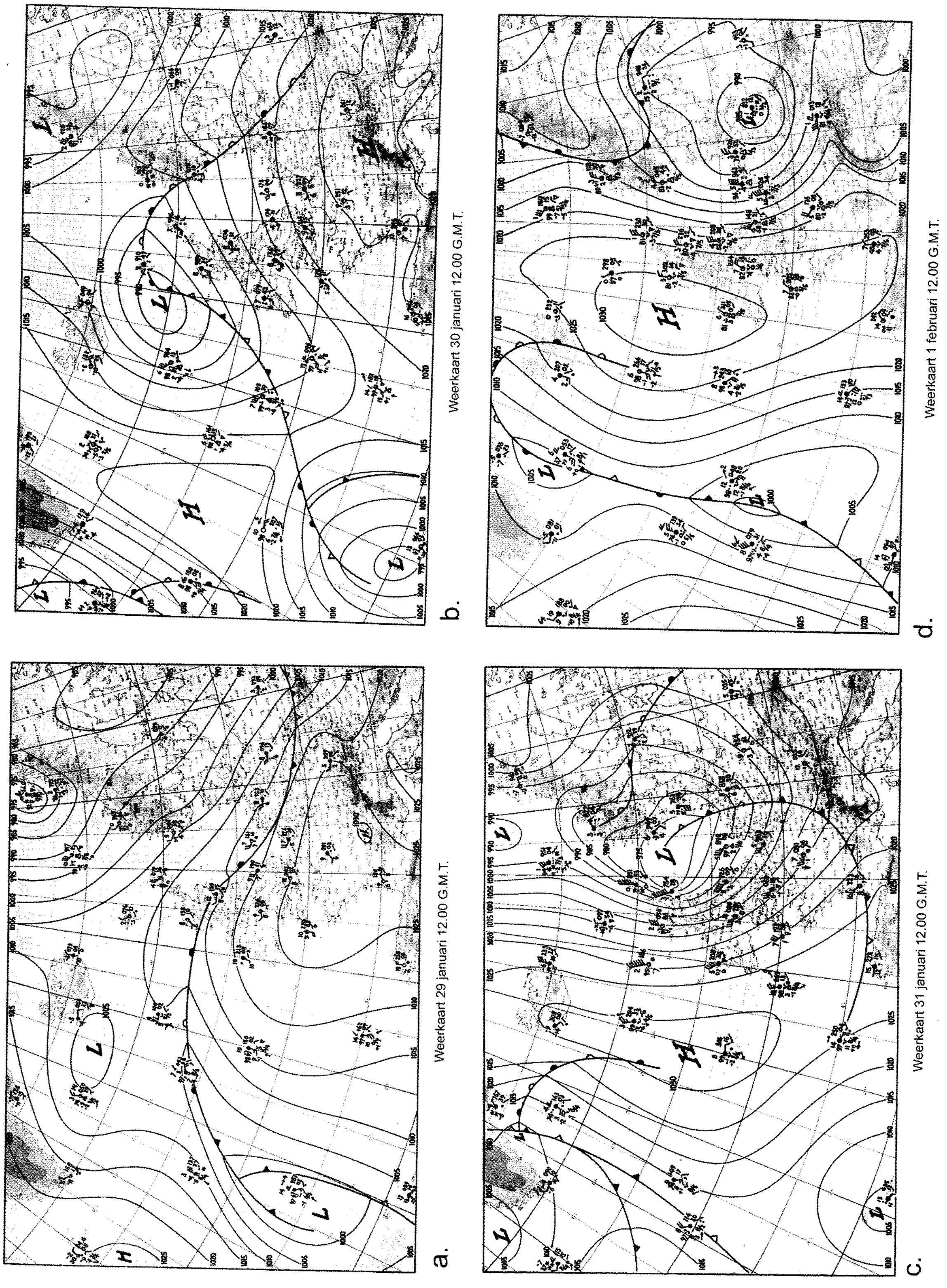

Fig. 1. Weather charts showing the development of the storm surge of 1953 in the North Atlantic area and above the North Sea: a.29 January 1953 at 12.00 G.M.T.; b. 30 January 1953 at 12.00 G.M.T.; c.31 January 1953 at 12.00 G.M.T. and d. 1 February 1953 at 12.00 G.M.T. (Bijvoet et al. 1960).

High and the Icelandic Low relate to the mean values of pressure between both air masses. If there is a positive NAO-index the differences in pressure between the Icelandic Low and the Azores High is above the average. And if the difference in pressure between the Icelandic Low and the Azores High is below average, there is, of course, a negative NAO-index. So a positive NAO-index correlates with more frequent eastward bound gales and must therefore be taken into consideration while reconstructing storms and storm surges on a longer time scale in the North Sea Region. Moreover, a positive NAO-index strongly correlates with the cyclonic W and NW-types from the Lamb classification of wind directions.

Survey of Historic Storms

In this chapter an attempt is made to see whether we have a complete overview of storms on a thousand years, time scale in the North Sea region as such and parts of it, such as the Dutch coast, the north western coast of Germany, the western coast of Denmark and the entire eastern coast of Britain. Therefore we need to know what the results are of the investigations on the subject under discussion carried out in these four countries and how these have contributed to the completing of the time series of storms.

The Medieval Period until 1800

Lamb and Frydendahl (1991) mention a storm that occurred around 120 BC, however his time series only starts in 1500. Gottschalk (1971) only considers the storms of AD 583 and AD 838 to have enough credibility to be considered as the oldest storms recorded in the Low Countries. For the German Bight Gram-Jensen (1985) found the first reliable storm for the period 1400 to 1449 (Table 1). For the medieval period a particularly great frequency of storm surges in the 14th century for the Netherlands can be distinguished. Gottschalk (1975) also noticed a marked increase of storm surge activity during the 1420s and from 1460 to 1483.

For the 16th century much more reliable documentary sources are available Consequently the reliability of the storm observations as mentioned by Gram-Jensen (1985) is now 73%. To the end of the century the number of storm observations for Denmark seems to be larger than for the Netherlands. This is partly explained by the fact that Gottschalk was interested in storm surges only, leaving out all other storms of minor importance. Her findings for the German part of the North Sea coast for the four quarters of the 16th century are: 6, 7, 8 and 13. Whereas this survey of the 16th century storms remains far from complete, no mayor conclusions may be deduced from the Danish, German and even British historical evidence, except for the fact that there seems to have been an increase in storm surges along the German and Danish part of the North Sea during the first decade and again starting from the middle of the 16th century. Recent research results of storm surges and the minor storms (De Kraker 1997, 1999) from the Wester Scheldt estuary, in-cluding all high tides, suggest a very unequal distribution of storms throughout the 16th century. It also reveals much more detail about every particular storm, storm surge sea flood that occurred in that small area.

For the 17th century storminess and storm surges tend to hit the northern part of the North Sea more frequently. But again the geographical scale is quite different. The storm surge that led to a large scale inundation in the southern Netherlands on 26th of January 1682, is not mentioned by Gram-Jensen (1985), nor by Lamb and Frydendahl (1991). Again it is impossible to have a complete picture of the 17th century storms, because the historical evidence shows some severe gaps and is by no means uniform and continuous.

On the other hand, Lamb has shown clearly that towards the end of the 17th century it becomes possible to use pressure maps, reconstructing historic storms and storminess for the period storms lasted. However, these maps can only be used as soon as a period is sufficiently covered by detailed storm observations (Douglas et al. 1978; Kington 1994; Pfister et al. 1994).

For the 18th century still more detailed information about storms and sea floods is available, especially from the instrumental recording of weather. Unfortunately, in the Netherlands this period has not been investigated yet. Only for the second half of the century data are available from the small

	Netherlands (Gottschalk 1971-1977)	Denmark (Gram-Jensen 1985)	Germany (Rohde 1977)	England (Lamb et al. 1991)	Vier Ambachten (De Kraker 1997)
< 1000	1	0			
1000-1099	2	0			
1100-1199	4	0			
1200-1299	6	0			
1300-1399	12 to 14	0			
1400-1499	17 to 20	0			
1400-1449	7 to 8	1			
1450-1499	11 to 13	0			
1500-1524	8	0		1	31 to 36
1525-1549	4	4		2	7
1550-1574	3	11		2	37 to 38
1575-1599	3	18		3	35 to 38
1600-1624	6	29	9	1	
1625-1649	1	30	11	2	
1650-1674	4	13	17	9	
1675-1699	3	11	13	9	
1700-1724		23	6	4	6
1725-1749		9	2	10	3
1750-1774		12	2	4	
1775-1799		10	22	9	

Table 1. Storm surges, storms and high tides in the North Sea Area, 838 to 1800.

coastal area along the Wester Scheldt, mentioned earlier. Evidence from Denmark is different again, especially for the first quarter of the 18th century, while storm and flood data from the Netherlands, the British Isles and Germany are very similar. Some of the storms and floods recorded between 1702 and 1704 were observed at Hamburg and on the British coast as well, e.g. the storm of 8th of December (Fig. 2).

The storm surge of 3rd and 4th March 1715 (Tables 1 and 2) seems to have caused disaster on the southern Dutch coast only, while the 1717 storm surge caused large scale flooding on the German and on the Danish coast, but was only mentioned in the southern Netherlands as just another severe storm. Recent study by Jakubowski-Tiessen (1992) has shown that the 1717 storm surge was by far the severest natural disaster that hit that part of the North sea coast, causing 'only ' 8374 casualties.

During the last quarter of the 18th century there seems to have been a strong increase in high floods on the German coast, which cannot be attributed to the fact that more measurements became available. For Hamburg alone values for the four quarters of the 18th century are respectively 5, 2, 2 and 22.

Thus in spite of the more detailed information on storms of the 18th century much remains to be investigated still, particularly for the early part of it. Questions such as, do we know all relevant storms and sea floods, do our data cover the entire region around the North Sea, and do we have

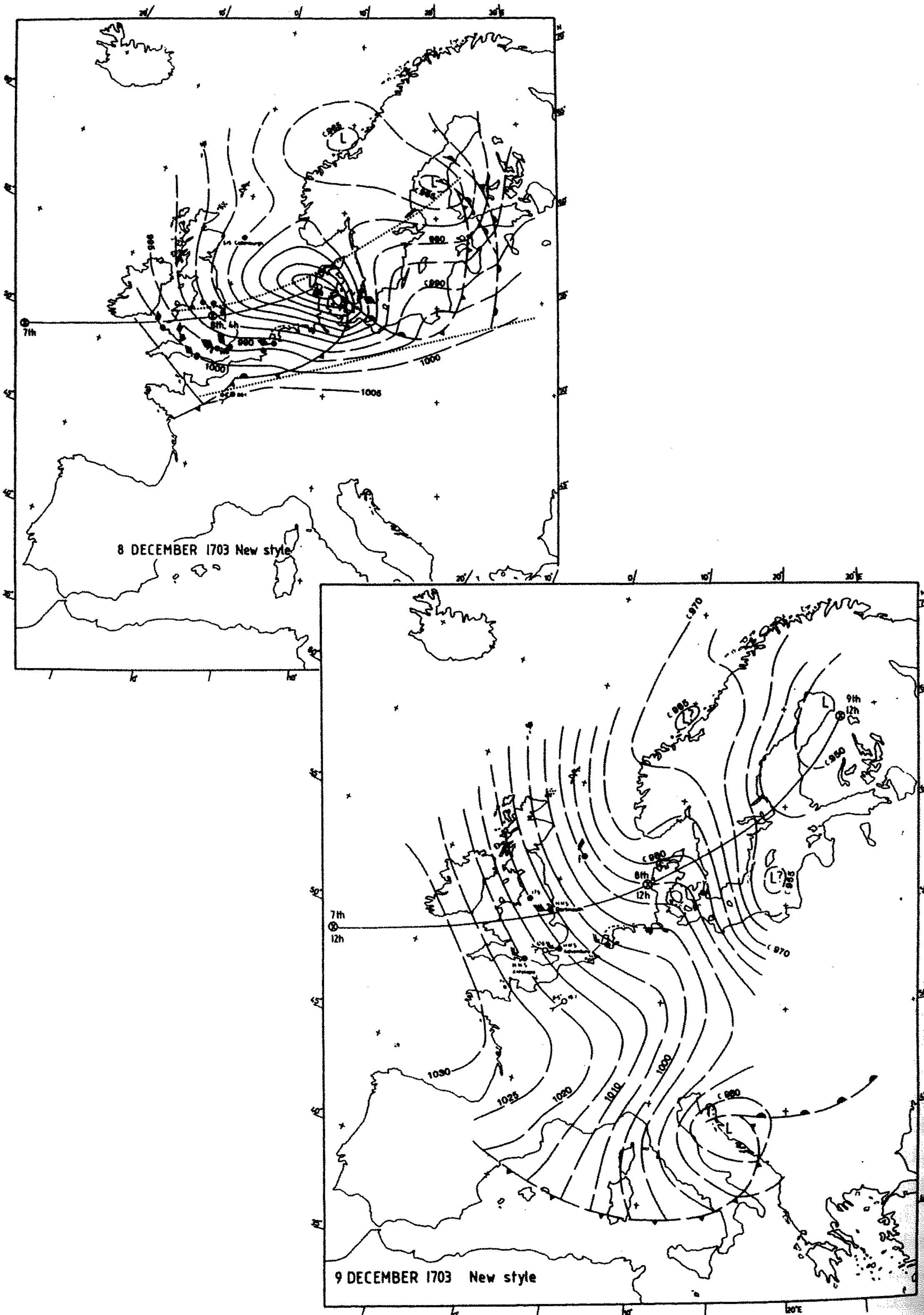

Fig. 2. Storm surges of 8th and 9th of December 1703 (Lamb and Frydendahl 1991).

date	Hamburg	Embden	Damgast	Cuxhaven	Bremerhaven
1701, 17 Oct.	433 cm				
1702, 28 Febr.	444 cm				
1703, 8 Dec.	468 cm				
1715, 4 March	477 cm				
1717, 24 Dec.	562 cm	462 cm	490 cm	(425 cm)	(465 cm)
1720, 31 Dec.		398 cm			

Table 2. Water levels and storm surges on the German coast, 1700-1725 (Source: Rohde 1977).

details of known storms necessary to be able to determine their importance in time and space, can only be answered following more research in different areas around the North Sea. Jakubowksi-Tiessen not only has corrected recent research results (Gram-Jensen 1985) considerably but makes us again aware of the need to be careful in using older studies for the reconstruction of 'historical' weather observations (Arends 1833).

Storms, Storm Surges and Sea Floods of the 19th and 20th Centuries

Data for storms, storm surges and sea floods of the 19th and 20th century are as complete as they can be. Unfortunately and in spite of the large quantities of accurate data of 'Rijkswaterstaat', the picture for the Netherlands remains far from complete.

Table 3 shows a large number of storm surges on the entire Dutch stretch of the North Sea coast. This large number is partly due to the way storm surges have been registered. When a severe northerly or westerly lasted longer than one day, of course it caused two or even three storm surges at each high tide as given in column A. Considering two or three successive storm surges as being one severe gale, the corrected figures for the Netherlands are given in column B. Still it can be concluded there was a considerable increase in the number of storm surges and consequently in storminess during the second half of the 20th century on the Dutch coast (Van Malde 1996; De Kraker 1999). The same is concluded by Rohde (1977), Gram-Jensen (1985) and Lamb and Frydendahl (1991) for the British Isles (Fig. 3). Higher frequency in the number of storm surges and storminess is closely related to the slow rise of the general sea level, at least as far as the North Sea is concerned (Jelgersma 1992).

It is clear that there is a general but, especially during the 19th century a very irregular sea level rise. This in turn calls for a careful comparison with time series of temperature and wind patterns and the reconstruct on maps of surface air pressure covering the period from 1850 to 2000 (see below).

Judging from the overview of storms on a thousand years, time scale and on a geographical scale for the North Sea region, it is clear that this does hardly exist. This makes it impossible to deduce general conclusions from the present state of research on storms and storminess in this area. In fact, this leaves us with the question, why does our knowledge show such serious gaps. Can it be that there is not enough historical evidence left or was there no tradition in observing wind in the coastal zone of the North Sea?

Studying Wind in and of the Past

People living on the shores of the North Sea were well aware of the dangers of storms and storm surges. This is not only sustained by the many reports and stories regarding such natural disasters. It may also be assumed that they developed a kind of system to record or measure these events for future reference long before the instrumental observations of wind direction and wind force was introduced in the course of the 18th century. As there is a marked difference between the recording of wind on land and at sea the two will be discussed separately.

period	Netherlands			Germany	Denmark	Great Britain
	number	number	number	number	number	
	A.	B.	(Rohde)	(Jensen)	(Lamb)	
1800-1824			33	13	3	
1825-1849	9	8	30**	17	12	
1850-1874	14	12		26	7	
1875-1899	31	23		10	11	
1900-1924	26	22		13	6	
1925-1949	25	19		13	17	
1950-1974	49	36		11	17	
1975-1999	44*	39*			18***	

A. storm surge
B. storm
** until 1991*
*** until 1840*
**** until 1989*

Table 3. Historic storms, storm surges and sea floods of the 19th and 20th century in the North Sea area.

Observing Wind on Land and at Sea before 1800

Wind enabled man to operate windmills, which were constructed with large sails so that they could catch enough wind to drive the millstones. Whenever the wind was changing direction, the entire mill could be turned around on its post or - as its construction evolved through time - only the rooftop had to be turned to the wind. At least in Holland mills remained the dominant factories until the second half of the 19th century.

Next to millers, still others had a profound knowledge of wind. One of them was Noppen (1706-1774), who was working for the 'Hoogheemraadschap van Rijnland' at Bilderdam, some miles south of Amsterdam, keeping a daily record of wind. Of course, there are some years and months missing, but his series begins in 1701 and continues until 1825 (Geurts and Van Engelen 1992). At the same time he recorded water levels at Amsterdam as well.

Starting in 1782 he observed winds twice a day as he did water levels. This leaves us with some 27,000 wind data before 1782 of the Amsterdam area and for the period 1782 to 1825 there are another 32,000 wind data. As it is shown in Fig. 4, the observer had only to fill in a form, indicating the year and particular month and, of course, his daily observations. Handling this kind of data statistically was rather easy. The contemporary example of observations at Amsterdam, which started in 1700 and continued right through until 1936 containing over a million observations, however shows that there are some serious calculation problems to be solved first, before these data can be fully utilised (Van Veen 1940).

During the 18th century others gradually began observing daily weather in the Dutch coastal zone using the first instruments to measure temperature and the amount of rain (Geurts and Van Engelen 1992). However, no satisfactory method of measuring wind force was applied yet. The observers on land had to restrict themselves to monitoring the direction of the wind and by using a kind of wording to express the wind force throughout the 18th century (Table 4).

Before the introduction of steamships, sailing ships were dominant. Life long experience led seamen to sail only during the 'summer' season when storminess was less than during 'winter' season. The calmer season was from April to October,

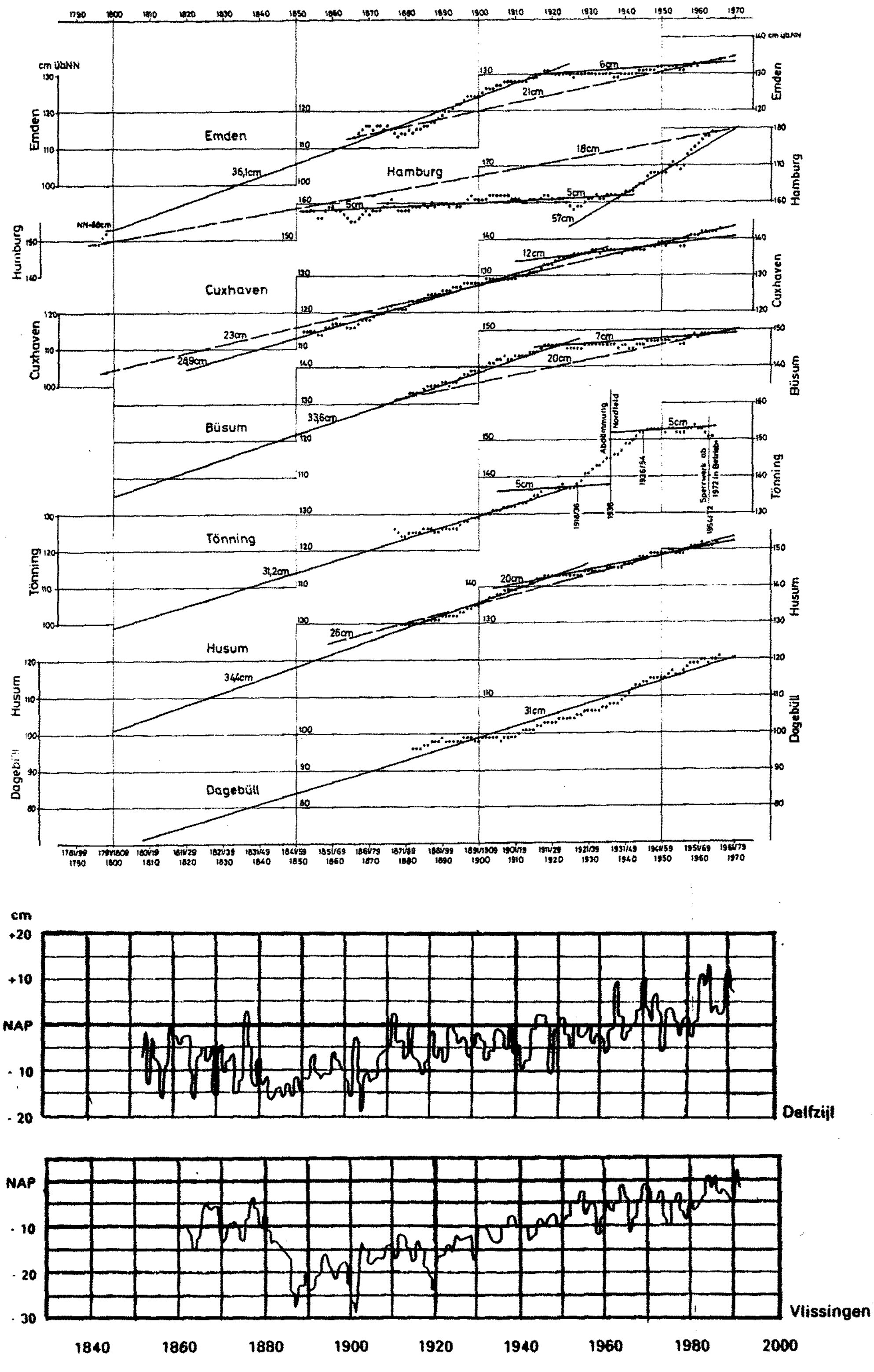

Fig. 3. Rising sea level Flushing, Delfzijl and Hamburg.

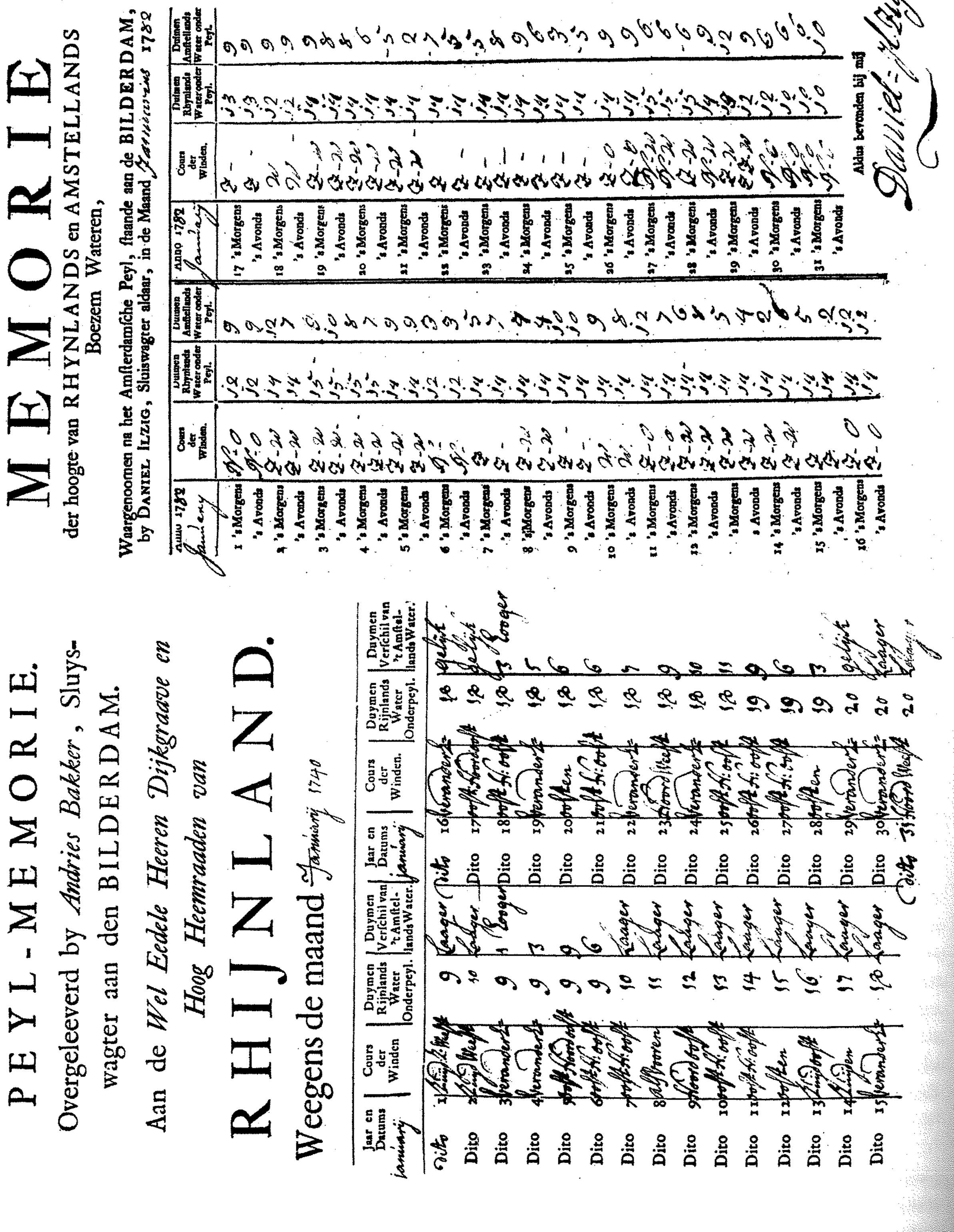

Fig. 4. Recording of wind directions at Bilderdam in January 1740 **(a)** and January 1782 **(b)** (Leiden, Hoogheemraadschap Rijnland, no 976-977).

windmill scale	*specification for the use of windmills*	*Beaufort scale of 1806*	
0	*calm*	*0*	*calm*
1	*some movement of the sails*	*1*	*light air*
02. Jan	*sails turn around gently*	*2*	*light breeze*
3 to 4	*staedy grinding*	*3*	*gentle breeze*
5 to 6	*steady grinding, perhaps striking one or more sails*	*4*	*moderate breeze*
7 to 8	*steady grinding with the striking of 1/4 or 1/3 of the sails*	*5*	*fresh breeze*
9 to 10	*steady grinding with the striking of 1/2 or 2/3 of the sails*	*6*	*strong breeze*
11 to 12	*steady grinding with the striking of 3/4 of the sails*	*7*	*moderate gale*
13 to 14	*steady grinding with the striking of all 4 sails*	*8*	*fresh gale*
15 to 16	*grinding too dangerous (stop the mill)*	*9 to 10*	*strong gale*
16 +	*grinding too dangerous (stop the mill)*	*11+*	*storm*

Table 4. The Dutch miller's wind scale of Jan Noppen, 18th century (Source: Geurts and Van Engelen 1992).

while from October to April more frequent storms were to be expected.

Whereas ship construction evolved rapidly, it became possible to sail even during the season of storminess. By the 16th century many ships sailed for the Americas and the Indies. So the seamen's knowledge of the wind and the various wind systems and patterns evolved as well. By the sixteenth century and even much earlier, seamen knew the best courses on the North Sea, in the Channel and even as far as Portugal and in the passage along the Sont into the Baltic. Unfortunately for us, few reports of such travels have been made and fewer still were kept. Those reports that have survived are Dutch ship logs of voyages to find the most suitable passage to the Indies. These documents are daily records of various aspect of synoptic weather. In Table 5 it is shown that wind direction, sailing direction, latitude, the speed of the ship and sometimes a description of the wind force are the most common features in ship's logs. However, some midshipmen even went so far as to distinguish ten columns, recording all kinds of data about the latitude, the number of day of the month, the name of the day, the part of the day and the hour, the direction the wind was blowing from, the change in the direction of the wind, and the number of miles sailed each part of the day, etc. (De Kraker 2000). Of course, such historical evidence is of the highest quality and rare!

In the course of the 18th century, the authorities of the Dutch East India Company gave instructions how official ship's logs had to be kept on their ships. In Great Britain such official naval instruction were given as early as 1731 (Oliver and Kington 1970). Dutch naval officers did not bother to develop an instrument for measuring wind force, but there seems to have existed a system of labels comprehensible and simple enough to be used at least until far in the 19th century. Whereas a descriptive wind force scale already existed at about 1700 in Britain and apparently one Danish example of about 1690 (Lamb and Frydendahl 1991), we must be confident that Dutch wording systems of wind force at sea must have been well developed. It is important that these are found in the immense archives of the Dutch East India Company at the Hague! From the wind direction's survey at the Bilderdam, which covers the period 1701 to 1770 it appears there has been some kind of wind scale in use ranking wind force from 1 to 16. Severe gale ('harde wind') was given 12/16 and severe storm or hurricane ('stormen') was given 16/16.

The Beaufort scale, introduced by the British naval officer, Sir Francis Beaufort at the beginning of the 19th century, was also introduced on Dutch

April 1595	wind	poistion of the ship	sailing direction, distance covered and other details
4	NE, ENE	Dover	
5	E		SSW and SW
6	E, ENE	Quissant	
7			SSW and SW
7 to 8	ENE, NE		SW, 32-33 miles
8 to 9	NE, N	Cape Fynistere	SW and SSW, 36 miles
9 to 10	N, NNW		
	morn. WNW		24 miles
10 to 11	unstable	40 degr. NL	SES, 9 miles, WSW 4 miles
11 to 12	calm		W, 6 miles
12 to 13	WN, NW, NE, EN		SSW, 14 miles (afternoon
13 to 14	N, NW, WNW		SSW, 28 miles
14 to 15		35 degr. 40 min NL.	SSW 28 miles
15 to 16	NW, NNW		SW, 30 miles
16 to 17			SSW, 24 miles
17 to 18			SSW-W, 30 miles
18 to 19			SSW, 4 miles until the morning
19 to 20	NE, ENE		W, 30 miles
20 to 21	NE, NE-E		SSW, 36 miles
21 to 22	NE, ENE	23 degr. 6 min. NL	SSW, 12 miles
22 to 23	NE, ENE		SW, 30 miles
23 to 24	NE, NNE	18 degr. 30 min. NL.	SSW, 36 miles
24 to 25			SW, 20 miles close to the coast
25 to 26		Isle of St. Jacob	sailing for 303 miles

Table 5. Monitoring wind on Dutch ships, April 1595 (Sources: National Archives at The Hague, Archives of the East India Companies, no 15, National Archives in Zealand (Middelburg), 'Staten van Zeeland' Archives, no 1210-II).

naval ships. According to a communication by Gunther Können the old system and the Beaufort scale were in use simultaneously for some decades. Further research will be necessary on this subject in order to reconstruct and calibrate the 17th and 18th century wind observations.

Studying Wind During the Recent Two Centuries

By the time the Beaufort scale was introduced national governments began to pay more attention to the impact of climate on society by founding various national meteorological institutes; measuring wind (direction and speed) reached a scientific level.

In the Netherlands the national institute 'Rijkswaterstaat' was founded in 1798, nowadays having its special department for the North Sea and its estuaries. As soon as the 'Rijkswaterstaat' had established itself firmly as a national government department, it gradually began to carry out observations all along the Dutch coast. In the course of the 19th century these statistics laid the foundation for all kinds of calculations and estimates of high and low tides, ranging from Flushing in the south as far as Bolsward in the Northeast.

And although 'Rijkswaterstaat' had to share its authority with the 'Provinciale Waterstaat', founded around 1851, many observations were carried out collectively, from which everyone involved in defending the dikes benefited. So starting about 1850s detailed information about storms, sea levels and all kind of particulars for the Dutch part of the North Sea coast are available.

Next to 'Rijkswaterstaat' the 'Royal Dutch Meteorological Institute' also began to carry out some investigations in this field and on wind observations in the Netherlands in general (see below).

From Germany observations of water levels dating from the period 1720 to 1753 have been kept (Rohde 1977). Although water levels have been observed at various places along the German part of the North Sea coast during the 18th century, most of these data must be considered lost. However, from seven places, some time series of observation of water levels have survived, such as those at Hamburg and Cuxhaven dating as far back as 1786 (Rohde 1977). During this century and perhaps even earlier, there must have been monitoring of wind as well. But this is not mentioned by Rohde (1977). Most of these early data are not uniform and have to be reworked.

It was only in the middle of the 19th century that a general and systematic recording of water level along the German North Sea coast began and consequently the recording of wind also. All these recordings have become the basis of the German research on sea levels and sea floods. Perhaps Arends (1833) was the first one to study the storm surges on the North Sea coast. Because it lacks a scientific basis, the results can hardly be considered reliable.

For Denmark the story seems to be very different. Here research on the history of sea floods was carried out by Gram-Jensen (1985). In his book he discusses some old chronicles and chroniclers in detail. He also elaborates on a variety of causes for the flooding of coastal lands. However, it does not become clear from which period the first Danish instrumental recordings of water level and floods date. Nevertheless, his time series of sea floods must be considered useful.

As for the recording of storms and sea floods in Great Britain, it is a story roughly similar to that of the Netherlands. Wind has been observed and consequently and systematically recorded at several observatories distributed over the British Isles. Much additional data came from ships' logs. All these data had to be collected and compiled in order to obtain a time series of historic storms. In this respect, much credit is due to Hubert Lamb, who has done a lot of investigations on historic storms in the North Sea region. Perhaps as much influenced by the work carried out by Gottschalk (1971, 1975, 1977) as by the eagerness to have a clear picture of the history of storms of the period from 1500 to the present day, Lamb finally succeeded in compiling the results of his research on the subject in a volume on historic storms of the North Sea (Lamb and Frydendahl 1991).

Present Position of Research and Prospects

Apart from the historical aspects of storm surges and sea floods, much research has been done on recent storms and storminess in general in all countries surrounding the North Sea

The British, Danish and German Situation

Judging from the British series of historic storms, it seems that there are no sufficient reliable observations until the second quarter of the 18th century. Recent research on wind seems to be much focusing on wind resource research (Palutikof et al. 1992) or individual storm surges only (Harding and Binding 1978).

Nevertheless, based on the Lamb classification of wind directions (Lamb 1972), the past record of circulation changes has been pushed back to 1861 (Kelly et al.1997). It would be a major step forward to push it much further back. It would be helpful indeed, to search for all relations between the time series of circulation changes 1861 to 2000 for the British Isles and the time series of sea floods and sea levels at various places along the Dutch, Danish and German coast for the same period as well. This can only be achieved by detailed information based on documentary sources which are reliable enough to reconstruct time series of wind. Such data have to be found in all kinds of record offices and local archives. In spite of the fact that the instrumental measurements of weather on a daily basis began in the late 17th century, including many wind observations, however, British documentary sources seem to be used predominantly for the reconstruction of temperature series (Jones and

Hulme 1996). So this leaves us with a great opportunity to work on the instrumental wind observations and still to investigate the remaining documentary sources, such as the ships' logs and e.g. the accounts of landed property situated in coastal regions of the North Sea (cf. below). Other recent British research (Hulme and Barrow 1997; Kelly et al. 1997) aiming at the reconstruction of surface air pressure patterns in Northern and Western Europe on a 10 or even on a 5 degree grid-scale going as far back as possible and searching for linkages with the NAO-index, has given some fine results, will also benefit from such a detailed research for historical weather observations.

As for the German and Danish wind research, much effort is spent on the more recent period. Important in this respect is the research carried out by Frydendahl et al. (1992) and Frich and Frydendahl (1994) on the Danish ships' logs (1675 to 1875) aiming at the transcription and the coding of over one million weather observations of which only a preliminary report exists. German research is focusing on finding causes of rising sea level (Von Storch et al. 1997). Still the outcome of this kind of research can only benefit from a complete and reliable time series of storms and sea floods over the last four or five centuries. Looking at the results published by Gram-Jensen (1985), the problem of reliability of storm data for the medieval period is about 0% and for the 16th to the 18th centuries it is about 73% to 90%. Thus the Danish time series earlier than 1700 and that of North Germany must remain far from complete as long as no final results of the research carried out by Frydendahl are known. On the other hand case studies on individual historical storm surges (Jakubowski-Tiessen 1992) supplying us with detailed information on the weather conditions leading to the natural disaster and its consequences remain important as well and should be carried out at the same time.

The Dutch situation

In the Netherlands storm patterns have been reconstructed for the period 1931 to 1960, from which it appears that the average wind force at Den Helder was stronger than at Flushing. Bouws (1978) studied winds during the period 1949 to 1976 and noticed an apparent increase in north-westerly gales. From recent research on wind and storm surges (Augustyn et al. 1990) ranging from at least Beaufort 8, it appeared that the dominant wind direction is SW (32%), except for the very heavy storms which tend to blow from the West (45%). Furthermore, sea level research in the Netherlands is very much restricted to the present and future condition of dikes and dunes along the North Sea (Jelgersma 1992). Because of increasing emphasis on environmentalist issues in politics and the 'Rijkswaterstaat' during recent years, research on historic storms seems to become neglected.

Other recent research on wind has been carried out within the framework of supplying parts of the Netherlands with cheap and clean wind energy (Wieringa 1981). The results of this kind of wind research have not been largely used for the research of historic storms.

As soon as Gottschalk finished her 'historical storm surge research' in 1977, only Dekker (1980) contributed to the discussion demonstrating that the periods of transgressions followed by periods of sedimentation must be clearly connected with the period proceeding the building of dikes. On the other hand he also demonstrated that as soon as the building of dikes began in the 11th and 12th centuries, flooding of large areas occurred at very irregular intervals and at different places. However, looking at the general picture we have of storms and storm surges, this is ready now for a fundamental review.

One of the shortcomings of Gottschalk's research proved to be the fact that she only has consulted chronicles, of which the larger part has been printed. Only for a few small areas additional documentary evidence kept in archives has been consulted. Because Gottschalk's sources were not uniform nor continuous, she could not construct a time series. Secondly, she ended her research with the year 1700, which leaves us with three centuries to be investigated still. Thirdly, Gottschalk covered a large area and has consulted a huge number of very different chronicles. That is why she was not able to discover the real cause of many a flooding of a particular area which in turn can be very helpful to assess the real character and force of a storm.

Recent research on storms in the Netherlands, covering only a small area of polders west of Antwerp, has revealed that human impact on the landscape during and after storm surges have been flooding an area is strongly conditioned by nature, economy and politics (De Kraker 1997). Of these economy and politics must be considered as being the dominant factors. Especially during wartime large areas were flooded. The same research has been carried out by consulting series of documentary sources which can be considered uniform and continuous. This has been very helpful in constructing a time series of storms. Moreover, it has enabled us to construct a method to measure the severity of storms (De Kraker 1999).

Still, other research on historic storms remains very restricted to smaller areas as well, such as the assessment of water levels reached by successive storms at Goeree and the number of storms observed at the Hondsbossche Zeewering between 1840 and 1879 reaching heights of over 1 m above the average (Aten 1997).

It appears that there are sufficient documentary sources still to be consulted, so that finally there will be a fairly complete picture of sea floods, storms and storminess on the North Sea coast of the Low countries starting as early as the 16th century. Several hundreds of independent polder boards ('waterschappen') have kept their archives fairly complete over the centuries. In the province of Zeeland and the northern part of Flanders, with its many former isles, dike accounts enable us to study wind from all directions. Furthermore the entire region around Amsterdam and as far north as Den Helder offers some fine opportunities to study winds from all directions. The Rijnland general dike account's series starts at 1509 and is almost complete. Finally the entire region surrounding the former Zuiderzee offers no fewer opportunities. In short, there are sufficient series of documentary sources which are uniform and continuous and which can enable us to construct a complete time series of storms, storm surges and sea floods over the last five centuries!

However, more is needed than a sufficient amount of documentary sources. Existing instrumental observations starting as early as around 1700 at e.g. the Bilderdam and Amsterdam should be made uniform in order that such a series can be use to reconstruct time series of winds (Table 6). The same applies to the existing series of observations on water levels.

Furthermore, constructing a time series of wind is one, assessing the intensity of wind is another. That is why some kind of uniform system must be applied, in which all details about storms (De Kraker 1997, 1999), such as time, space, cause (natural and human), consequences, etc., are of particular importance (Fig. 5).

For the Netherlands, a number of four test regions as mentioned (Fig. 6), perhaps to be extended with a fifth region somewhere on the Wadden coast will be enough to do the job. In addition to the storm data obtained from these four test regions, there is still much documentary source material from international and national shipping. Studying the busy overseas trade from the Netherlands to Denmark and the Baltic during the 16th to 18th century can supply us with many storm data to help us to complete our time series of storms and storm surges for the German Bight and western Denmark. Combining the efforts of economic historians and climatologists on the subject would be a major step.

Conclusions

In this paper the object has been to review the historic storms which have been recorded in the North Sea area. The main source of information consists of four distinctive time series of storm surges, sea floods from the Netherlands, Denmark and the British Isles and a time series of sea level recordings from Northern Germany. From this survey it has become clear that only as late as the second quarter of the 18th century there is a reliable series of storm surges and sea floods which seems to look rather complete. However, for the Netherlands no major research has been done for the period later than 1700. Moreover, storms of lesser importance have been included in neither time series on the subject . Except for the period 1861 to about 2000 for the British Isles, it is not possible yet to reconstruct a series of storms on e.g.

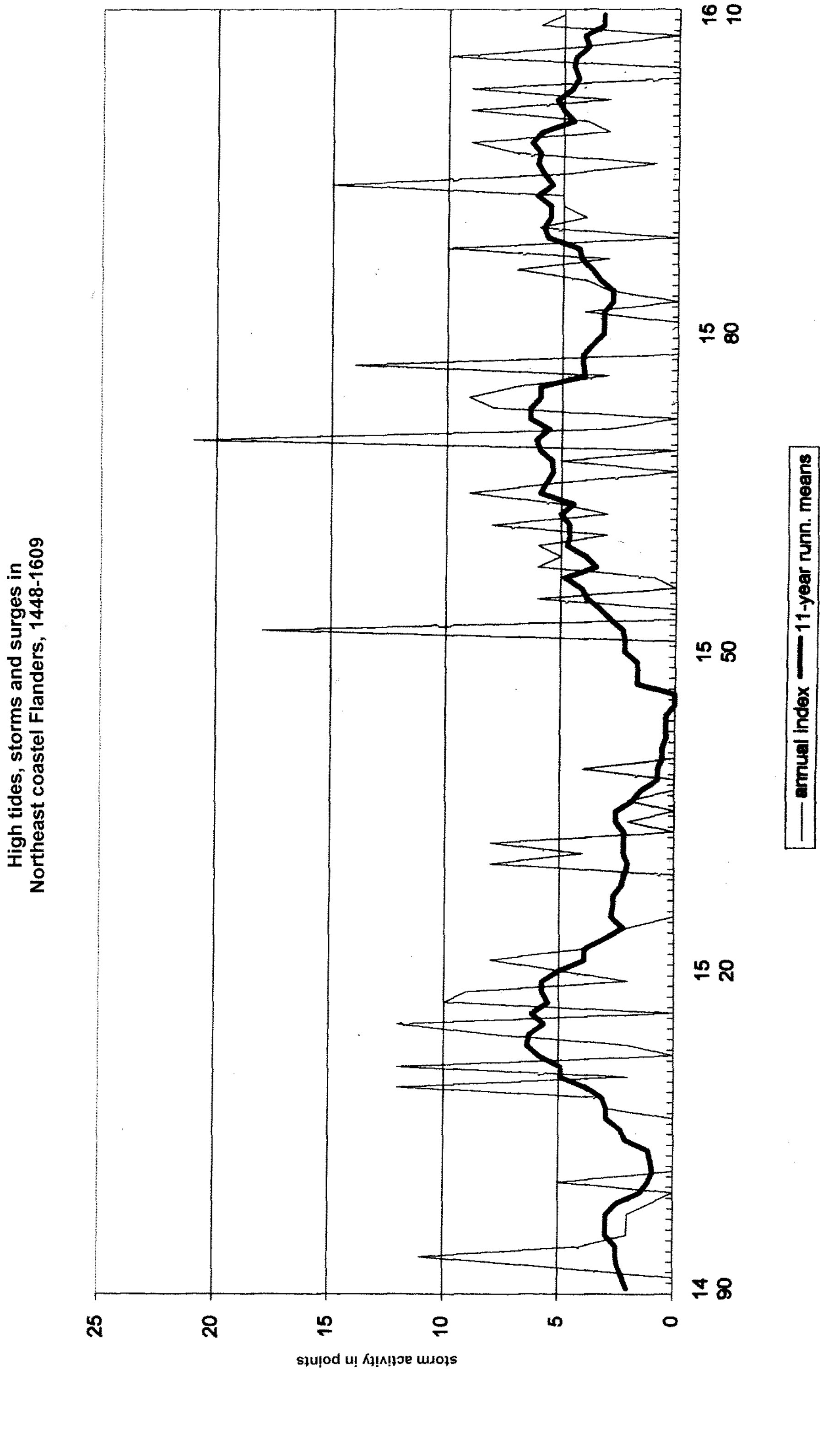

Fig. 5. Variability of storminess in the Wester Scheldt estuary during the 16th century (De Kraker 1997, 1999).

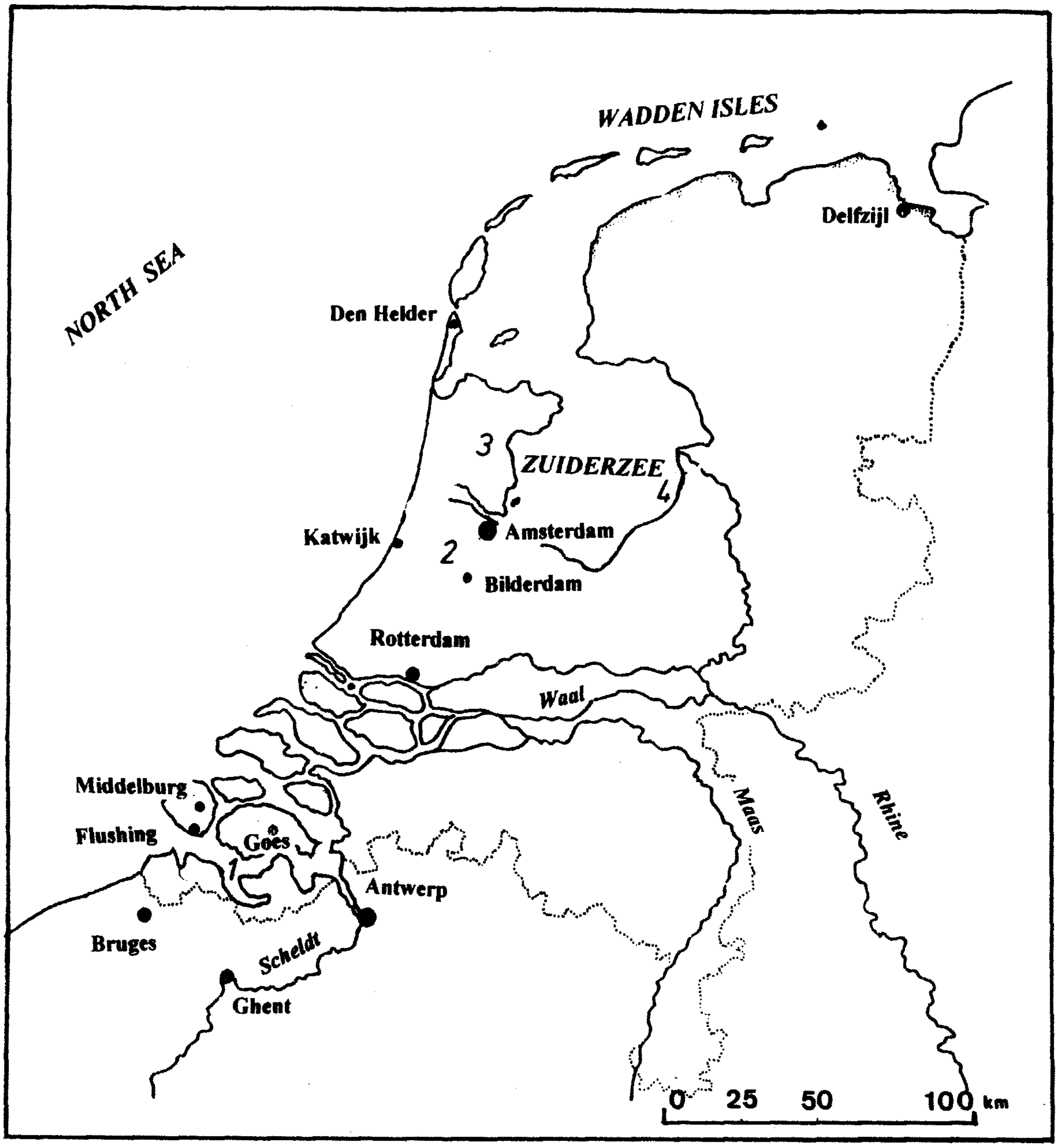

Fig. 6. Map of the Low Countries about 1700. Four areas for possible storm research in the future (author).

1. Delta area: North Flanders and the Dutch province of Zealand.

2. Area at Bilderdam-Amsterdam and the coastal region of the Haarlemmermeer.

3. The northern part of Holland and its coastal area: Noorder Kwartier.

3. Area surrounding the former Zuiderzee.

Bilderdam, 1701 - 1770			Amsterdam, 1700-1750			Amsterdam, 1890-1937	
wind direction	days	%	wind direction	days	%	days	%
N	24.5	6.7	N	25	6.8	35	9.7
NNE	7.0	1.9					
NE	30.0	8.2	NE	42	11.5	39	10.8
ENE	6.5	1.8					
E	48.5	13.3	E	49	13.4	44	12.0
ESE	6.0	1.6					
SE	21.0	5.5	SE	25	6.8	49	13.4
SSE	7.0	1.9					
S	24.0	6.6	S	35	9.7	23	6.3
SSW	8.5	2.2					
SW	67.0	18.4	SW	87	23.8	84	23.0
WSW	12.0	3.3					
W	54.0	14.8	W	55	15.0	52	14.2
WNW	13.0	3.6					
NW	31.0	8.5	NW	47	13.0	39	10.6
NNW	5.0	1.4					
	365.0	100.0		365	100.0	365	100.0

Table 6. Wind directions in Holland, 1700 - 1937 (Sources: Leiden, Hoogheemraadschap Rijnland, no 973 (Bilderdam); Van Veen 1940 (Amsterdam)).

a thousand years' time scale and on a geographical scale for the entire North Sea area or parts of it.

Still there are very good prospects for research to continue. There are enough weather observations from instrumental measurements of the recent two centuries that can be included fairly easily into the reconstruction of time series of wind and wind patterns. If four or five distinctive areas in the Netherlands are chosen which are very sensible to wind and sufficient time is spent at record offices and in archives there is a fair chance of reconstructing a time series beginning in the 16th century. This kind of research includes, of course, all storms of lesser importance as well. And if documentary sources studied are continuous and uniform, new methods to assess storminess might be applied at the same time. Starting in the 17th century this also applies to the reconstruction of sea level recordings at various places along the Dutch, Flemish and (perhaps also) the British coast.

Finally, it would be very helpful to compare time series of sea level recordings with various other kinds of climatic time series for the North Sea area, starting with the 20th century and then going back from there. In the end there would be a fairly continuous thousand or 500 years' time scale of storms and sea level recordings on a geographical scale for the North Sea region. And linking it to the Lamb classification and the NAO-index, this time series of storms would be very helpful to understand the variability of air masses penetrating into the European hinterland as far as temperature and moisture are concerned.

Acknowledgments

I thank Dr. Meinte Blaas, Institute for Marine and Atmospheric research (IMAU), Utrecht University, Utrecht, the Netherlands; Prof. Dr. Chr. Pfister, Institute of History, University of Bern, Switzerland; Dr. David Prandle, Bidston Observatory, Birkenhead, United Kingdom; Prof. Dr. Wolfgang H. Berger, University of California, USA; Prof. Dr. G.J. Borger, University of Amsterdam, Amsterdam, the Netherlands; Dr. Gaston R. Demarée, Royal Meteorological Institute, Brussels, Belgium; Otto Knottnerus, Uiterburen, Netherlands for their invaluable help.

References

Arends F (1833) Physische Geschichte der Nordsee-Küste und deren Veränderungen durch Sturm-fluthen seit der Enbrischen Fluth bis jezt. Verlag Schuster in Leer, Emden 1833. Reprinted in 1974, pp 1-355

Aten D (1997) Beslissende jaren voor de Hondsbossche. Dijkgraaf Foreest en de prijsvraag van 1864, in: Vrienden van de Hondsbossche, 13e, pp 1-32

Augustyn B, Daan H, Van Mourik B, Messerschmidt D, Zwart B (1990) Stormenkalender 1964-1990. KNMI T.R. no. 2 revised, pp 1-138

Bijvoet HC, van der Ham CJ, Groen P, Rijkoort PJ, Schmidt FH, Verploegh G, Weenink MPH (1960) Meteorological and oceanographic aspects of storm surges on the Dutch coast. K.N.M.I. Bijdrage tot het rapport van de Deltacommissie, pp 1-200

Bouws E (1978) Wind wave climate in the Netherlands sector of the North Sea between 53 and 54 north latitude, KNMI Scientific Report W.R. 78-9, De Bilt, pp 1-54

Dekker C (1980) Resultaten van het historisch-geografisch onderzoek in Zeeland. In: Verhulst A, Gottschalk MKE (eds) Transgressions and the history of settlement in the coastal areas of Holland and Belgium. Proceedings Colloquium Gent 5-7 September 1978, pp 75-93

De Kraker AMJ (1997) Landschap uit balans. De invloed van de natuur, de economie en de politiek op de ontwikkeling van het landschapin de Vier Ambachten en het Land van Saeftinghe tussen 1488 en 1609. Uitgeverij Matrijs Utrecht. Thesis University of Amsterdam, Amsterdam, pp 1-464

De Kraker AMJ (1999) A method to assess the impact of high tides, storms and storm surges as vital elements in climatic history. The case of stormy weather and dikes in the northern part of Flanders, 1488 to 1609. Pfister Chr, Brázdil R, Glaser R (eds) Climatic variability in sixteenth-century Europe and its social dimensions. Special issue of 'Climatic Change', 43, no. 1: 287-302

De Kraker AMJ (2000) The oldest Dutch ships' logs (1595 - 1610), their interest for climate history in general and global climatic change in particular. In: Mikami T (ed) Proceedings of the International Conference on Climate Change and Variability - Past, Present und Future - held at Tokyo metropolitan University Tokyo, Japan, September 13-17, pp 95-101

Douglas KS, Lamb HH, Loader C (1978) A Meteorological Study of July to October 1588: The Spanish Armada Storms. Norwich CRU RP-6, pp 1-76

Frich P, Frydendahl K (1994) The summer climate in the Oresund region of Denmark A.D. 1675 tot 1715. In: Frenzel B, Pfister Chr, Gläser B (eds) Climatic trends and anomalies in Europe 1675-1715. High resolution spatio-temporal reconstructions from direct meteorological observations and proxy data. Methods and results. Gustav Fischer Verlag - Stuttgart - Jena - New York, pp 33-41

Frydendahl K, Frich P, Hansen C (1992) Danish Weather Observations 1615-1715. Danish Meteorological Institute, technical report 92/99, pp 1-22

Geurts HAM, Van Engelen AFV (1992) Beschrijving antieke meetreeksen, part V. KNMI publication, no. 165-V, pp 1-310

Gottschalk MKE (1971) Stormvloeden en rivieroverstromingen in Nederland. I. De periode voor 1400. Van Gorcum & Comp. N.V. Assen, pp 1-581

Gottschalk MKE (1975) Stormvloeden en rivieroverstromingen in Nederland. II. De periode 1400-1600. Van Gorcum & Comp. N.V. Assen, pp 1-896

Gottschalk MKE (1977) Stormvloeden en rivieroverstromingen in Nederland. III. De periode 1600-1700. Van Gorcum & Comp. N.V. Assen, pp 1-474

Gram-Jensen IB (1985) Sea Floods. Contributions to the climatic history of Denmark, Kopenhagen, pp 76

Harding J, Binding AA (1978) Windfields during the gales in the North Sea and the gale of January 1976 In: Met Mag 107:164-182

Hulme M, Barrow E (1997) Climates of the British Isles, present, past and future. London/NewYork

Jakubowski-Tiessen M (1992) Sturmflut 1717. Die Bewältigung einer Naturkatastrophe in der Frühen Neuzeit, R. Oldenbourg Verlag München

Jelgersma S (1992) Vulnerability of Coastal Lowlands of the Netherlands to a future sea-level rise. In: Tooley MJ, Jelgersma S (eds) Impacts of sea-level rise on European coastal lowlands, Blackwell, Oxford/Cambridge, pp 94-124

Jones PD, Hulme M (1996) Calculating regional climatic time series for temperature and precipitation: methods and illustrations, in: Internat Journ of Climat vol. 16:361-377

Kelly PM, Jones PD, Briffa K (1997) Classifying the winds and weather In: Hulme M, Barrow E (eds) Cli-

mates of the British Isles, present, past and future, London/New York, pp 153-173
Kington J (1994) Synoptic weather mapping, 1675 to 1715. In: Frenzel F, Pfister Chr, Gläser B (eds) Climatic trends and anomalies in Europe 1675-1715. High resolution spatio-temporal reconstructions from direct meteorological observations and proxy data. Methods and results. Gustav Fischer Verlag - Stuttgart - Jena - New York, pp 390-400
Lamb HH (1972) British Isles weather types and a register of the daily sequence of circulation patterns, 1861 to 1971. Geophysical Memoir, 116. H.M.S.O. London, pp 1-85
Lamb HH, Frydendahl K (1991) Historic Storms of the North Sea, British Isles and Northwest Europe, Cambridge University press, pp 1-20
Oliver J, Kington JA (1970) The usefulness of ships' logbooks in the synoptic analysis of past climates. Weather 25:520-528
Palutikof JP, Guo X, Halliday JA (1992) Climate variability and the UK wind resource. Journal of Wind Engineering and Industrial Aerodynamics 39:243-249
Pfister Chr, Kington J, Kleinlogel G, Schüle H, Siffert E (1994) High resolution spatio temporal reconstructions of past climate from direct meteorological observations and proxy data. In: Frenzel B, Pfister Chr, Gläser B (eds) Climatic trends and anomalies in Europe 1675-1715. High resolution spatio-temporal reconstructions from direct meteorological observations and proxy data. Methods and results. Gustav Fischer Verlag - Stuttgart - Jena - New York, pp 329-375
Rohde H (1977) Sturmfluthöhen und säkularer Wasserstandsanstieg an der deutschen Nordseeküste, Die Küste. Archiv für Forschung und Technik an der Nord- und Ostsee, Heft 30:53-143
Van Malde J (1996) Historical extraordinary water movements in the North Sea area, Mededeling Rijks Geologische Dienst 57:27-40
Van Veen J (1940) Is de heerschende windrichting te Amsterdam sedert 1700 gekrompen? Tijdschrift KNAG, 2nd series, 57e:686-707
Von Storch H, Reichardt H (1997) A scenario of storm surge statistics for the German Bight at the expected time of doubled atmospheric carbon dioxide concentration. Journal of Climate 10:2653-2662
Wieringa J (1981) Veranderlijkheid van de wind op korte en lange termijn, in: Nationale windenergie conferentie 1981. Den Haag/Veldhoven, B1 1-17