

CHANGING WIND PROPERTIES IN SOUTH SWEDEN SINCE THE DAYS OF TYCHO BRAHE

Ändrade vindförhållande i södra Sverige sedan Tycho Brahes dagar

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Abstract

The famous Danish astronomer Tycho Brahe initiated meteorological observations on the Island of Ven that were recorded in a diary, starting in October 1582 and lasting almost uninterruptedly until April 1597. Although the observations were mainly qualitative due to the lack of proper instruments and procedures in those days, a lot of useful information can be extracted from the diary regarding cloud cover, precipitation characteristics, wind speed and direction, heat conditions, and the occurrence of thunder, halos, and northern lights. After the diary was found in the mid-19th century, La Cour (1876) transcribed the observations to quantitative measures, obtaining four values per day for a number of meteorological parameters. The transcribed observations from the diary may be used to investigate whether changes in the climate have occurred since the 16th century. In the present paper, the wind properties (direction and speed) from the diary, were compared to measurements from the 19th and 20th/21st century to determine if such changes have taken place. In accordance with results from previous studies, the data analysis showed shifts in the wind direction from the sector north-east – southeast to the sector south – west. These changes are more pronounced for the winter months compared to the summer months. No conclusions could be made regarding the wind speed, probably due to problems in transcribing the observations in the diary to quantifiable values. The observed changes in the wind direction are of significance for the wave and water level conditions around the south coast of Sweden, which in turn affect sediment transport and shoreline evolution.

Key words – Meteorological observations, historical data, climate change, wind speed and direction, coastal evolution

Sammanfattning

Den kände astronomen Tycho Brahe initierade meteorologiska observationer på ön Ven som noterades i en dagbok, nästan oavbrutet från oktober 1582 till april 1597. Fastän observationerna huvudsakligen är kvalitativa på grund av dåtida brist på instrument och metoder kan en stor mängd användbar information erhållas från dagboken beträffande molntäcke, nederbörd, vindhastighet och riktning, temperaturförhållanden samt förekomsten av åska, halos och norrsken. Efter dagboken påträffades i mitten av 1800-talet, tillordnade La Cour (1876) observationerna i dagboken kvantitativa värden, varvid han erhöll fyra värden per dag för ett antal meteorologiska parametrar. Dessa kvantitativa värden från dagboken kan användas för att undersöka om förändringar i klimatet förekommit sedan 1500-talet. I denna artikel analyseras vindkaraktäristika (hastighet och riktning) från dagboken och jämförs med mätningar från 1800- och 1900/2000-talet för att identifiera om sådana förändringar inträffat. I överensstämmelse med resultat från tidigare studier visade analysen här på förändringar i vindriktning från sektorn nordöst-sydöst till sektorn syd-väst. Dessa förändringar är mer uttalade för vintermånaderna jämfört med sommarmånaderna. Inga slutsatser kunde dras beträffande vindhastigheten, förmodligen på grund av svårigheterna att tillordna tillförlitliga kvantitativa värden. De förändringar i vindriktning som observerades är av betydelse för våg- och vattenståndsförhållandena runt Sveriges sydkust, vilka i sin tur påverkar sedimenttransport och strandförändringar.

Introduction

Tycho Brahe, the famous Danish astronomer (see Figure 1), has gained world-wide recognition for this pioneering work on developing instruments for astronomical observations and for collecting data from his observatory at the Island of Ven using these instruments. However, less well-known is the meteorological diary that was kept on his initiative and under his supervision between the 1st of October 1582 and the 22nd of April 1597. Observations of a number of meteorological parameters were made almost uninterruptedly, including cloud cover, precipitation characteristics, wind speed and direction, heat conditions, and the occurrence of thunder, halos, and northern lights. Since these observations were made before any quantitative, standardized instruments and methods were developed they tend to be rather qualitative; however, useful information may still be extracted from the diary that could provide indications on changes in the climate since the end of the 16th century. Very few records of that age are available (Pfister et al., 1999) and the diary is unique in the careful and systematic way it was kept considering the knowledge about meteorology in those days.



Figure 1. Portrait of Tycho Brahe (from Brahe, 1602).

One of the few parameters in the diary that can quantitatively be compared with data collected today is the wind direction. The wind direction is important for the generation of waves and currents in the sea with implications for the transport of water and material, particularly in limited water bodies like the Strait of Öresund where the Island of Ven is located (see Figure 2). For example, in the coastal areas, wave direction, which tends to be equal to the predominant wind direction over limited seas, determines the orientation of the coastline, if it consists of transportable material. The coastline strives towards equilibrium, aligning itself with the orientation of the wave crests to produce negligible longshore sediment transport (Komar, 1997). Thus, changes in the wind climate imply changes to the coastline orientation that cause movement of sediment with associated areas of erosion and accretion. If a stretch of coastline is bounded by non-erodible features, an equilibrium bay may develop that keeps the sediment in the bay. The orientation of the bay coastline reflects the prevailing wave direction, which in turn is a function of the wind and the general configuration of the sea area. Figure 2 indicates four such equilibrium bays on the Swedish side of Öresund with varying size, orientation, and shape.

The main purpose of this paper is to present and analyze the wind properties recorded in the Tycho Brahe meteorological diary and to compare them with observations carried out in the 19th and 20th/21st century to detect possible changes in these properties. Emphasis is put on the wind direction, but for completeness the



Figure 2. Map over Öresund, the strait between Denmark and Sweden with the Island of Ven where Tycho Brahe had his observatory (the Roman numerals indicate locations with equilibrium bays).

wind speed transcribed from the notations in the diary (La Cour, 1876) is also analyzed, although the results are mainly qualitative. The paper starts with a brief account of Tycho Brahe's life, followed by a description of the meteorological diary. The wind direction and speed obtained from the diary, as well as one 67-year long time series recorded in Copenhagen during the 19th century and a 20-year long series from Helsingborg between 1996 and 2015, are then presented. These data series are analyzed and compared with regard to direction and speed to identify any differences, indicating changes in the wind climate on the centennial scale. The comparison is made both on an annual and a monthly basis. The paper ends with a set of conclusions.

The life of Tycho Brahe

The first biography published about Tycho Brahe was by Gassendi (1654), and it is available in translation to Swedish by Norlind (1951) together with a large number of comments to the text. Other noticeable biographies are by Helfrecht (1798), Friis (1871), and Dreyer (1890). Kragh (2003) summarized some of the more significant studies on Tycho Brahe and discussed different views on Tycho Brahe's scientific work through history. Norlind (1963) published a brief, popular account of Tycho Brahe's life, followed by a more extensive study (Norlind, 1970), both in Swedish.

Tycho Brahe was born on the 14th of December 1546 at the family estate in Knutstorp located in the province of Scania, which in those days was a part of Denmark (in 1658 Scania, including the Island of Ven, was ceded to Sweden in the peace treaty of Roskilde). He was of old Danish nobility and among his ancestors there were many distinguished militaries and diplomates (Norlind, 1963). Tycho Brahe was the oldest son of 10 children, five sons and five daughters, but was mainly brought up by his uncle. In April 1559, when he was 12 years old, Tycho Brahe started to attend the University of Copenhagen. At the age of 14 he witnessed a solar eclipse that is said to have stimulated his interest in astronomy (Gassendi, 1654; see translation by Norlind, 1951), although this has not been confirmed by Tycho Brahe's own writing (Norlind, 1963). In 1562 he continued his education at the University of Leipzig, where he more and more dedicated his studies to astronomy. During his stay in Leipzig he began to design and build his own instruments for astronomical observations. In 1565 he briefly returned home, but already the following year he left Denmark and spent several years visiting the universities in Wittenberg, Rostock, Basel, and Augsburg.

In 1570 he returned to Denmark and set up an astronomical laboratory close to Knutstorp. On the 11th of



Figure 3. *The combined castle and astronomical observatory Uraniborg on the Island of Ven used by Tycho Brahe (from Brahe, 1602).*

November 1572 he made his famous discovery of a “new star”, which was really a supernova, and published his observations the following year in a small booklet (Brahe, 1573). Based on the reputation gained from his astronomical observations, Tycho Brahe was invited to give a series of lectures at the University of Copenhagen in 1574. Although hesitant at first, he eventually conceded and gave a set of highly appreciated lectures, after being encouraged by king Fredrik II himself (Gassendi, 1654). In the spring the following year he embarked on another European trip that eventually took him all the way to Venice in Italy, and he returned only at the end of the year. Actually, at this stage Tycho Brahe had plans to leave Denmark permanently, in order to continue his work as an astronomer abroad. However, on the 14th of February 1576 he received a letter from the king while he was at Knutstorp ordering Tycho Brahe to report to him. During the ensuing meeting Tycho Brahe was offered the Island of Ven, as well as financial support, to carry out astronomical observations (Norlind, 1951).

The construction on Ven started in August 1576 with the combined castle and astronomical observatory Uraniborg (Mortensen, 1926; see Figure 3). On top of the main cupola a weather vane was placed in the shape of a Pegasus, close to 20 m above the ground. In the ceiling of the building there was a plate that displayed time and the wind direction. After a few years, the space at Uraniborg was not sufficient for all the instruments constructed. Also, the foundation of the existing building had some stability problems, affecting the observations, and in 1584 the construction of a new building,

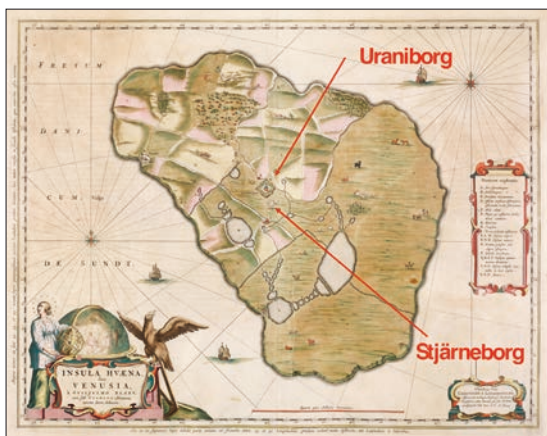


Figure 4. *Map of the Island of Ven with the locations of Uraniborg and Stjärneborg (Blaeu, 1662).*

Stjärneborg, south of Uraniborg, started (see Figure 4). The instruments in Stjärneborg were located underground, which allowed for undisturbed observations. In October 1582 Tycho Brahe initiated the recording of the meteorological conditions in a diary (Brahe, 1876), which was to a large degree kept by his assistant Elias Olsen Morsing (in Latin known as Cimber; Friis, 1889). The diary was continued until the end of April 1597 and besides meteorological information it contains brief comments of general interest, including visitors to Tycho Brahe, special activities at Uraniborg, nature observations, and historical events. Morsing was also the author of the first book on astronomy published on Ven (Cimber, 1586); Tycho Brahe had his own printing press on the island.

In 1588 Fredrik II passed away, but since his son and heir to the throne, Christian, was underage he did not become king of Denmark until 1596. When Christian IV took power Tycho Brahe lost a lot of the economic benefits conferred on him by Fredrik II, mainly because of the negative influences from some of the King's advisors who were the enemies of Tycho Brahe. Although Tycho Brahe was allowed to keep Ven, he decided in 1597 to leave the island, mainly for economic reasons (Norlind, 1963). First he travelled to Copenhagen, but shortly after that he left for Rostock. In Rostock he tried to negotiate a deal with Christian IV so that he could return to Denmark and carry out his astronomical work under satisfactory conditions. However, the negotiations failed and in 1599 he arrived in Prague, where he met with Rudolf II, the Holy Roman Emperor. The emperor offered Tycho Brahe a yearly allowance and a castle in the countryside (Benatky) where he could live and perform his astronomical observations. In 1600 Johannes

Kepler arrived at Benatky to start working on the analysis of Tycho Brahe's observations, which subsequently resulted in Kepler's famous laws for planetary motion. However, Kepler only got access to all the observations after Tycho Brahe's death.

Tycho Brahe returned in the latter part of 1660 to Prague on the emperor's request, since he needed Tycho Brahe's assistance in matters related to astrology and alchemy. In October the following year, when Tycho Brahe attended a dinner, after substantial drinking, he got problems with his urine bladder and on the 24th of October 1661 he passed away in his bed. Tycho Brahe died at an age of 54 years and 10 months. After his death Uraniborg and Stjärneborg declined, so that 50 years later nothing remained from the buildings.

Tycho Brahe's meteorological diary

As previously mentioned, the first entry in Tycho Brahe's meteorological diary was made on the 1st of October 1582, when it was written "Mørcktt formiddag och tørtt, men efftermiddag regn undertijden medt westen blest" ("Dark in the morning and dry but in the afternoon rain with westerly winds"). The last entry was in April 1597 and during this period observations were made daily, except from May 1st to July 31st, 1584 when Elias Olsen Morsing brought the diary on a trip to Frauenburg (during this period the diary describes the weather conditions in Frauenburg). Also, during the final months, entries from some days are missing in the diary.

The meteorological diary was discovered 1863 in the library of Vienna by Friis (1876) during a visit to study documents related to Tycho Brahe. The handwritten diary encompasses about 200 pages, mostly parchment; however, some pages consist of paper manufactured on the Island of Ven, where Tycho Brahe had his own paper mill. After Friis' visit, the diary was lent to the Royal Danish Academy of Sciences and Letters in Copenhagen that published its content. The diary also includes comments of historical interest, starting on the 27th of April 1585. A large part of the diary was written by Elias Olsen Morsing, although several other assistants to Tycho Brahe also made entries in the diary.

The meteorological observations in the diary are mainly qualitative, describing most of the parameters through a set of words that can vary greatly and is subject to interpretation. The wind direction should be directly comparable to observations made today as well as the occurrence of frost, thunder, halos, and northern lights (number of events/days), but precipitation and heat conditions (*e.g.*, temperature) are quite difficult to compare with more recent observations. Reliable meth-

ods to measure temperature and the amount of precipitation only started in the early 18th century and systematic observations were much later (Nebeker, 1995).

La Cour (1876) made a pioneering effort to transcribe the meteorological observations in the diary and to assign them quantitative values that are possible to make comparisons with. In order not to be influenced by any analysis results, the entire transcription was performed before the derived data were analyzed. La Cour realized that there was a strong subjective element in the transcription, recognizing that another person would not arrive at the same results for individual observations; however, he believed that the averages obtained over suitable time periods would be robust and reliable.

Every day was divided into four parts, yielding four values per day for each of the parameters observed. However, in La Cour (1876) only mean values were presented on a monthly or annual basis. Here, wind direction and speed will be subject to analysis and comparison with more recent observations to see if any changes may be detected with regard to the wind properties. Details of the transcription for wind direction and speed from the diary is discussed below. La Cour (1876) was also interested in identifying any changes in the climate from the days of Tycho Brahe to the 19th century; thus, he made comparisons with data from Copenhagen, including a 67-year long wind time series. These data will be employed in this study as well, as discussed below.

Data employed

Series from Tycho Brahe's (TB) meteorological diary

Tycho Brahe's diary contains close to 15 years of daily observations of a wide range of meteorological parameters. As opposed to most of the parameters in the diary, the wind direction was rather straightforward for La Cour (1876) to obtain; no interpretation was really needed, but the compass directions noted in the diary was employed directly. Eight compass directions were used by La Cour, namely North (N), Northeast (NE), East (E), Southeast (SE), South (S), Southwest (SW), West (W), and Northwest (NW), as well as calm conditions. In La Cour (1876) tables are presented over the number of observations for each day and respective wind direction. Here, only mean data on monthly and annual basis will be discussed. As previously indicated, the wind direction measurements were carried out using a weathervane placed about 20 m above ground.

The wind speed was more difficult to transcribe since a wide range of qualitative statements was used in the diary to characterize the wind conditions that needed to

be given a quantitative interpretation to arrive at representative values (speed). La Cour assigned an 11-grade scale to the wind observations in the diary based on the verbal descriptions, from "calm" to "very strong storm", including one category for which no quantification could be made. In each of these categories a large number of words found in the diary to characterize the wind conditions were placed in the transcription process. Furthermore, in order to be able to compare the scale developed by La Cour to more recent measurements, he related his scale to the more commonly used Beaufort scale, which is based on the number and type of sails a ship could hold under certain wind conditions (Fryden Dahl et al., 1992). Subsequently the Beaufort scale has been converted into wind speed measured in m/s or knots. La Cour's conversion from his own scale to the Beaufort scale will be used here, as was done in Fryden Dahl et al. (1992) when comparing the wind speed observations from the diary with Danish weather observations recorded in ship logbooks made from 1686 to 1715.

Series from Copenhagen (CPH)

La Cour (1876) compared the wind data from the diary, both wind direction and speed, with measurements from Copenhagen (CPH; see Figure 2). Limited information is given on the CPH data, but summary information is given in graphical form. In this study, the CPH data on wind direction were digitized from the graphs yielding the relative contribution from each wind direction on a monthly or annual basis. The summary statistics presented from CPH on wind direction originates from a 67-year long time series collected by the Royal Danish Academy of Sciences. It should be noted that the frequency of calm weather was not presented, but it was instead derived based on the data from the requirement that the sum of all occurrences should be 1.0. The frequency of calm weather was quite low (near zero), indicating that for this time series a wind direction was more or less always assigned. La Cour (1876) also compared the transcribed wind speed from the diary with measurements from Nyholms Hovedvagt in central Copenhagen; the result will be discussed here, but the data not used.

Series from Helsingborg (HBG)

In order to compare the two previous data sets with present conditions, a 20-year data series on wind speed and direction (1996–2015; 20 years) from a station located in Helsingborg (HBG; see Figure 2) and managed by the Swedish Meteorological and Hydrological Institute (SMHI) was employed. Another data set was

actually available from the Island of Ven, but it only encompassed two years, so it was too short for any type of reliable analysis. The HBG data were obtained at the closest station to Ven from where a longer time series exist.

Wind data were available every hour with the wind direction given in degrees true north (TN) and the wind speed in m/s with one decimal. In the comparison with the other data sets, the measured wind direction was converted to the eight compass directions previously mentioned, including calm conditions, which were defined as wind speeds below 1 m/s (compare with the Beaufort scale). Thus, all measured winds within a sector of 22.5 deg centered on a specific compass direction was referred to that direction. The wind speed was classified following the Beaufort scale interpreted according to the British Met Office for marine forecasts (www.metoffice.gov.uk). The wind measurements were given at a reference elevation of 10 m above the ground.

Results

Analysis of wind direction

Figure 5 displays a comparison between the recorded wind directions on an annual basis for the three studied time series (TB, CPH, and HBG) in terms of the frequency of occurrence for the different compass directions (see also Table 1). The plot shows that the peak in the distribution of wind direction is different between TB and the other two series (CPH and HBG). In the TB series, the peak occurs for winds from SE, whereas for the other two series the peaks are for SW winds. The TB series has much lower values for winds from S to W, as well as higher values for winds from NE to SE, than the CPH and HBG series.

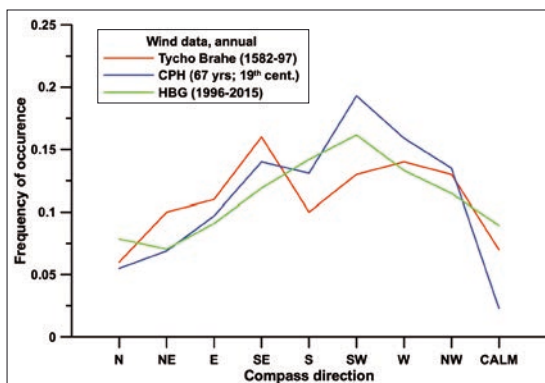


Figure 5. Frequency of occurrence with regard to wind direction for data on an annual basis from Tycho Brahe's diary, Copenhagen in the 19th century, and Helsingborg 1996–2015.

Table 1. Annual wind distribution for main compass directions in percent for the three data series investigated (La Cour, 1876; and SMHI).

Direction	Tycho Brahe diary	Copenhagen data	Helsingborg data
N	6	6	8
NE	10	7	7
E	11	10	9
SE	16	14	12
S	10	13	14
SW	13	19	16
W	14	16	13
NW	13	14	11
Calm	7	2	9

This tendency of a shift in the wind directions from NE – SE to S – W is even clearer if data from the winter months are investigated. Figures 6 and 7 illustrate the frequency distributions for wind direction for February and March, respectively. For the TB series, winds from NE and E are twice as likely to occur as in the CPH and HBG series. The reverse is true for winds from S and SW, at least for the CPH series; the HBG series has a slightly lower frequency value for winds from SW compared to the HBG series, although still 50% higher than the TB series. For the March data, the trend is also clear and the same as for the February data; however, the aforementioned ratios are somewhat lower. Table 2 presents the values on the distribution of winds from different directions for the TB series as given by La Cour (1876).

If wind data for the summer months are studied, there is no obvious trend similar to the winter months, as the distributions for the three data sets are quite similar.

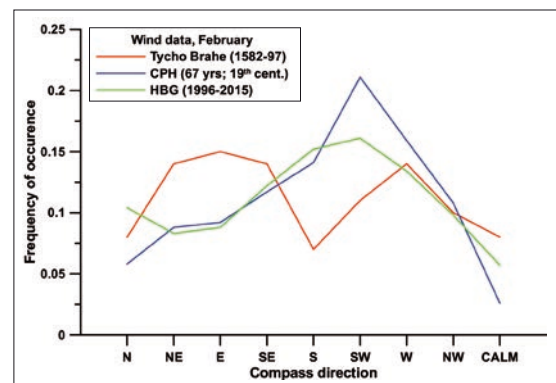


Figure 6. Frequency of occurrence with regard to wind direction for data in February from Tycho Brahe's diary, Copenhagen in the 19th century, and Helsingborg 1996–2015.

Table 2. Monthly wind distribution for main compass directions in percent for data from Tycho Brahe's diary (*La Cour, 1876*).

Month	N	NE	E	SE	S	SW	W	NW	Calm
Jan	7	9	4	19	10	16	14	12	8
Feb	8	14	15	14	7	11	14	10	8
Mar	6	11	15	18	10	9	10	13	9
Apr	5	13	16	12	11	9	13	14	8
May	7	7	14	20	7	8	13	14	9
Jun	6	9	9	13	11	10	17	19	7
Jul	6	5	4	12	13	17	19	18	6
Aug	6	5	9	17	8	14	19	16	6
Sep	8	13	8	14	9	11	15	16	7
Oct	4	12	13	22	12	16	8	7	6
Nov	5	10	12	18	12	20	10	7	5
Dec	5	14	12	17	13	13	15	7	4
All	6	10	11	16	10	13	14	13	7

Figures 8 and 9 display the frequency distributions for wind direction for June and July, respectively. The HBG data have slightly lower frequency values for winds from NE – SE, and higher values for winds from SW – W compared to the TB series. However, the CPH series is similar to the TB series over the former interval and with the HBG series over the latter interval. The distributions for July (Figure 9) are even more similar than for June, making it difficult to identify any trends. The much less pronounced shift for the summer months compared to the winter months, where the shifts are in the opposite directions, implies that the changes in wind direction can be seen in the annual data as well (Figure 5).

Several previous studies have noted the changes in wind direction that have occurred since the 16th century. La Cour (1876) observed that on the annual time scale,

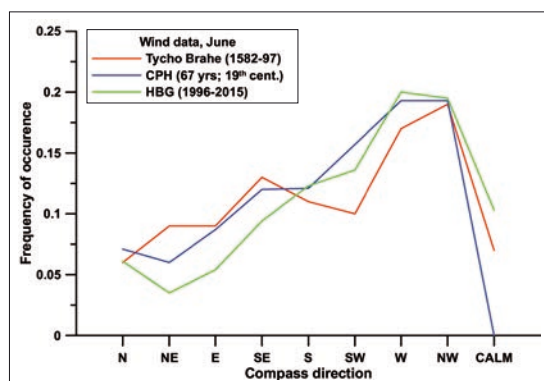


Figure 8. Frequency of occurrence with regard to wind direction for data in June from Tycho Brahe's diary, Copenhagen in the 19th century, and Helsingborg 1996–2015.

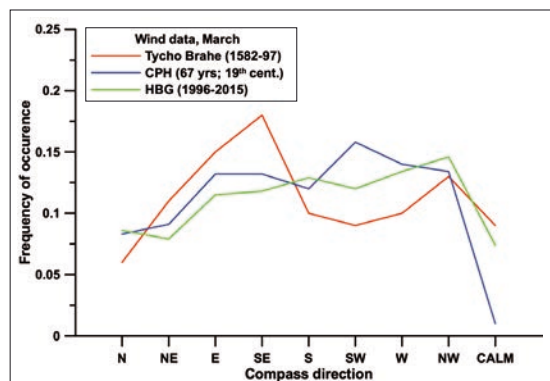


Figure 7. Frequency of occurrence with regard to wind direction for data in March from Tycho Brahe's diary, Copenhagen in the 19th century, and Helsingborg 1996–2015.

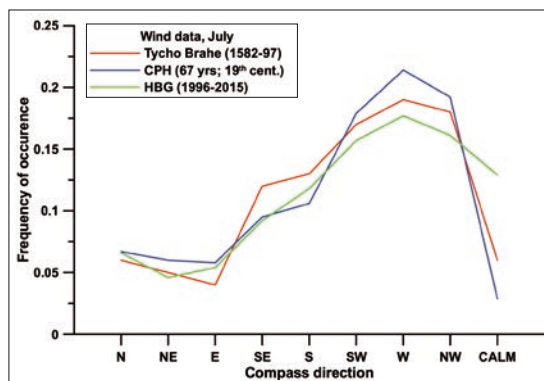


Figure 9. Frequency of occurrence with regard to wind direction for data in July from Tycho Brahe's diary, Copenhagen in the 19th century, and Helsingborg 1996–2015.

the TB series had similar number of winds from NW and N as for the CPH series, whereas the former had more NE, E, and SE winds and less S, SW, and W winds than the latter. When looking at the monthly time scale, the same trend was visible, although more pronounced for the winter months compared to the summer months. Ekholm (1899, 1901) in his studies on the variations in the climate referred to La Cour (1876) with regard to the number of snow days, rain days, and the wind direction as observed in the Tycho Brahe diary. Based on the observations of changing wind direction, Ekholm (1901) concluded that the distribution of atmospheric pressure during the winter was different in the days of Tycho Brahe compared to the early 20th century. In the 16th century, it was hypothesized that in general low-pressure systems (cyclones) would take a more southerly track, passing west and south of Ven (from the North Sea through the southern part of Denmark to Germany). During the time of Ekholm (also at present), the low-pressure system typically originated between Norway and Greenland, passing over the northern and middle part of the Scandinavian Peninsula, producing south-west winds in Öresund.

Flohn (1949) referred to the study by Ekholm (1901) regarding changes in the wind direction since the 16th century and the associated explanation. He referred to other data from the Tycho Brahe diary, such as frost days and the occurrence of snowfall, to investigate changes in the climate and to compare with observations made in Zurich during the 16th, 19th, and 20th century. Lenke (1968) also discussed the changes in flow pattern proposed by Ekholm (1901), making comparisons with two other meteorological series from 16th century. Although Lenke (1968) speculated over the influence on the meteorological observations by the particular conditions prevailing at Ven, an island between two land masses, he concluded that the changes observed from the 16th century until present in the study of the Tycho Brahe data were significant and supported by the two other data sets.

Jönsson and Holmquist (1995) also referred to Tycho Brahe's diary in their study of wind direction in southern Sweden between 1740 and 1992. They summarized the observations made by La Cour (1876) and concluded that the climate in south Scandinavia was more continental in the 16th century compared to recent times. Their analysis of a wind direction series, obtained in the city of Lund (see Figure 2), indicated gradual changes towards a more maritime climate, although the trend was not strictly linear and time periods with reversing behavior were observed. From the measured wind direction inferences could be made about the flow pattern (circulation) over southern Scandinavia during the last 250 years. A distinct change from a continental flow

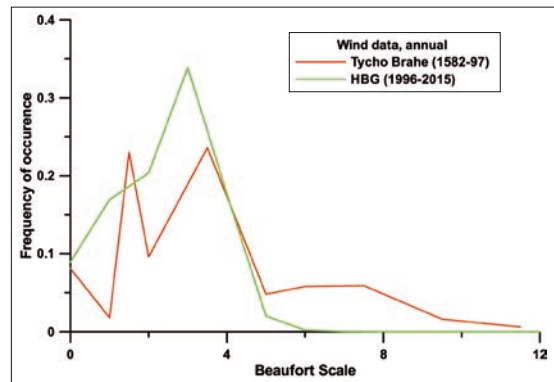


Figure 10. Frequency of occurrence with regard to wind speed for data on an annual basis from Tycho Brahe's diary and Helsingborg 1996–2015.

pattern to a maritime (oceanic) pattern was detected in the mid-19th century. This change caused a reduction in the frequencies of the northerly and northeasterly winds, which promotes a warmer climate. Pfister et al. (1999) reviewed 32 weather diaries from the 15th and 16th centuries, mostly from central Europe, although Tycho Brahe's diary was also included. The reiterated observation by Lenke (1968) that Tycho Brahe's diary agreed with records from northwestern Germany, lending credibility to the conclusion that cyclonic patterns over northern Europe indeed have changed since the 16th century. Pfister et al. (1999) stated that the situation during the 16th century agreed with an extreme mode of the North Atlantic Oscillation.

Analysis of wind speed

Figure 10 displays a comparison between the transcribed wind speed from Tycho Brahe's diary and the data from Helsingborg, where the wind speed is given according to the Beaufort scale (BFT). No data from Copenhagen, as for the wind direction, were available to compare with. La Cour (1876) presented some summary statistics from Nyholms Hovedvagt, but only average values for each month. The figure shows that the observations from the diary are less smooth than the ones from HBG, indicating that certain wind classes were more often selected than others. In his transcription, La Cour (1876) had one class for which no quantitative estimates could be made and those values have been ignored in the present analysis, implying that the total percentage are slightly less than one for the TB data in Figure 10 (and subsequent plots).

The most marked differences between the annual statistics for wind speed data from the TB and the HBG data are the ratios observed for higher Beaufort classes.

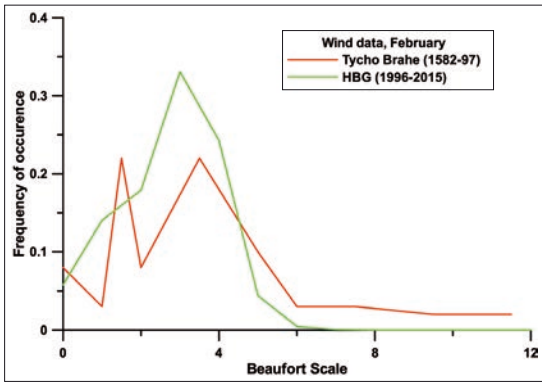


Figure 11. Frequency of occurrence with regard to wind speed for data in February from Tycho Brahe's diary and Helsingborg 1996–2015.

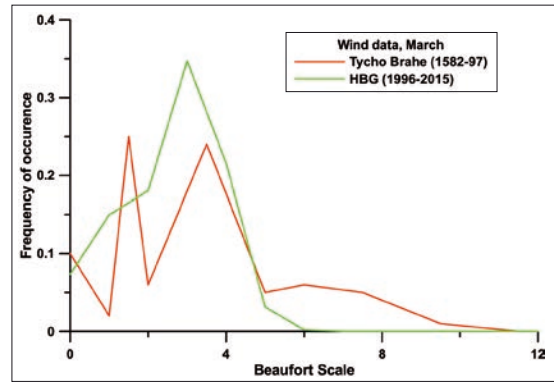


Figure 12. Frequency of occurrence with regard to wind speed for data in March from Tycho Brahe's diary and Helsingborg 1996–2015.

The TB data series includes much higher ratios for large winds compared to the HBG series. Whether this is a result of a bias in the observations made by the different assistants or associated with the transcription made by La Cour (1876) (or possibly both factors) is difficult to determine. La Cour (1876) noted this discrepancy himself when he compared the TB data to the records from Nyholms Hovedvagt. The average annual wind speed for the former data was BFT 3.1, whereas for the latter data it was BFT 2.3. La Cour mentioned the possibility to calibrate the TB observations with the help of the Nyholms Hovedvagt data, based on the overall magnitudes recorded, but doing so would defeat the purpose of detecting any changes in the properties. Thus, the transcribed wind speed data from Tycho Brahe's diary mainly provide qualitative information, although some quantitative results may be extracted from comparing the distribution at lower BFT values with more recent data. Also, if an analysis is carried out for individual measured values from the diary on wind speed and direction simultaneously, possibly some information may be extracted on the joint distribution of speed and direction and how that may have changed since the 16th centuries. This type of analysis was beyond the scope of the present study.

Figures 11 and 12 illustrate the distribution of wind speed with regard to the Beaufort scale for the winter months of February and March, comparing the TB and HBG data series. The same observations can be made as for the annual data; the TB data display much more uneven distributions and the higher BFT values are more frequent than for the HBG data. The same type of analysis was performed for the summer months, that is, June, July, and August, and the result for these months was combined to be able to compare with the data from Danish ship logbooks presented by Frydendahl et al.,

(1992). The data set discussed by Frydendahl et al. (1992) encompassed records from 1675 to 1873, but the data used here are only from the period 1686 to 1715. In one of the figures in their report, the frequency distribution for the summer months was presented and compared with the TB data as well as some data sets from the 19th and 20th century. In Figure 13, the data from ship logbooks are given together with the TB and HBG data for the three summer months. Again, the same behavior is observed as before, if the TB and HBG data are compared. The ship logbook data have the same uneven distribution as the TB data; however, they tend to include less values in the high BFT range, although both data sets still have significantly more values in this range than the HBG data.

In summary, it is difficult to assess whether there have been any changes in the wind speed since the 16th cen-

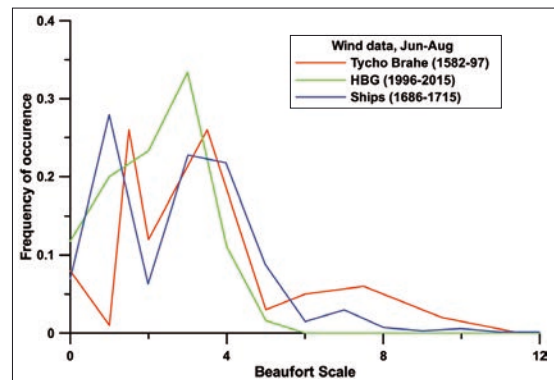


Figure 13. Frequency of occurrence with regard to wind speed for data in June, July, and August from Tycho Brahe's diary, Helsingborg 1996–2015, and observation in Danish ship logbooks 1686–1715.

tury based on the TB data. This is mainly due to the subjective method for observing the wind speed conditions, followed by the transcription carried out by La Cour (1876). Two features stand out when the wind speed distribution is analyzed: (1) the uneven shape of the distribution, probably related to a tendency for the observer (and interpreter) to select certain characteristic words for the wind conditions; and (2) an overestimation of the number of events with large wind speeds.

Consequences of changing wind properties

The previous analysis, in agreement with several earlier studies, indicates that the wind direction distribution has changed since the 16th century, making winds from S – W more prevalent today, whereas no firm conclusions can be made regarding the wind speed. The implications for the physical processes in coastal areas of changes in the wind direction may be pronounced, especially in southern Sweden, which is bordering an enclosed water body. The effects on the shoreline orientation were briefly discussed in the introduction and here some other related impacts on the coastal areas due to changes in the predominant wind direction will be reviewed.

A change in wind direction in southern Sweden directly affects the wave and water level conditions around the coast. Waves generated by the wind over the sea surface are a function of the wind speed and duration as well as the fetch, which is the length over which waves can be built up by the wind. For an enclosed water body, such as Öresund and the Baltic Sea, the fetch is closely related to the wind direction. In such water bodies, the wave properties at a certain location at the coast are basically a function of the distance to the land mass on the opposite side in the direction of the wind. Thus, a change in the wind direction affects the fetch length and the wave height that are generated for a specific wind speed and duration. Also, the wave period and the wave angle towards the coastline will change.

Another effect is related to wind setup and storm surge, which refer to changes in the mean water level associated with the wind-induced large-scale movement of water masses due to the wind shear stress acting on the water surface. For an enclosed basin such as the Baltic Sea, winds in a certain direction cause water to move downwind, creating an increase in the mean water level at the exposed coastline. For example, northerly winds will push water towards the southern part of the Baltic Sea, creating high water levels here (Hanson and Larson, 2008). On the other hand, winds from the south and southwest move water away from the southern part of the Baltic Sea, generating low water levels on the Swedish coast under such conditions. In Öresund the water

level variations are also coupled to changes in Kattegat and the local bathymetry, making the situation a bit more complicated, but similarly changes in wind direction have implications for the coastal water levels.

The observed changes in wind direction from the 16th century imply that more waves are generated by winds from a sector S to W, which will change the local wave conditions around the coastline. Besides different design conditions for structures and activities in the coastal areas, the transport of sediment will change as well as the equilibrium conditions for the beaches and their orientation. For example, if it is assumed that the change in wind direction as observed from the TB data are representative not only in Öresund, but also for the Swedish south coast, it is expected that the sediment transport pattern along this coast would have changed during the last centuries. The response of the coastline to changes in the forcing conditions may be quite slow, depending on the wave conditions, sedimentology, and general geological conditions, implying that it can take decades for the coastline to achieve a new equilibrium state.

The worst example of coastal erosion in Sweden is in Löderup on the south coast of Sweden, where the coastline has retreated 1–2 m/year during the last 200 years (Larson and Hanson, 2013). This erosion is most likely due to changing net sediment transport conditions because of a changing wind climate that generates more transport to the east related to increased winds from the sector S – W. The disequilibrium between the wave climate and the shoreline orientation has existed for at least two centuries, and the erosion will probably continue until the shoreline orientation becomes similar to the orientation in the eastern part of Ystad Bay (Larson and Hanson 1992), which has a shoreline orientation more or less in equilibrium with the incoming waves. In order for the shoreline in Löderup to reach similar equilibrium conditions, approximately a further shoreline retreat of 300 m would be required (Larson and Hanson, 2013). However, several different shore protection measures have been taken there, such as seawalls, groins, and beach nourishment, preventing the shoreline to move freely. Figure 14 illustrates how the shoreline has evolved at Löderup since the mid-19th century.

Conclusions

The diary kept on the initiative of Tycho Brahe on the Island of Ven regarding the meteorological conditions from October 1582 to April 1597 contains a wealth of information from which changes in the climate from the 16th century to today may be detected. In this paper, focus was on the wind conditions (direction and speed),

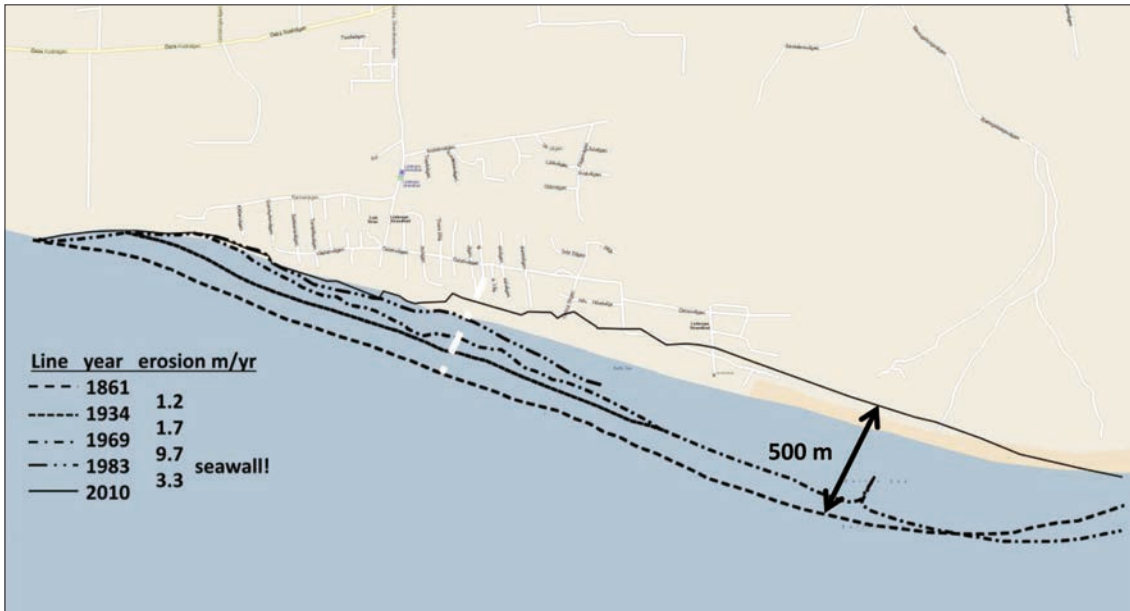


Figure 14. Observed shorelines at Löderup on the Swedish south coast from the mid-19th century until recent times showing a retreat of up to 500 m.

and transcribed data from the diary by La Cour (1876) were compared to data from the 19th and 20th/21st century.

In agreement with several previous studies, including the one made by La Cour (1876), analysis showed that prevailing wind directions have changed since the 16th century. Shifts in the wind direction from the sector northeast – southeast to the sector south – west were identified, and these changes were more pronounced for the winter months compared to the summer months. No conclusions could be made regarding the wind speed, probably due to problems in transcribing the observations in the diary to quantifiable values.

Changes in the wind direction affect wave and water level conditions in coastal areas, especially for enclosed seas such as Öresund and the Baltic Sea. New design conditions for structures and activities near the coast will be necessary, if the wind properties change. Also, the sediment transport pattern will be different as the net transport changes due to altered incident wave angles and breaking wave heights, which in turn cause re-orientation of the shoreline. The associated shoreline evolution implies areas of erosion and accretion, as the shoreline adjusts to the new wave climate. Such adjustments may take decades or longer and at present are most likely going on at Löderup on the Swedish south coast, where the shoreline has retreated 1–2 m at least over the last 200 years.

In order to study if the observed changes in the wind direction during the last centuries is responsible for the shoreline adjustment on the south coast of Sweden, comparisons should be made between wind measurements discussed in this paper and wind measurements on the south coast. If correlation can be established for shorter time periods, it is probable that the observed long-term changes around Öresund also are valid for the south coast, which may explain the shoreline evolution occurring along some of the coastal stretches.

An interesting aspect of climate change is what to expect in the future and how such information can be used in the design, planning, and management of the coastal areas. In a steady-state situation, having a system (e.g., the climate) with constant properties, the future may be extrapolated from the past, at least over time scales similar to the available records. However, if the system properties change, for example, because of influences by man, extrapolation from existing records becomes more difficult. In such cases physically based models to simulate the climatic system may be employed; however, calibration and validation of these models are required, which could be performed over shorter time periods. Other possibilities for obtaining longer data series for analysis are to study quantities that are more indirectly related to the climate and how it changes, for example, ice cores, sediment cores (from lakes or the ocean), and tree rings.

Acknowledgements

Many of the older books are available electronically as full text through Google Books or different libraries, for example, the Royal Library in Copenhagen. The access to these texts are gratefully acknowledged.

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