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Jens Esmark's Christiania (Oslo) meteorological observations 1816-1838: The first long term continuous temperature record from the Norwegian capital homogenized and analysed

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Abstract

In 2010 we rediscovered the complete set of meteorological observation protocols made by professor Jens Esmark (1762-1839) during his years of residence in the Norwegian capital of Oslo (then Christiania). From 1 January 1816 to 25 January 1839 Esmark at his house in Øvre Voldgate in the morning, early afternoon and late evening recorded air temperature with state of the art thermometers. He also noted air pressure, cloud cover, precipitation and wind directions, and experimented with rain gauges and hygrometers. From 1818 to the end of 1838 he twice a month provided weather tables to the official newspaper *Den norske Rigstidende*, and thus acquired a semi-official status as the first Norwegian state meteorologist. This paper evaluates the quality of Esmark's observations, presents new metadata, new homogenization and analysis. The air temperature in Oslo during this period is shown to exhibit a slow rise from 1816 towards 1825, followed by a slighter fall again towards 1838.

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1 Introduction

The current concern with climate change has increased the interest in early meteorological observation series and evaluation of their quality (e.g. Bergström & Moberg, 2002; Auer et al., 2007). In a recent paper we analysed the temperature record for the Norwegian capital made 1837-2012 by the astronomical Observatory at the University of Oslo and the Norwegian Meteorological Institute (MET Norway) (Nordli et al., 2015). Previous to 1837 long term observations of the Oslo weather were known to have been made by Jens Esmark (1762-1839), professor of mining sciences at the University of Oslo (then Christiania). A first reanalysis of Esmark's observations was made by meteorologist B. J. Birkeland (Birkeland, 1925). Our rediscovery in 2010 of Esmark's original meteorological observation protocols has provided an opportunity to digitize, homogenize and analyze his data with modern methods.

Esmark is today mostly remembered for his pioneer ascents of many of Norway's highest peaks (Esmark 1802, 1812; Hestmark 2009), his discovery of Ice Ages, and his astronomical explanation of such dramatic climate change as caused by variations in the eccentricity of the orbit of the Earth is now recognized as a precursor of the theories of James Croll and Milutin Milankovich (Esmark, 1824, 1826; Andersen, 1992; Worsley, 2006; Rudwick, 2008; Berger, 2012; Krüger, 2013). In his own lifetime he was primarily known as a skillful mineralogist and geologist. Throughout his life Esmark maintained a passion for meteorological observation with instruments he crafted himself in accordance with the highest contemporary standards. His main inspiration for this activity were his teachers at Copenhagen University, which he attended 1784-89; first among them the Astronomer Royal, professor Thomas Bugge (1740-1815), who in his observatory tower Rundetårn in the middle of Copenhagen made daily measurements of the weather (Willaume-Jantzen 1896). Esmark also befriended Bugge's instrument maker, the Swede Johan(nes) Ahl (1729-1795) (Esmark, 1825; Anonymous 1839). In addition Esmark followed the lectures of Christian Gottlieb Kratzenstein (1723-1795), professor of medicine and experimental physics, a 'hands on' practical man who enjoyed crafting instruments and all sorts of machines (Snorrason, 1974, Splinter, 2007). From 1789 to 1791 Esmark studied mining sciences at the Norwegian silver town of Kongsberg, and after further studies in Freiberg, Saxony and Schemnitz, Austria-Hungary, he in 1798 moved

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back to Kongsberg to take up a position as Assessor in the central mining administration (*Overbergamtet*) of the dual kingdom Denmark-Norway. At Kongsberg he also lectured in mineralogy, geology and experimental physics at the Royal Norwegian Mining Seminar, acting as its temporary Inspector (Headmaster) from 1799, and permanent Inspector 1802-1815. From 1 January 1799 he three times a day recorded observations of the Kongsberg weather - air pressure on mercury barometers (in inches and lines), and air temperature in degrees of Reaumur; documented in a series of small notebooks running continuously with some lacunae until 16 September 1810, and rediscovered by the authors in 2010 (Esmark 1799-1810). When Esmark in 1815 moved to the Norwegian capital Christiania (now Oslo) to become the first professor in the mining sciences at the University he continued this habit. At least from January 1816 up to and until the day before his death on 26 January 1839 he recorded air temperature and barometric pressure three times a day. The complete set of his 23 Christiania observation protocols, long believed lost, was rediscovered in 2010 by the authors, and is now safely deposited in the Norwegian National archives (Riksarkivet) (Esmark 1816-1838). They provide a unique and detailed picture of the weather in Oslo in the early 19th century. From January 1818 to December 1838 tables of Esmark's observations were published every fortnight in the official newspaper *Den norske Rigstidende* (cf. Appendix A), and he thus acquired a semi-official position as Norway's first state meteorologist. Based on a number of previously unpublished documents (cited as Document 1 etc, with archival location in Reference list) we here present new metadata for Esmark's meteorological observations from Christiania, and homogenize, reanalyse and evaluate his original data with modern statistical tools to characterize the weather in the Norwegian capital in this period.

2 Metadata

2.1 The location - No. 308, Vestre Rode - Øvre Vollgate 7.

Esmark's observations were made at his home (cf. Esmark 1823b: *De ere tagne i min Bopel*), and there is no evidence indicating that he changed the location. On 19 August 1815 Esmark was registred as owner of property No. 308 in Vestre Rode (i.e. Western Quarter), one of the four old quarters of Christiania town (Document

1). It was a modest one-and-half storey house built late in the 18th century with an adjoining a garden. Esmark's continued residence at this address until his death is documented in annual censuses and tax protocols (Document 2 & 3). Property No. 308 was situated on the north-western side of the street Øvre Vollgate (Øvre Woldgaden), laid out literally *on* what used to be the outermost western rampart (*voll*) of nearby Akershus Castle and Fortress (Fig. 1). It was a natural rock promontory above a meadow to the west where the poor fishing village Pipervigen would develop later in the 19th century, today the site of Oslo Town Hall. In 1815 Øvre Vollgate constituted the south-western limit of Christiania, a town with only about 15000 citizens (Myhre 1990). Until 1814 the main administration centre of the dual kingdom was in Copenhagen, but with Christiania in that year acquiring the new parliament and government after the separation of Norway from Denmark, the town expanded rapidly. When street numbers were introduced, Esmark's property was numbered Øvre Vollgt No. 7. The present Øvre Vollgate 7 – an office highrise – comprises previous numbers Øvre Vollgate 3, 5 and 7.

Esmark's property No. 308 and all neighbouring properties were measured and mapped for the new matriculation of Christiania in the summer of 1830, and thus we have very precise data on his house and the surrounding properties at the relevant time (Document 4). The whole property roughly constituted an elongated rectangle, approximately 14 m x 60 m (Fig. 2). The unit used in these measurements was the 'Norwegian alen' (*Norsk alen*), determined by law in 1824 to be 62.75 cm. It was divided into two feet, each divided into 12 inches, each divided into 12 lines. No. 308 was measured to 2026 square alen, of which the house (including a yard) was 733 ½ and the garden 1292 ½ square alen (1 square alen = 0.3937 m^2). Thus the whole property was ca. 800 m^2, and the house (including yard) ca. 290 m^2. The house had a 22 alen 6 inch (ca. 14 m) long façade towards the street Øvre Voldgate, constituting the south eastern border of the property, with windows, doors, and a gate leading in to the back yard (Fig. 3). Øvre Vollgate street runs from SW to NE at an angle of roughly 32^o NE (400 degrees). At the back the house surrounded a small yard, with a narrow passage opening out to the garden in the NW. As it would have been hazardous to place the meteorological instruments on the street-side of the house, where passers-by could have tinkered with them, it is almost certain that they were placed in Esmark's back yard, a well guarded space. When the house was finally demolished in 1938,

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it was in such bad condition that the Oslo city health authorities demanded the whole property be sprayed with hydrocyanic acid and that none of the fungus-infected material be used for construction elsewhere (Document 5).

Esmark's garden on the NW side of the house and court yard was a continuous slope, dropping ten alen (6,25 m) down along 66 alen length towards Pipervika. Here it was most probably limited by a fence towards the Præste Gade street which later changed name to todays Rosenkrantz gate. In 1841, a couple of years after Esmark's death, most of this garden was indeed sectioned out and sold to form the new property Rosenkrantz gate 26. In Esmark's time, however, the promontory remained an open garden space. His neighbours on both sides (No. 307 and No. 309) had the same arrangement of house and garden, with facades to Øvre Vollgate and gardens sloping down on the back to Præstegaden (Document 6). To the north of the lowermost part of Esmark's property was an open space called Jomfru Wold's Løkke (No. 368). South of this lower part of the garden was the street Pipervigbakken, leading down from Rådhusgaten street passing by the outer ramparts of Akershus fortress and Castle. The sea with Pipervika bay (Piperviks Bugten) was less than 200 m south of Esmark's garden. His garden was not an entirely constant environment. In 1823 for instance, he received several fruit trees from a Danish friend which he planted in the garden (Document 7).

It was a modest residence for a professor, situated in a comparatively poor part of town, with mainly craftsmen, tradesmen and artisans in the neighbourhood (Myhre 1990: 40). Here Esmark, a widower since 1811, moved in with his three sons Hans Morten, Petter and Lauritz, a maid and a manservant (Document 2 & 3). His daughter Elise resided with her grandparents in Copenhagen, but later returned to Norway to take up residence in No. 308.

2.2 The observers

The great majority of the Christiania observations were made and noted down by Esmark himself who has an easily recognizable handwriting. His position as professor in the mining sciences did however sometimes cause him to leave town on short or long field excursions, some lasting several months. He was away from Christiania on long voyages in 1818 (Hallingdal), 1819 (Kristiansand); 1822 (Bergen), 1823 (round-trip south Norway), 1826 (Setesdalen), 1827 (Trondhjem) and 1829 (Copenhagen). In his absense his sons seem to have been instructed to

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continue daily observations, and there are extremely few missing data points. The oldest son Hans Morten Thrane Esmark (b. 1801) in 1825 became a chaplain in Brevig and moved from Christiania; Axel Petter (b. 1804) became a sailor and was often away from home; Lauritz Martin (b. 1806), later a professor of zoology at the Christiania university, and daughter Elise Cathrine (b. 1800) remained at home until Esmark's death. The sons evidently did not fully share their father's passion, and although instrument readings were meticulously maintained, the qualitative notes on weather are often restricted to a single word in Esmark's absence. A claim (Birkeland 1925: 5) that the botanist Martin Flor performed the observations in Esmark's absence has not been substantiated, and anyway Flor committed suicide in 1820.

2.3 The hours of day

Esmark's Christiania observation protocols do not indicate the precise hours when the observations were made. The columns are given as morning, noon and evening (*Morgen, Middag, Aften)*. A note on the first published table in *Den norske Rigstidende* on 24 January 1818, also says *Morgen, Middag og Aften* without further specification (Fig. 6). In a summary table of 15 years (1818-1832) published 1833 Esmark is more explicit: "The barometer observations have been made daily in the morning, afternoon and evening; in later years at 8 ½ o'clock morning, at 3 ½ o'clock afternoon and 9 ½ o'clock evening; thermometer observations at the same times in the afternoon and evening and in the morning with the help of the night thermometer. From this the middle hight is taken." **(***Barometerobservationerne ere dagligen gjorte om Morgenen, Eftermiddagen og Aftenen; i de senere Aar Kl. 8 ½ Morgen, Kl. 3 ½ Eftermiddag og Kl. 9 ½ Aften; Thermometerobservationerne paa samme Tider om Eftermiddagen og Aftenen og om Morgenen ved Hjælp af Natthermometret. Heraf er taget Middelhøiden*.) (Esmark 1833: 235). Thus 8.30 AM, 15.30 (PM), 21.30 (PM). The hour 3 ½ PM probably coincided with Esmark's return to his house from the lectures at the University just a few blocks away. The phrasing "in later years" suggests that the hours had not been constant throughout the whole series. This problem we analyse further below. Also that a night-thermometer (for measuring minima) was introduced some time after the start of the series.

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2.4 The instruments and their position

In a note to his first table presented in the journal *Den norske Rigstidende*, on 24 January 1818, Esmark provides a few details of his measurements: "The observations are made 34 Rhinelandic feet [i.e. 10.68 m] above the sea, and are the middle value of observations made morning, noon and evening. The barometer heights are corrected as they would have been if the barometer was subject to a temperature of 0^o. The thermometer hangs freely against north." *(Observationerne ere anstillede 34 Rhinlandske Fod over Havet, og ere Middeltallet af Observationer, anstillede Morgen, Middag og Aften. Barometerhøiderne ere corrigerede saaledes, som de skulle være, dersom Barometret havde været udsat for 0^o Temperatur. Thermometret hænger frit imod Nord.*) (Fig. 6). Esmark also notes for these (average?) data that "The barometer height is reduced to 0^o R. If one wants it reduced to sea level, one must add a line or 1/12 of an inch to its height, so that the barometer height at sea level becomes 28.1,20 in French measure." (*Barometerhøiden er reduceret til 0^o R. Vil Man have den reduceret til Havets Overflade, maa Man til den anførte Høide lægge en Linie eller 1/12 Deel af en Tomme, saa at Barometerhøiden ved Havets Overflade bliver 28.1,20 i Fransk Maal.*) (Esmark 1833: 235).

Thermometers. Esmark all his life used the Reaumur scale; "R". The precision of his Reaumur thermometer was 1/2 of a degree. On a table of averages for the years 1816-1822 Esmark notes: "The thermometer observations are made in shadow in free air with a Reaumur thermometer, which boiling point is determined at 28 inches 2 lines (French measure) barometric height." (*"Thermometerobservationerne ere gjorte i Skyggen i fri Luft med et Reaumurs Thermometer, hvis Kogepunkt er bestemt ved 28 Tommers 2 Liniers (fransk Maal) Barometerhöide.")* (Esmark 1823).

Barometer. Of the barometer used Esmark (1833: 235) states: "The barometer is a simple barometer, the tube of which is 2 ½ line in diameter and which capsul is 40 lines in diameter, and calibrated after a hevertbarometer." (*Barometret er et simpelt Barometer, hvis Rør er 2 ½ Linie i Diameter og hvis Capsel er 40 Linier i Diameter, samt justeret efter et Hævertbarometer.*)

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2.5 The protocols and data recorded

Esmark's Christiania protocols are handmade, folded sheets of white paper cut up and sewn in with a thin grey cardboard cover, one protocol for each year (Fig. 4), 23 protocols in all (Esmark 1816-1838). Esmark interfoliated the official printed *Almanach* for Christiania. This had for each month 16 days on each page, and thus Esmark wrote down his data for 15 or 16 days on the first page of a month and the remaining days from 17 to 28, 29, 30 or 31 on the next page (Fig. 5). The protocols start on 1 January 1816 and end 31 December 1838, only 26 days before his death; altogether 8401 days of continuous measurements. There are only a few small lacunae. Photographs of all the protocols are available at MET Norway (Klimadata samba server, HistKlim skanna dokument), and digitized values might be downloaded from MET Norway's home page: http://www.met.no. Esmark continued observations in January 1839 until the day before his death 26 January, but these observations are only known through the newspaper *Morgenbladet*, which had published Esmark's daily measurements since 1834.

Three times a day Esmark recorded temperature to a half degree, and air pressure with one or two decimals (Fig. 5). In the right hand margin he noted the weather (*Veirliget*) with qualitative terms; see also Esmark (1833). He used a fairly limited number of categories: *Precipitation*: *lidt Regn (a little rain)*; Fiin Regn (drissle); *Regn* (rain); *Regn Bygger/Bÿgger* (showers); *Regn af og til* (Rain now and then); *megen Regn* (much rain); *Sne* (snow); *Sne Flokker* (snow); *Sne Bygger* (snow showers). *Cloud cover*: *Klart* (clear), *enkelte Skyer* (a few clouds); *tynde Skyer* (thin clouds); *skyet* (cludy); *skyer i Horizonten* (clouds in the horizon); *disig* (haze); *Taage* (fog). The most common category was *tykt* (thick) which means a grey day with haze, often with precipitation. *Wind*: Wind direction was usually recorded only once a day, at midday, with categories N, S, V and O, and combinations , e.g. N. O. (nord ost/north easterly). *Other*: *Torden* (thunder); *Nordlys* (northern lights); *Flekker i Solen* (sunspots); one or two circles around the sun; *Høyt vand* (high sea level). In June 1818 Esmark introduced a new parameter: *precipitation*, measured with a rain gauge, and in the June summary, he could announce: "In this month there has, according to the rain gauge, fallen rain to a height, which, if it had been standing, had constituted a height of 1 inch and 9 and 7/12 line. The rain gauge is situated 15 feet above sea level." The low altitude of the rain gauge suggests that it was placed at the lower part of the slope in his

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garden. In October 1820 he presented the readers of *Rigstidende* to his new design for a hygrometer – an instrument to measure air humidity (Esmark, 1820). It was modified from a model developed by John Livingstone, and M.D. from Canton, China, published in the *Edinburgh Philosophical Journal* in 1819 (Livingstone 1819). The general idea was to put a moisture absorbing/releasing chemical substance (Livingstone used pure sulphuric acid, which was also used to produce ice) on one side of a balance, balanced against a weight on the other side. The balance was placed under a glass jar open in the bottom to let air freely flow in and out, and to protect it from precipitation. Esmark made two new hygrometers according to this model. ”Anyone who desires to see these hygrometers, can see them at my house” *(“Enhver, som har Lyst dertil, kan see disse Hygrometere hos mig.”*)(Esmark, 1820) He had tested them for several months, and thought they could be used by farmers to predict weather change as substitute for barometers. He did not, however, use the hygrometer data for his meteorological tables. For the year 1821 he presented more regular monthly data on precipitation in inches – from 1 May through October – apparently the months without frost.

2.6 The published tables

Starting on Saturday 24 January 1818, with a table presenting weather data for the first half of the month, the semi-official daily *Den norske Rigstidende* published Esmark’s meteorological observations, which thus acquired an official air. (Fig. 6). It became a regular series, published twice a month – one table for the first half of the month, one for the second half – a total of 24 tables each year, all with the same title ”Meteorologiske Iagttagelser i Christiania [year], anstillede af Prof. Esmark.” (Meteorological observations in Christiania [year], made by Prof. Esmark) etc.. This series running from 1 January 1818 to 15 December 1838 is absent from all previously published bibliographies of Esmark’s works, but in fact runs to no less than 503 published tables (!) (Appendix A). They present 7665 days of continuous observations. In addition comes the two full years of 1816 and 1817, only published summarily by Esmark (1823) but with complete record preserved in the original protocols. The whole year 1818 was summed up on 8 January 1819 with means etc., and here Esmark also compared the Christiania data to those obtained by Wargentin in Stockholm, by Bugge in Copenhagen, and (no observator given) in St. Petersburg, Russia. It was not a weather forecast but

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rather a weather 'backlog', and this may have dimmed their public interest somewhat. The data given in these published tables differ from the raw data of the protocols by being daily averages. For each day he gave the barometric pressure and temperature, averaged from observations made in the morning, at noon, and in the evening (at first without further precision of hour). To calculate these averages he apparently used the formula:

$$T_m = {}^1\!/_4\,(T_I + 2T_{II} + T_{III}) \quad (1)$$

where T_m is Esmark's daily "mean" temperature, and T_I, T_{II}, and T_{III} are the observed temperature morning, noon and evening, respectively. To the tables for the second half of each month, he also appended a note with the mean barometric pressure and temperature for the entire month, and indicated which days had the maximum and minimum air pressure and temperature. The mean temperature was given to 1/100th degree (a spurious precision). The series continued in 1820, now also with the daily wind direction. Esmark evidently trusted only himself to calculate the averages and set up the tables, and thus the readers of *Rigstidende* sometimes had to wait for months to read the weather for the last fortnight. From 1834 Esmark's observations were also published in the Christiania newspaper *Morgenbladet* every day, with two days delay, i.e. observations for the 1st day of the month were published on the 3rd etc. This was initiated after Christiania doctors suspected a connection between the weather and the cholera epidemics which struck Norway from 1833 and forward.

3 Methods

3.1 Homogeneity testing

A homogenous climatic time series shows variations in climate without being disturbed by other factors involved, like changes in the environment, observational procedures or instrument calibration. For the study of climate variations the use of homogenous series is of paramount importance, otherwise the climate analysis might be wrong (e.g. Auer et al., 2007; Moberg and Alexandersson, 1997; Tuomenvirta, 2001). For testing the homogeneity of Esmark's temperature series we selected the Standard Normal Homogeneity Test (SNHT) that has been widely used for testing of both precipitation series and temperature series (Alexandersson, 1986; Alexandersson and Moberg, 1997; Ducré-Robitaille et al., 2003). The

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first version of the test (Alexandersson, 1986) had one step change as the only possibility, whereas in the version of 1997 both double shifts and a trend were possible outcomes of the test. In any year the significance of a potential break is examined. The testing followed the principle of comparing a candidate series (the series under testing) against a reference series. The reference might be series from one or more neighbouring stations. A candidate series might also be observations at one particular time of the day, which are compared with other observation times for the same station. In the latter case we call it "internal testing". Without contemporary neighbouring stations internal testing is the only possibility. If no significant break occurs the series is considered homogenous. Esmark's station at Øvre Vollgate 7 as well as other observation stations used in this article are given in Table 1, with their national station number (identifier) and name. Before the analysis started all observations were calculated from degree of Reaumur to degree of Celsius by multiplying Esmark's Reaumur readings by the factor 1.25.

4 Results

4.1 Homogeneity testing

For much of Esmark's period of observation there was no other nearby station in operation so internal testing was the only possibility. The testing was performed both for seasonal (see Table 2) and monthly (see Table 3) resolutions where observations taken in the morning (I), noon (II) and evening (III) were compared with each other. By comparing several test results it was possible to decide at which observation time a shift (inhomogeneity) occurred. Most striking are the huge shifts detected in spring, summer and autumn when the morning observation was involved. The most probable year for the shift was 1827; in particular this was true for the single shift test. Here we apply the common convention to define the shift year as the last year before the shift. We have to conclude that the morning observation is inhomogeneous. A further investigation of the daily observations (not shown) suggested that the change took place within the month of March 1828.

When evening observation was tested against the midday observation a shift seemed to occur in 1820 or 1821, most probably in 1821. But this break in homogeneity was much less than that of the morning observation. The shift seems to be absent or very weak during winter so exact dating was impossible. For convenience the end of 1821 was adopted as the year of the inhomogeneity.

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Tests including the midday observation revealed no additional shifts than those already detected. The occurrence of the shifts in the tests I vs II and III vs II seemed to reflect shifts either in the morning or in the evening observations. For the winter season a shift in the last part of the series was detected, possible shift years were 1832, 1833 or 1834.
The large shift in the morning observation could have masked possible smaller shifts in the series on both sides of this shift. Therefore the single shift SNHT was applied on two different parts of Esmark's series: 1816.01-1828.02 and 1828.03-1838.12, parts 2 and 3 in Table 2. However, no further shifts in the series were detected. The shifts detected in part 1 in the evening observations of 1821 and in the morning observation in the 1830s for the winter season were confirmed.

The reliability of the results was further tested on monthly resolution and also evaluated by comparison with the metadata. Esmark (1833) tells that he uses "a night thermometer" for the morning observation. Our hypothesis is that in Esmark's terminology "night thermometer" means "minimum thermometer", and that the introduction of the minimum thermometer is the reason for the shift in March 1828. This hypothesis was tested by studying the difference between Esmark's evening observation and the morning observation the following day for the three homogenous intervals (see Table 4) (the winter inhomogeneity in the 1830s was ignored). For comparison this was also done for the observations at the modern station Oslo – Blindern. In the earliest interval (row 1) the differences in Esmark's observations were very much smaller than those from Blindern, so it is impossible that Esmark could have noted the nightly minimum temperature in the column for the morning observation. In the next interval (row 2) the differences are somewhat larger, but far too small compared to Blindern so the same conclusion has to be drawn: no minimum thermometer was in use. However, in the third interval (row 3) the differences are nearly the same as those for Blindern. Even the monthly variations throughout the year are realistic. We conclude that Esmark for the morning observation used a minimum thermometer in the period 1828.03-1838.12. Before that he observed temperature in the morning with an ordinary thermometer. If the minimum thermometer was set at the evening observation the notes in the column for morning observation should always be equal or lower than the evening temperature the previous day. In December this is not true for 26% of the observations and in June for 6%. These figures reduce to 6% and 2% in December and June respectively for violations no more than 1 ^{o}C. In practice different exposure of the two thermometers may violate this logical test, and one should also take into account the possibility of instrumental errors in Esmark's thermometers. We may conclude that the percentage of violation is not large enough to contradict our conclusion that a night minimum thermometer was in use.

4.2 The shift in 1821

An inhomogeneity in the evening observation was detected by the homogeneity testing. It was adjusted for by the mean difference between the midday observation and the evening observation on each side of the shift, cf. Methods. The adjustments terms are presented in Table 5. The adjustments are largest in the months where the daily temperature wave in largest, so it is much likely that one reason for the shift was an earlier evening observation time before 1822. If so it seems that the observation was taken at least one hour earlier before this shift. Strictly speaking we know Esmark's observation times only in 1833, so this result is not in contradiction to metadata. Other factors than the observation times might as well have been involved, as the adjustments in winter is too large to be due to observation time only.

4.3 A shift in the 1830s

significant in winter, was detected by the SNHT double shift as well as the single shift when the time window for the test was 1828.03-1838.12. The shift has the character of a continuous inhomogeneity (Fig. 7). The difference between the evening observation and the morning observation increased quite steadily from 1831 to 1838, whereas it was constant during the years 1829-1831. The explanation may be a change in the observation times. According to Esmark (1833) his observation times were, see Metadata.

- Morning: 08:30 ChT = 08:43 CET = 7:43 UTC
- Midday: 15:30 ChT = 15:43 CET = 14:43 UTC
- Evening: 21:30 ChT = 21:43 CET = 20:43 UTC

ChT = Christiania time i.e. local time for Christiania (Oslo), CET = Central European Time, UTC = Universal Time Coordinated.

These observation times were for the barometric pressure, but at midday and evening the thermometer were read at the same time as the barometer, but Esmark does not explicitly say that the morning thermometer was read at the same time as the barometer. He also use the term "in the latest" years so we do not know from which year these observation times were introduced or if he continued to use them also in the following years 1834-1838.

Our hypothesis is that Esmark has had another observation time for the temperature observations in the morning than for the pressure observations. Pressure was observed inside

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the house, but for the temperature observations he had to leave the house for his garden. Esmark might originally have observed temperature and pressure at the same time also in the morning, but with the introduction of the minimum thermometer he could have thought that the observation time for the morning temperature was not important. In spring, summer and autumn he obviously was right in his thinking as minimum temperature occurs earlier than at the morning observation time (8:30 ChT), but in winter the minimum temperature occurs often later in the day as the systematic daily temperature wave is weak. This can explain the changing difference during winter and the stable differences during the other seasons. As Esmark grew older he might have gone outside for carrying out the morning observation later and later. This might explain the trend shift in the morning observation. Following this hypothesis the minimum temperature was adjusted, ΔT, by use of formula (2) for the winter season in accordance with the regression line shown in Fig. 7, where a = year (period 1832-1838). No adjustments were undertaken for the period 1829-1831.

$$\Delta T = 0.2861 \cdot a - 523.85 \qquad (2)$$

4.4 Overheating of the midday observation

The midday observation turned out to be homogenous, but it might have been overheated by insufficient radiation protection in Esmark's yard. This was tested by comparison with the Oslo – Blindern station that is well protected by a Stevenson screen. Difference between the midday observation and the evening observation reveals a characteristic pattern (Fig. 8). Whereas the differences were almost equal in the months September – March, the differences in the Esmark series were larger than the differences in the Blindern series for the months April – August. They were particularly large in MJA where the sun is highest on the sky and the radiation reaches its annual maximum. Therefore our interpretation is that Esmark's thermometer was overheated at the midday observation by (reflected) short wave radiation in the period April – August, but not for the rest of the year. Based on the differences between the two curves the adjustments of the midday observation are also given (lower panel in Fig. 8).

4.5 Homogenisation of the monthly mean temperature.

Esmark observed only three times a day, so it is far from obvious how monthly mean temperature should be calculated without bias. This problem confronts meteorological institutes worldwide so formulas for the calculation are developed (see Appendix B). The

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formulas contain specific constants valid for each month and site. Strictly speaking the constants were unknown for Esmark's observation site at Øvre Vollgate, but well known for the station 18700 Oslo – Blindern lying 3.4 km to the north of Esmark's site. Fortunately there are indications that the constants for Blindern could be used also for Øvre Vollgate (see Appendix 2). Given the constants the calculation of homogenous monthly mean temperature was trivial when the homogenised version of the observations at fixed hours was used. We found that the adjustments for seasonal means vary from -0.7°C to +0.3°C (Fig. 9). The adjustments were negative except from the last part of the series in winter and autumn. For the annual means the adjustments are much less, they vary from -0.4°C to -0.1°C.

4.6 The climate in Esmark's period of observation, 1816-1838

Esmark's observations exhibit a long-term variation pattern characterised by lower values in the start and in the end of the period, whereas the middle of the period was somewhat warmer, cf. Fig. 10. This is true not only for the annual means, but also for all seasons of the year. For individual years 1822 is warmest except in summer. The coldest year is 1816 followed by the years 1817, 1820 and the last one 1838. In the year 1816 stands out as coldest also in two seasons, spring (MAM) and autumn (SON), and also in the two individual months March and May (not shown).

The year 1816 is of particular interest as it has gone into history as "the year without summer" (Fagan, 2001). However, Esmark's observations show that this summer (JJA) was not very extraordinary in Oslo, as the following summer of 1817 was colder, and in particular that of 1821. More extraordinary is the spring temperature in 1816, being the only one with mean temperature below zero. For agriculture the first years of Esmark's period of observation must have been bad taking into account that low temperature is a limiting factor. For the grain growing months (AMJJA) the mean temperature was about 8.5°C in the three consecutive years 1816, 1817 and 1818, i.e. the lowest temperatures in Esmark series of observation.

5 Discussion

From 1816 to the mid-1820s the annual Christiania temperature as recorded by Esmark rose by approximately 1.5°C, then subsequenly slowly fell by almost 1°C towards 1840 (Fig. 10). This general pattern is consistent with that found for the same time interval in the Swedish capital Stockholm (compare with Fig. 5 in Moberg et al., 2002).

5.1 Adjusting for inhomogeneities

An important inhomogeneity was detected in Esmark's data at the end of 1822 in the evening observation, and was adjusted for. Alternatively the inhomogeneity could be considered only as a change of observational time, and not adjusted for by the testing. The series of mean temperatures could then have been kept homogenous by assessing how much the observation time had changed, leading to a corresponding change in the constants in Føyn's formula for calculation of monthly mean temperature (see Appendix B). Probably also other changes could have taken place at the end of 1822, so therefore we considered it better to apply the adjustments directly to the temperature data, and use the same constants on both sides of the shift for mean monthly temperature calculation. Moreover, there is some indication that a changed environment could have played a role for this inhomogeneity as Esmark in 1823 planted fruit trees in his garden, cf. Metadata.

No doubt Esmark possessed a minimum thermometer from 1828. Such instruments were available even before Esmark started his Oslo series in 1816. Already in 1790 a spirit thermometer with a glass index, very much like those used up to this day at manual stations, was described to the Royal Society in Edinburgh (Middleton, 1966: p. 152). In our work the change from an ordinary thermometer reading at the morning observation to a minimum thermometer reading was accounted for by a change of formula for mean monthly temperature calculation. Therefore the series of mean monthly temperatures was kept homogenous without adjusting for this shift in the morning observation.

The size of the adjustments of Esmark's observations gives an indication of the uncertainty of Esmark's observations (Fig. 9). These are adjustments for both homogeneity errors and short wave radiation errors. They are largest during summer, which also are expected due to the lack of radiation screens other than the wall of houses. For annual mean temperature the adjustments are within the interval [-0.4^{o}C, -0.1^{o}C]. For individual observation times the adjustments were higher [-0.7^{o}C, +0.3^{o}C].

5.2 Comparison with other observations

During the period 1822.11-1827.02 the Christiania professor Christopher Hansteen carried out observations at his home in Pilestredet at the corner of Keysersgate (Hansteen 1823, 1824, 1828; Birkeland, 1926: p. 12). The distance from Esmark's site was only about 600 m. Hansteen's observation times varied much but for each month he gives the observation times together with the data (Hansteen, 1824). The distribution of the observation times in UTC is as follows: morning 06^h 4%, 07^h 44%, 08^h 52%; midday 13^h 20%, 14^h 78%, 15^h 2%; evening

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21^h 6%, 22^h 88%, 23^h 6%. Hansteen's observations were adjusted to Esmark's observation times, approximately 08, 15 and 21 UTC by use of the mean daily temperature wave at Blindern so that Esmark's observations could be compared with the adjusted ones of Hansteen, Fig 11. It is evident that Hansteen's morning observation is much warmer than that of Esmark except during winter. Much likely the thermometers of Hansteen had been overheated as his two thermometers hang at the southern and northern side of the house (Birkeland, 1925: 12). Then it must have been difficult to find shadow in the morning. Also the midday observation is warmer by Hansteen than by Esmark. This is harder to understand. If Birkeland's account of the thermometer at the north wall of the house is correct the house is expected to give sufficient protection of that thermometer (Nordli et al., 2015), but as nothing is known about the environment other factors might have been involved.
The evening temperature, however, is much in agreement with that of Esmark during summer unlike for the two other observation times. The evening observations occurred after sunset at both sites, whereas the two other observations occurred after sunrise. This supports the suggestion that the differences at the morning and midday observations are due to radiation errors.

Unlike the situation during summer, Hansteen's temperatures are lower than those of Esmark in the period November – March (Fig. 11). In many weather situations the air loses energy by long wave radiation because the short wave radiation is too small to compensate for the loss. The result is that the coldest air is found at the lowest places in the local terrain, not necessarily at the lowest sites above sea level. Esmark's house lies high in the local terrain at the edge of a slope down to Pipervika cf. Metadata, whereas Hansteen's house lies low in the local terrain at a floor of a small valley. The difference in winter temperature is therefore must likely due to different local climate.

At The Astronomical Observatory in Oslo meteorological observations started in April 1837 that lasted almost for one hundred years (Nordli et al., 2015), so this series overlaps Esmark's series by 21 months. For comparison of the two series we have used unadjusted observations from the observatory, whereas both adjusted and unadjusted Esmark observations are used (Fig. 12). It is evident that for all seasons but winter Esmark's temperatures are lower than those from the Observatory. Esmark died on 26 January 1839 (see Metadata), so probably the quality of the latest months of his series may be questioned. However, we cannot see any declined quality directly from is observation protocols, but it is possible that the last two years

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of his observations are not representative for Esmark's observational practice. Moreover, the overlapping period is very short; only two years for most of the months, and only one year for the months January to March. It is therefore possible that the present comparison is not valid for Esmark's entire period of observation.

5.3 The accuracy of the thermometers

In Esmark's protocol for 1816 some instrumental corrections are given for what is claimed to be Esmark's thermometer, Table 6. They are not written by Esmark himself, most probably they are notes written by Birkeland, who says he has them after Hansteen 1821-23, but it is not certain that they belong to the thermometer used by Esmark. The corrections are very small for the frequent winter temperatures, but as high as 0.5°C for frequent summer temperatures. Due to the uncertainty with the identification of Esmark's thermometer we have not applied the corrections to his observations. It should also be kept in mind that Esmark used another thermometer, i.e. a minimum thermometer for the period 1828.03-1838.12, which might also have instrumental corrections. However, Esmark was a skilled instrument builder, so it is not likely that he used thermometer with larger corrections that those in Table 6.

There were several volcanic eruptions that affected the world climate in the first years of Esmark's period of observation. The Tambora eruption in 1815 was probably the greatest one. It has given rise to the paradigm for 1816: "the year without a summer". Esmark's observations show, however, that albeit being cold the summer was not extraordinary cold in Oslo. And in the Stockholm series ("Bolin Centre Database,") the summer of 1816 was rather warm, No 17 of the 23 summers from 1816-1838, ranged from low to high (Table 7). May, however, was very cold in both cities, and July was quite warm in both cities, but in June and August Oslo was much colder relative to the mean value than Stockholm.

There exist climate reconstructions for the period 1816-1838, independent from Esmark's observations, based upon ice loss from Lake Randsfjorden (Nordli et al., 2007) temperature proxy for the season February-April, and upon the date of grain harvest for Austlandet (Nordli, 2001a), Vestlandet (Nordli et al., 2003), Lesja (Nordli, 2001b) and Trøndelag (Nordli, 2004) temperature proxies for the seasons April-August and May-August (Table 8). The three reconstructions within the county of South-Eastern Norway are all in agreement with Esmark's observations that the summer of 1816 was among the coldest in the grain

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growing seasons, whereas the reconstructions for the two other counties, Western and Mid Norway, show relatively warm summers, even more so than those in Stockholm.

Anomalies of surface temperature and precipitation for the summer months of 1816 has been reconstructed (Luterbacher and Pfister, 2015). They show a positive gradient from a cold core of air lying over France towards Eastern and Northern Europe, so the paradigm of the severe summer of 1816 has to be modified when it comes to Scandinavia and Eastern Europe. It looks like this is easy to forget, e.g. "…weather patterns were disrupted worldwide for months, allowing for excessive rain, frost, and snowfall through much of the Northeastern U.S. and Europe in the summer of 1816"(Klingaman and Klingaman, 2014). It is therefore important that the temperature gradient is recognised. The results in Table 8 are a part of the pattern showing the spatial variability in Europe that summer.

6 Conclusions

Esmark's observations are almost complete for the years 1816-1838. Homogeneity testing revealed a shift in the evening observation at the end of 1822. From March 1828 Esmark noted nightly minimum temperature instead his previous notation of morning temperature. During the years 1831 to 1838 the nightly minimum temperature increased almost steadily in the winter season, i.e. it was inhomogenous. The homogenized temperature series showed low temperature in both ends of the series, with higher temperature in the middle, i.s. the 1820s. The starting year, 1816, is of particular interest as it has been referred to as the year without a summer. The summer in Oslo was cold, but not extraordinary cold, as it was only the third coldest in the period of observation. However, the annual mean of 1816 and also the months March and May that year were the coldest ones in that period.

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Figure texts

Fig. 1. Map of Christiania (now Oslo) 1811 with the location (red star) of Esmark's house in Øvre Vollgt. 7 marked.

Fig. 2. Matriculation and survey 1830 of Esmark's property No. 308, Øvre Voldgate 7, in Oslo Byarkiv (City archives). Arrow indicates N. Garden to the left, house surrsounding back yard to the right.

Fig. 3. Street view of Esmark's house in Øvre Voldgate 7. Photograph from around 1900. Oslo Bymuseum, No. OB.F00897. High buildings on each side built late 19th century.

Fig. 4. Esmark's Christiania protocol for 1817. Now deposited at Riksarkivet (National archives), Oslo. S-1570. Det norske meteorologiske institutt. F/Fa. Materiale etter professorer. L0002.

Fig. 5. The January page from Esmark's meteorological observation protocol from 1823, the year he discovered ice ages. Now deposited at Riksarkivet (National archives), Oslo. S-1570. Det norske meteorologiske institutt. F/Fa. Materiale etter professorer. L0002.

Fig. 6. The first published Christiania weather table, from *Den norske Rigstidende*, 24 January 1818.

Fig. 7 The temperature difference (°C) between Esmark's evening observation and the morning observation the following day for the winter season (Dec-Feb).

Fig. 8 Temperature differences (°C) between the observations at Blindern at 15 UTC and at 21 UTC for the period 1993.01-2015.09. Also the difference between the midday and evening observations of Esmark is shown for the period 1816.01-1838.12. (The adjustments of the evening observations, Table 5, are added to the data for the period 1816.01-1821.12 before the calculation of the differences. In the table below the figure are shown the adjustments of Esmark's midday observation

Fig. 9. Adjustments added to Esmark's series for each season during his period of observation, 1816-1838.

Fig. 10. Annual and seasonal means of Esmark's temperature series (symbols), and Gaussian filter (curves) with standard deviation 3 in the Gaussian distribution (e.g. Nordli et al., 2015), corresponsing roughly to a 10 year regtangular filter.

Fig. 11. Difference between Esmark's observations at Øvre Vollgate and Hansteen's observations at Pilestredet (Esmark minus Hansteen) during the period 1822.11-1827.02 at 08, 15 and 21 UTC. The monthly means are calculated by Føyn's formula, cf. Appendix 1

Fig. 12. Differences in mean monthly temperature between Esmark's observations at Øvre Vollgate and those at the Astronomical Observatory (Esmark minus Observatory) during the period 1837.04-1838.12. Esmark's observations are presented both unadjusted and adjusted. For the observatory the temperatures are unadjusted.

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Tables

Table 1 Esmark's station at Øvre Vollgate 7 as well as other observation stations used in this article: national station number (identifier) and name, period of observation and station altitude. The star before the start year marks the start of hourly observations

No. and name	Period (from-to; year, month, day	H_s (m)
18651 Oslo II	1837.04.02-1933.12.31	25
18654 Oslo - Øvre Vollgate	1816.01.01-1838.12.31	11
18655 Oslo - Pilestredet	1822.10.19-1827.02.28	16
18700 Oslo - Blindern	*1993.01.05 to present	94
18815 Oslo - Bygdøy	*2012.01.01 to present	15

Table 2 The SNHT test used for comparison of observations at time x versus observations at time y (x vs y). The shifts are given by the last year of each part of the series. For the single shift test also the adjustment needed for the x-series to be homogenous with y-series (Non-significant results are given in italic).

Part 1, 1816.01-1838.12: The whole length of the series						
SNHT tests	Obs. times	Winter	Spring	Summer	Autumn	Year
Single shift	I vs II	1833; -1.1	1827; -2.1	1827; -3.3	1824; -1.4	1827; -1.8
Single shift	I vs III	1832; -1.5	1826; -2.8	1827; -4.0	1827; -1.7	1827; -2.4
Single shift	III vs II	1821; 0.7	1820; 1.5	1821; 1.3	*1821; 0.6*	1821; 0.9
Double shift	I vs II	1826; 1834	1818; 1827	1817; 1827	1824; 1829	1823; 1827
Double shift	I vs III	1819; 1832	1820; 1826	1818; 1828	1823; 1829	1818; 1827
Double shift	III vs II	*1821; 1832*	1819; 1835	1821; 1835	*1817; 1834*	1821; 1835
Part 2, 1816.01 – 1828.02						
SNHT-tests	Obs. times	Winter	Spring	Summer	Autumn	Year
Single shift	I / II	*1826; -0.8*	*1818; -0.7*	*1817; -0.8*	1824; -1.0	*1823; -0.5*
Single shift	I /III	1818; -1.0	1820; -1.7	1818; -1.7	1821; -0.9	1818; -1.3
Single shift	III / II	*1821; 0.6*	1819; 1.4	*1821; 1.2*	*1817; 0.8*	1821; 0.8
Part 3, 1828.03 – 1838.12						
SNHT-tests	Obs. times	Winter	Spring	Summer	Autumn	Year
Single shift	I / II	1834; -1.0	*1834; 0.4*	*1830; -0.4*	*1829; -0.4*	*1830; -0.5*
Single shift	I /III	1832; -1.3	*1836; -0.6*	*1836; -0.8*	*1829; -0.9*	*1836; -0.8*
Single shift	III / II	*1833; 0.4*	1835; 0.8	*1835; 0.9*	*1834; 0.6*	*1835; 0.7*

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Table 3. The same as Table 1, but the single shift test used on monthly resolution. In the 1st and 3rd rows are given the year of the shifts, and in the 2nd and 4th rows the adjustments.

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
I/II	1834	1826	*1826*	1830	1827	1827	1827	1827	1825	1827	1824	1833
	-1.2	-1.4	*-1.0*	-2.2	-3.3	-3.4	-3.5	-2.9	-1.9	-1.1	-1.5	-1.2
III/II	1828	*1832*	1820	1819	1819	1826	*1821*	1821	*1821*	1820	*1834*	1820
	0.6	*0.7*	1.1	1.7	1.8	1.3	*1.3*	1.3	*0.8*	0.9	*0.6*	0.7

Table 4 Difference, Diff (oC), of median temperature between Esmark's evening observations and the observations the following morning during different time intervals. The similar differences for the modern station Oslo – Blindern are also shown, i.e. the observation at 21 UTC and the minimum temperature at 08 UTC. Also the standard deviations, STD (oC), of the differences are shown.

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Esmark	Diff	0.0	0.0	0.0	-0.7	-1.8	-1.6	-1.3	-1.2	0.0	0.5	0.0	0.0
1816.01-1821.12	STD	3.4	2.6	2.4	2.1	2.4	2.3	2.6	2.1	2.1	2.0	2.6	2.2
Esmark	Diff	0.9	0.7	1.2	0.6	0.6	-0.7	-0.6	0.0	1.2	0.6	0.8	0.6
1822.01-1828.02	STD	3.1	2.5	2.3	1.8	2.2	2.4	2.2	2.1	2.9	2.5	2.5	2.4
Esmark	Diff	1.3	1.5	1.9	2.2	3.1	3.1	3.1	3.1	2.5	1.9	1.6	1.3
1828.03-1838.12	STD	2.6	2.3	2.5	1.8	2.1	2.2	2.4	2.3	2.2	2.1	1.9	2.7
Blindern	Diff	1.0	1.5	2.3	2.6	3.2	3.0	2.7	2.4	2.0	1.5	1.0	1.0
1993.09-2015.09	STD	1.7	1.8	1.8	1.7	1.8	1.8	1.7	1.6	1.6	1.6	1.5	1.6

Table 5 Adjustment (oC) of the evening observation in the period 1816.01-1821.12

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
-0.6	-0.6	-1.0	-1.2	-1.3	-1.2	-1.3	-1.3	-0.9	-0.8	-0.3	-0.5

Table 6. Instrument correction (Corr) for thermometer readings (Temp.). The thermometer might have been used by Esmark, 1816-1838.

Temp. (oC)	25.00	18.75	12.50	6.25	0.00	-6.25	-12.50	-18.75	-25.00
Corr. (oC)	+0.50	+0.50	+0.38	+0.38	+0.13	+0.13	+0.13	+0.13	+0.63

Table 7 The range of mean temperature in 1816 for months and seasons during the years 1816-1838 for Oslo (Esmark's observations). For comparison also Stockholm is included. The range runs from low to high values.

	J	F	M	A	M	J	J	A	S	O	N	D	Yr	Wi	Sp	Su	Au
Oslo	14	5	1	3	1	3	12	2	2	3	7	10	1	9	1	3	2
Stockholm	14	3	6	9	1	16	18	9	13	5	8	12	7	6	4	17	3

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Table 8 The range of mean temperature in 1816 for seasons during the years 1816-1838 for Oslo (Esmark's observations), and for climate reconstructions from proxy data at different places in Norway. For comparison also Stockholm is included. The range runs from low to high values.

Place, County	February - April	April – August	May-August
Oslo, South-eastern Norway	2	1	3
Randsfjorden, South-eastern Norway	2		
Austlandet, South Eastern Norway		1	
Lesja, South-eastern Norway			1
Bergen, Western Norway		18	
Trøndelag, Mid Norway			18
Stockholm, Sweden	3	10	9

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APPENDIX A. ESMARK'S METEOROLOGICAL TABLES IN *DEN NORSKE RIGSTIDENDE.*

Esmark, J. 1818/19. Meteorologiske Iagttagelser i Christiania 1818, anstillede af Prof. Esmark. *Den Norske Rigstidende* 1818, No. 7 (24 January); No. 10 (4 February); No. 14 (18 February); No. 18 (4 March); No. 23 (21 March), No. 28 (8 April), No. 32 (22 April); No. 37 (9 May); No. 40 (20 May), No. 45 (6 June), No. 49 (20 June), No. 54 (8 July); No. 59 (25 July); No. 63 (8 August); No. 67 (21 August); No. 71 (5 September); No. 83, (17 October); No. 84 (21 October), No. 86 (28 October); No. 88 (4 November); No. 95 (28 November); No. 98 (9 December); No. 102 (23 December); No. 3 (8 January 1819).

Esmark, J. 1819/20. Meterologiske Iagttagelser i Christiania 1819, anstillede af Prof. Esmark. *Den Norske Rigstidende* No. 6 (19 January); No. 11 (5 February); No. 16 (23 February); No. 19 (5 March); No. 24 (23 March); No. 26 (6 April); No. 33 (23 April); No. 36 (4 May); No. 41 (21 May); No. 48 (15 June); No. 49 (18 June); No. 54 (6 July); No. 62 (3 August); No. 65 (13 August); No. 67 (20 August); No. 78 (28 September); No. 79 (1 October) No. 82 (12 October); No. 84 (19 October); No. 89 (5 November); No. 95 (26 November); No. 99 (10 December); No. 103 (24 December); No. 2 (7 January 1820).

Esmark, J. 1820/21. Meteorologiske Iagttagelser i Christiania 1820, anstillede af Prof. Esmark. *Den Norske Rigstidende*, No. 7 (25 January); No. 11 (8 February), No. 14 (18 February); No. 18 (3 March); No. 24 (24 March) ; No. 28 (7 April); No. 32 (21 April); No. 37 (9 May); No. 41 (23 May); No. 47 (13 June); No. 50 (23 June); No. 54 (7 July); No. 58 (21 July); No. 63 (8 August); No. 68 (25 August); No. 72 (8 September); No. 77 (26 September); No. 81 (10 October); No. 85 (24 October); No. 88 (3 November); No. 94 (24 November); No. 98 (8 December); No. 103 (26 December); No. 3 (9 January 1821).

Esmark, J. 1821/22. Meteorologiske Iagttagelser i Christiania 1821, anstillede af Professor Esmark. *Den Norske Rigstidende*, No. 7 (23 January), står bare snee,men ikke mengde, ; No. 11 (6 February); No. 16 (23 February); No. 21 (13 March); No. 23 (20 March); No. 29 (10 April); No. 33 (24 April), No. 38

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(11 May); No. 41 (22 May); No. 45 (5 June); No. 52 (29 June); No. 55 (10 July); No. 58 (20 July); No. 63 (6 August); No. 68 (24 August); No. 72 (7 September); No. 76 (21 September); No. 80 (5 October); No. 85 (22 October); No. 89 (5 November); No. 93 (19 November)(nytt moderne plusstegn); No. 98 (7 December); No. 102 (21 December); No. 2 (7 January 1822).

Esmark, Jens 1822/23. Meteorologiske Iagttagelser i Christiania 1822, anstillede ved Professor Esmark. *Den Norske Rigstidende*, No. 5 (18 January); No. 10 (4 February); No. 15 (22 February); No. 18 (4 March); No. 23 (22 March); No. 28 (8 April); No. 32 (22 April); No. 36 (6 May); No. 42 (27 May); No. 45 (7 June) not nedbørmåling; No. 50 (24 June); No. 81 (11 October); No. 82 (14 October); No. 83 (18 October); No. 84 (21 October); No. 87 (1 November); No. 89 (8November); No. 90 (11 November); No. 92 (18 November); No. 94 (25 November); No. 96 (2 December); No. 98 (9 December); No. 102 (23 December); No. 2 (6 January 1823).

Esmark, J. 1823/24. Meteorologiske Iagttagelser i Christiania 1823, anstillede ved Professor Esmark. *Den Norske Rigstidende* No. 7 (24 January); No. 11 (7 February) ; No. 15 (21 February); No. 20 (10 March); No. 24 (24 March); No. 27 (4 April); No. 31 (18 April); No. 36 (5 May); No. 40 (19 May); No. 46 (9 June); No. 49 (20 June); No. 75 (19 September); No. 76 (22 September); No. 77 (26 September); No. 78 (29 September); No. 79 (3 October); No. 81 (10 October); No. 82 (13 October); No. 84 (20 October); No. 88 (3 November); No. 93 (21 November); No. 98 (8 December); No. 102 (22 December); No. 2 (5 January 1824).

Esmark, J. 1824/25. Meteorologiske Iagttagelser i Christiania 1824, anstillede ved Professor Esmark. *Den Norske Rigstidende* No. 6 (19 January); No. 11 (5 February); No. 15 (19 February); No. 20 (8 March); No. 24 (22 March); No. 29 (8 April); No. 33 (22 April); No. 37 (6 May); No. 42 (24 May); No. 45 (3 June); No. 50 (21 June); No. 54 (5 July); No. 59 (22 July); No. 64 (9 August); No. 68 (23 August); No. 74 (13 September); No. 77 (23 September); No. 80 (4 October); No. 86 (25 Oktober); No. 89 (4 November); No. 96 (29 November); No. 98 (6 December); No. 103 (23 December); No. 2 (6 Januar 1825).

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Esmark, J. 1825/26. Meteorologiske Iagttagelser i Christiania 1825, anstillede ved Professor Esmark. *Den Norske Rigstidende* No. 7 (24 January); No. 11 (7. February), No. 15 (21 February); No. 18 (3. March); No. 24 (24 March); No. 29 (11 April); No. 33 (25 April); No. 36 (5 May); No. 40 (19 May); No. 45 (6 June); No. 49 (20 June); No. 53 (4 July); No. 70 (1 September); No. 71 (5 September); No. 73 (12 September); No. 74 (15. September); No. 76 (22 September); No. 79 (3 October), No. 85 (24 October); No. 89 (7 November); No. 93 (21 November); No. 97 (5 December); No. 102 (22 December); No. 2 (5 January 1826).

Esmark, J. 1826/27. Meteorologiske Iagttagelser i Christiania 1826, anstillede ved Professor Esmark. *Den Norske Rigstidende* No.8 (26 January); No. 12 (9 February); No. 17 (27 February); No. 19 (6 March); No.23 (20 March); No. 28 (6 April); No. 33 (24 April); No. 36 (4 May); No. 43 (29 May); No. 45 (5 June); No. 50 (22 June); No. 55 (10 July): No.58 (20 July); No. 62 (3 August); No. 67 (21 August); No. 72 (7 September); No. 77 (25 September); No. 80 (5 Oktober); No. 84 (19 October); No. 88 (2 November); No. 93 (20 November); No. 97 (4 December); No. 102 (21 December); No. 2 (4 January 1827).

Esmark, J. 1827/28. Meteorologiske Iagttagelser i Christiania 1827, anstillede ved Professor Esmark. *Den Norske Rigstidende* , No. 7 (22 January); No. 11 (5 February); No. 16 (22 February); No. 19 (5 March); No. 24 (22 March); No. 28 (5 April); No. 32 (19 April); No. 37 (7 May); No. 43 (28 May); No. 48 (14 June); No. 50 (21 June); No. 54 (5 July); No. 58 (19 July); No. 79 (1 October); No. 80 (4 October); No. 81 (8 October); No. 82 (11 October); No. 83 (15 October); No. 84 (18 October); No. 89 (5 November); No. 94 (22 November); No. 97 (3 December); 102 (20 December); No. 2 (7 January 1828) – also sums up last ten years, compares with Stockholm, the coldest years have been 1819 and 1820, the mildest 1822 and 1826.

Esmark, J. 1828/29. Meteorologiske Iagttagelser i Christiania 1828, anstillede ved Professor Esmark. *Den Norske Rigstidende* , No. 6 (21 January); No. 10 (4 February); No. 15 (21 February); No. 18 (3 March); No. 24 (24 March); No. 27 (3 April – mange solpletter); No. 32 (21 April); No. 36 (5 May); No. 40 (19 May); No. 45 (5 June); No. 49 (19 June); No. 53 (3 July); No. 59 (24 July); No. 63 (7 August); No. 78 (29 September); No. 79 (2 October); No. 81

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(9 October); No. 84 (20 October); No. 88 (3 November); No. 94 (24 November); No. 98 (8 December); No. 102 (22 December); No.2 (5 January 1829).

Esmark, J. 1829/30. Meteorologiske Iagttagelser i Christiania 1829, anstillede ved Professor Esmark. *Den Norske Rigstidende ,* No. 8 (26 January); No. 11 (5 February); No. 15 (19 February); No. 19 (5 March – den strengeste vinter på mange år); No. 24 (23 March); No. 27 (2 April); No. 33 (23 April); No. 37 (7 May); No. 42 (25 May); No. 46 (8 June); No. 50 (22 June); No. 54 (6 July); No. 78 (28 September); No. 79 (30 September); No. 80 (5 October); No. 81 (8 October); No. 85 (22 October); No. 87 (29 October); No. 89 (5 November); No. 90 (9 November); No. 94 (23 November); No. 99 (10 December); No. 103 (24 December); No. 2 (7 January 1830).

Esmark, J. 1830/31. Meteorologiske Iagttagelser i Christiania 1830, anstillede ved Professor Esmark. *Den Norske Rigstidende,* No. 7 (25 January); No. 11 (8 February); No. 14 (18 February); No. 18 (4 March); No. 22 (18 March); No. 27 (5 April); No. 31 (19 April); No. 36 (6 May); No. 40 (19 May); No. 46 (9 June); No. 50 (23 June); No. 53 (5 July); No. 57 (19 July); No. 63 (9 August); No. 70 (1 September); No. 73 (13 September); No. 78 (29 Septmerber); No. 81 (11 October); No. 84 (21 October); No. 91 (15 November); No. 95 (29 November); 98 (9 December); No. 102 (23 December); No. 3 (10 January 1831*).*

Esmark, J. 1831/32. Meteorologiske Iagttagelser i Christiania 1831, anstillede ved Professor Esmark. *Den Norske Rigstidende ,* No. 10 (3 February); No. 11 (7 February); No. 17 (28 February); No. 20 (10 March); No. 25 (28 March); No. 28 (7 April); No. 33 (25 April); No. 39 (12 May); No. 43 (22 May); No. 52 (12 June); No. 57 (23 June); No. 63 (7 July); No. 70 (24 July); No. 75 (4 August); No. 85 (28 August); No. 88 (4 September); No. 97 (25 September); No. 102 (10 October); No. 110 (3 November); No. 112 (10 November); No. 118 (1 December); No. 119 (4 December); No. 1 (1 January 1832) ; No. 2 (5 January 1832).

Esmark, J. 1832/33. Meteorologiske Iagttagelser i Christiania 1832, anstillede ved Professor Esmark. *Den Norske Rigstidende,* No.10 (2 February); No. 11 (5 February); No. 19 (4 March); No. 20 (8 March); No. 26 (26 March); No. 30 (12 April); No. 33 (22 April); No. 37 (6 May); No. 43 (20 May); No. 52 (10

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Juni); No. 57 (21 Juni); No. 63 (5 July); No. 70 (22 July); No. 78 (9 August); No. 86 (28 August – usedvanlig kold sommer); No. 92 (11 September); No. 98 (25 September); No. 103 (7 October); No. 108 (25 October); No. 111 (4 November); No. 117 (25 November); No. 122 (13 december); No. 127 (30 December); No. 4 (13 Januery 1833).

Esmark, J. 1833/34. Meteorologiske Iagttagelser i Christiania 1833, anstillede ved Professor Esmark. *Den Norske Rigstidende,* No.10 (3 February); No. 12 (10 February); No. 18 (3 March); No. 24 (24 March); No. 25 (28 March); No. 30 (14 April); No. 35 (2 May); No. 37 (9 May); No. 44 (26 May); No. 50 (9 June); No. 58 (27 June); No. 63 (9 July); No. 77 (11 August); No. 80 (18 August); No. 86 (1 September); No. 91 (12 September); No. 97 (26 September); No. 103 (13 October); No. 105 (20 October); No. 110 (7 November); No. 115 (24 November); No.120 (12 December); No. 123 (22 December); No. 2 (5 January 1834).

Esmark, J. 1834/35. Meteorologiske Iagttagelser i Christiania 1834, anstillede ved Professor Esmark. *Den Norske Rigstidende* ,No. 7 (23 Januery); No. 10 (2 February); No. 16 (23 February); No. 18 (2 March); No. 24 (23 March); No. 27 (3 April); No. 32 (20 April); No. 37 (4 May); No. 43 (18 May); No. 53 (10 June); No. 60 (26 June); No. 68 (15 July)(regnet som falt på en kvadratfods flate utgjorde 4 rhinlandskae tommer eller 576 kubikktommer); No. 71 (22 July); No. 79 (10 August), No. 83 (19 August); No. 90 (7 September); No. 96 (21 September); No. 102 (5 October); No. 107 (23 October); No. 111 (6 November); No. 117 (27 November); No. 119 (4 December); No. 126 (28 December); No. 2 (8 January 1835).

Esmark, J. 1835/36. Meteorologiske Iagttagelser i Christiania 1835, anstillede ved Professor Esmark. *Den Norske Rigstidende,* No. 10 (1 February); No. 12 (8 February); No.15 (19 February); No. 20 (8 March); No. 24 (22 March); No. 28 (5 April); No. 34 (26 April); No. 40 (10 May); No. 50 (2 June); No. 54 (11 June); No. 58 (21 June); No. 65 (7 July); No. 72 (23 July); No. 79 (9 August); No. 88 (30 August); No. 91 (6 September); No. 99 (24 September); No. 105 (11 October); No. 107 (18 October); No. 112 (5 November); No. 118 (26 November); No. 120 (3 December); No. 126 (24 December); No. 3 (10 January 1836).

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Esmark, J. 1836/37. Meteorologiske Iagttagelser i Christiania 1836, anstillede ved Professor Esmark. *Den Norske Rigstidende,* No. 7 (24 January); No. 15 (21 February); No. 17 (28 February); No. 19 (6 March); No. 23 (20 March); No. 27 (3 April); No. 32 (21 April); No. 38 (5 May); No. 45 (22 May); No. 50 (2 June); No. 59 (23 June); No. 66 (10 July); No. 70 (19 July); No. 78 (7 August); No. 85 (23 August?) ; No. 92 (8 September); No. 98 (22 September); No. 105 (9 October); No. 111 (30 October); No. 112 (3 November); No. 119 (27 November); No. 125 (18 December); No. 126 (22 December); No. 3 (5 January 1837).

Esmark, J. 1837/38. Meteorologiske Iagttagelser i Christiania 1837, anstillede ved Professor Esmark. *Den Norske Rigstidende*, No. 10 (22 January); No. 17 (7 February); No. 22 (19 February); No. 22 (2 March); No. 34 (19 March); No 41 (4 April); No. 48 (20 April); No. 53 (2 May); No. 61 (21 May); No. 67 (4 June); No. 74 (20 June); No. 82 (9 July); No. 86 (18 July); No. 93 (3 August); No. 100 (20 August); No. 106 (3 September); No. 113 (19 September); No. 120 (5 October); No. 126 (19 October); No. 132 (2 November); No. 139 (19 November); No. 145 (3 December); No. 152 (19 December); No. 2 (4 January 1838).

Esmark, J. 1838. Meteorologiske Iagttagelser i Christiania 1838, anstillede ved Professor Esmark. *Den Norske Rigstidende*, No. 10 (18 January); No. 19 (3 February); No. 29 (20 February); No. 36 (4 March); No. 45 (20 March); No. 53 (3 April); No. 62 (19 April); No. 70 (3 May); No. 79 (19 May); No. 87 (2 June); No. 98 (19 June); No. 108 (4 Junly); No. 117 (19 July); No. 127 (2 August); No. 137 (19 August); No. 148 (6 September); No. 156 (20 September); No. 164 (4 October); No. 173 (20 October); No. 181 (3 November); No. 190 (18 November); No. 199 (4 December); No. 207 (18 December).

Appendix B

MET Norway calculates monthly mean temperatures for manual stations by Føyn's and Köppen's formulas (Birkeland, 1936; Gjelten et al., 2014; Nordli et al., 2015), so we chose to use those formulas also for Esmark's observations: The monthly mean temperature, T, may be calculated by Føyn's formula and a modified Köppen's formula, Table A1.

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Table A1. Formulas for calculation of monthly mean temperature, T, where T_{08}, T_{15} and T_{21}, are monthly means at observation times 08, 15 and 21 UTC respectively, and T_n is monthly mean night temperature, k_g and k_f are constants.

Føyn's formula	$T = T_g + k_g(T_{15} - T_g)$	$T_g = \frac{T_{08} + T_{21}}{2}$
Köppen's formula	$\mathrm{T} = \mathrm{T_f} - \mathrm{k}(\mathrm{T_f} - \mathrm{T_n})$	$T_f = \frac{T_{15} + T_{21}}{2}$

A "true" monthly mean temperature, T, may be calculated by the arithmetic mean of hourly observation according to definition, so for a station that have hourly observations the constants, k_g and k_f, are easily calculated by rearranging Føyn's and Köppen's formulas. For Esmark's series from Øvre Vollgate the constants were unknown. It was assumed that the constants from Blindern could be used also for Øvre Vollgate. An indication of the robustness of this assumption was tested by comparison with a short series of hourly observations from the station 18815 Oslo – Bygdøy, 15 m a.s.l. The test procedure started with calculation of the constants for the Blindern series based on the period 2012.12-2015.09. These constants were then used for the calculation of mean monthly temperatures for Bygdøy for the same period, which were compared with the "true" monthly means, i.e. those calculated by the hourly observations. For Føyn's formula the deviation from the true means varied from -0.06°C in December to +0.18°C in March that gave +0.05°C for the whole year. Corresponding figures for Köppen's formula were -0.06°C in July, +0.16°C in September and +0.01°C for the whole year. These differences are so small that the lack of exact knowledge of the constants does add practically no uncertainty to the monthly temperatures.

Fig. 12. Differences in mean monthly temperature between Esmark's observations at Øvre Vollgate and those at the Astronomical Observatory (Esmark minus Observatory) during the period 1837.04-1838.12. Esmark's observations are presented both unadjusted and adjusted. For the observatory the temperatures are unadjusted.

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Fig. 1. Map of Christiania (now Oslo) 1811 with the location of Esmark's house in Øvre Vollgt. 7 marked with red star.

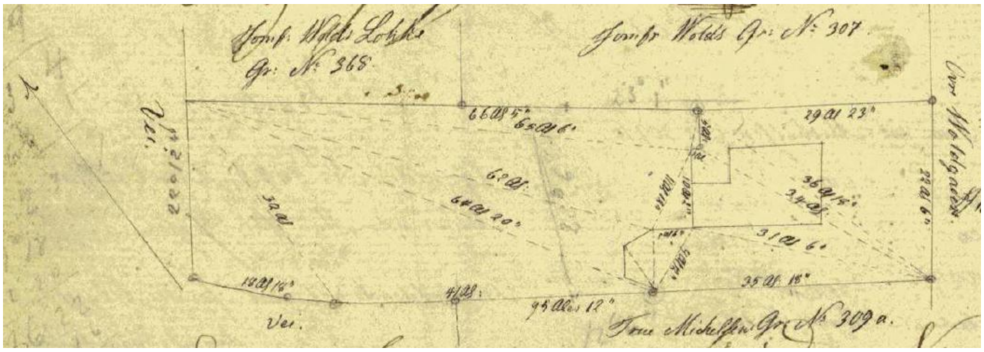

Fig. 2. Matriculation and survey 1830 of Esmark's property No. 308, Øvre Voldgate 7, in Oslo Byarkiv (City archives). Garden to the left, house surrounding back yard to the right.

Fig. 3. Street view of Esmark's house in Øvre Voldgate 7. Photograph from around 1900. The higher houses on both sides are late 19th century. Oslo Bymuseum, No. OB.F00897.

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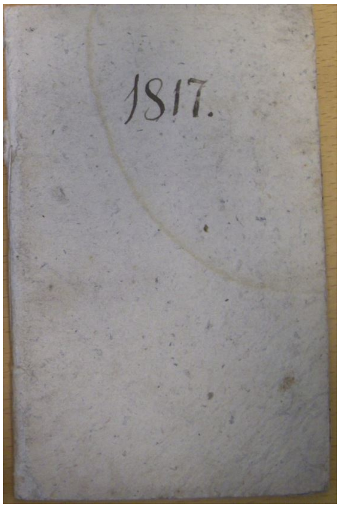

Fig. 4. Esmark's Christiania protocol for 1817. Now deposited at Riksarkivet (National archives), Oslo. S-1570. Det norske meteorologiske institutt. F/Fa. Materiale etter professorer. L0002.

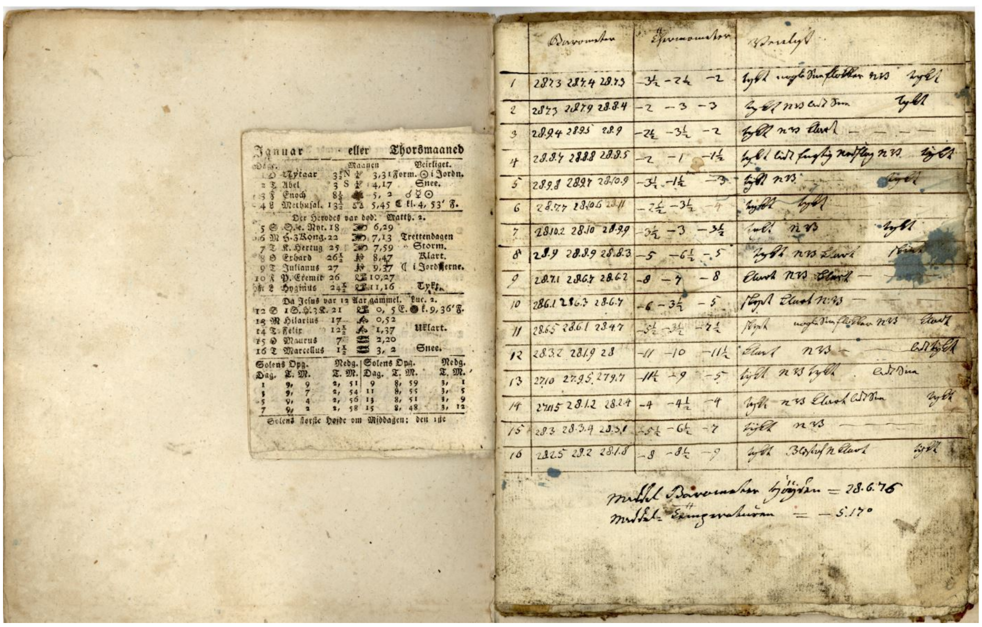

Fig. 5. The January page from Esmark's meteorological observation protocol from 1823, the year he discovered ice ages. Now deposited at Riksarkivet (National archives), Oslo. S-1570. Det norske meteorologiske institutt. F/Fa. Materiale etter professorer. L0002.

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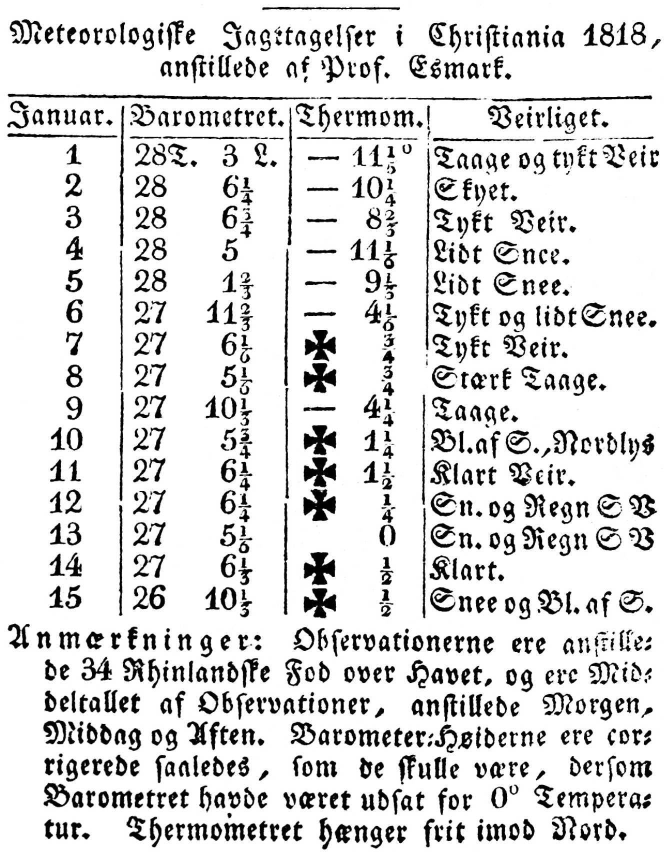

Meteorologiske Jagttagelser i Christiania 1818, anstillede af Prof. Esmark.

Januar.	Barometret.		Thermom.	Veirliget.
1	28 T.	3 L.	— $11\frac{1}{5}$°	Taage og tykt Veir
2	28	$6\frac{1}{4}$	— $10\frac{1}{4}$	Skyet.
3	28	$6\frac{3}{4}$	— $8\frac{2}{3}$	Tykt Veir.
4	28	5	— $11\frac{1}{6}$	Lidt Snee.
5	28	$1\frac{2}{3}$	— $9\frac{1}{3}$	Lidt Snee.
6	27	$11\frac{2}{3}$	— $4\frac{1}{6}$	Tykt og lidt Snee.
7	27	$6\frac{1}{6}$	+ $\frac{3}{4}$	Tykt Veir.
8	27	$5\frac{1}{6}$	+ $\frac{3}{4}$	Stærk Taage.
9	27	$10\frac{1}{3}$	— $4\frac{1}{4}$	Taage.
10	27	$5\frac{3}{4}$	+ $1\frac{1}{4}$	Bl. af S., Nordlys
11	27	$6\frac{1}{4}$	+ $1\frac{1}{2}$	Klart Veir.
12	27	$6\frac{1}{4}$	+ $\frac{1}{4}$	Sn. og Regn S V
13	27	$5\frac{1}{6}$	0	Sn. og Regn S V
14	27	$6\frac{1}{3}$	+ $\frac{1}{2}$	Klart.
15	26	$10\frac{1}{3}$	+ $\frac{1}{2}$	Snee og Bl. af S.

Anmærkninger: Observationerne ere anstillede 34 Rhinlandske Fod over Havet, og ere Middeltallet af Observationer, anstillede Morgen, Middag og Aften. Barometer-Høiderne ere corrigerede saaledes, som de skulle være, dersom Barometret havde været udsat for 0° Temperatur. Thermometret hænger frit imod Nord.

Fig. 6. The first published Christiania weather table, from *Den norske Rigstidende*, 24 January 1818.

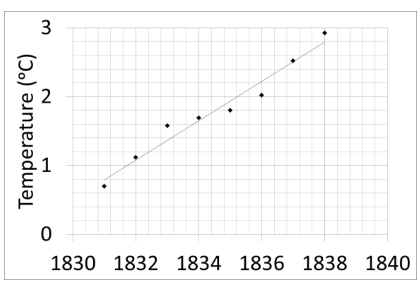

Fig. 7. The temperature difference (°C) between Esmark's evening observation and the morning observation the following day for the winter season (Dec-Feb).

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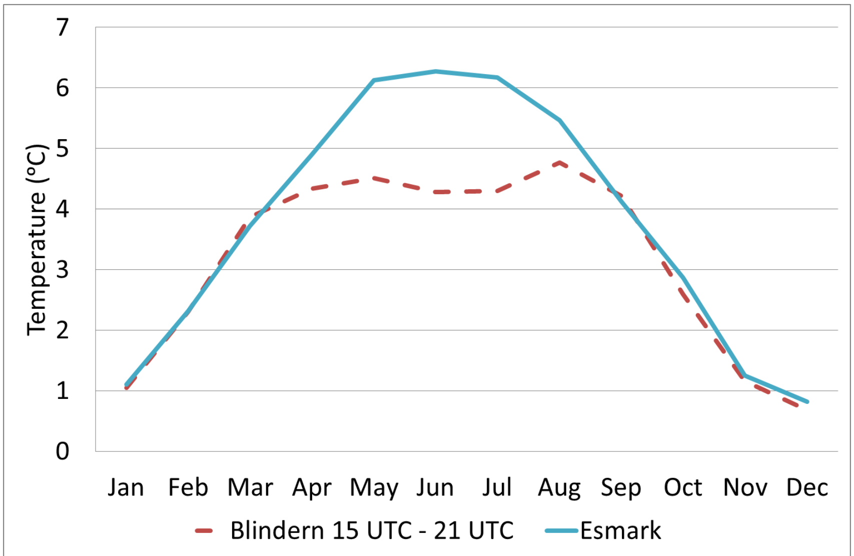

Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
0.0	0.0	0.0	-0.6	-1.6	-2.0	-1.9	-0.7	0.0	0.0	0.0	0.0

Fig. 8 Temperature differences (°C) between the observations at Blindern at 15 UTC and at 21 UTC for the period 1993.01-2015.09. Also the difference between the midday and evening observations of Esmark is shown for the period 1816.01-1838.12. (The adjustments of the evening observations, Table 5, are added to the data for the period 1816.01-1821.12 before the calculation of the differences. In the table below the figure are shown the adjustments of Esmark's midday observation.

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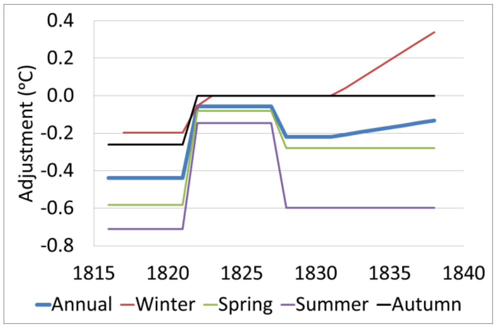

Fig. 9. Adjustments added to Esmark's series for each season during his period of observation, 1816-1838.

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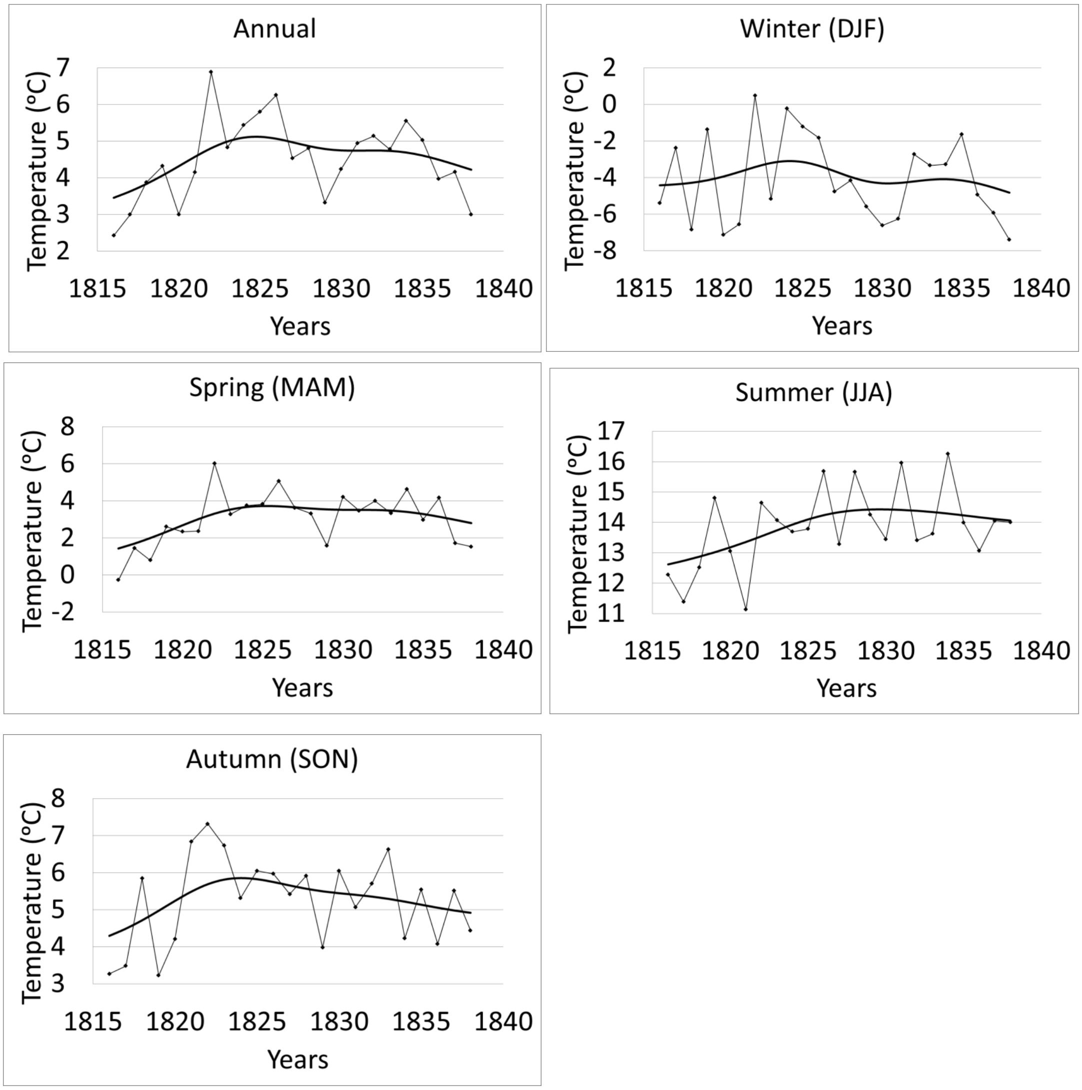

Fig. 10. Annual and seasonal means of Esmark's temperature series (symbols), and Gaussian filter (curves) with standard deviation 3 in the Gaussian distribution (e.g. Nordli et al., 2015), corresponsing roughly to a 10 year regtangular filter.

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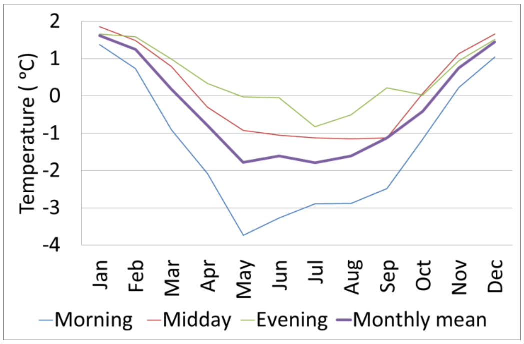

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1196
1197 Fig. 11. Difference between Esmark's observations at Øvre Vollgate and Hansteen's
1198 observations at Pilestredet (Esmark minus Hansteen) during the period 1822.11-1827.02 at
1199 08, 15 and 21 UTC. The monthly means are calculated by Føyn's formula (see Appendix B).
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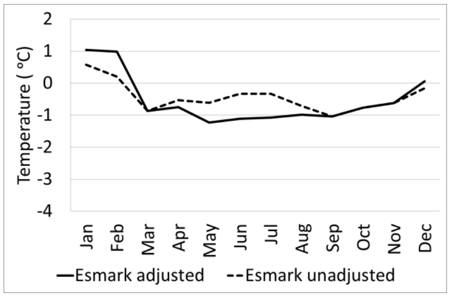

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