Small Publications in Historical Geophysics

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A Geophysical and Astronomical Analysis of an Old Painting of the Stockholm Sluice

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1. The painting

In 1780 the artist Anders Holm made an oil-painting of the Stockholm sluice, the sluice with lock gates between Lake Mälaren to the west of Stockholm and the Baltic Sea to the east. A picture of the painting is shown as the cover picture of the recent book on the Baltic Sea level during 300 years by the author (Ekman, 2009; see also www.historicalgeophysics.ax). The picture is also shown here as Figure 1.

On the painting the sluice is viewed from the east, with the Baltic Sea in the foreground and Lake Mälaren in the background. The level of the lake is so high that the water overflows the lock gate. A number of persons are standing at the lock gate looking at the water. The area is partly sunlit, partly in shade. The towers behind the lock gate mark the abutments of the bridge crossing the sluice and contain winches for raising the bridge halves when ships want to pass. To the right of the towers there is in the background a building of which only a small part can be seen; this is the sluice office. The sky above shows scattered clouds.

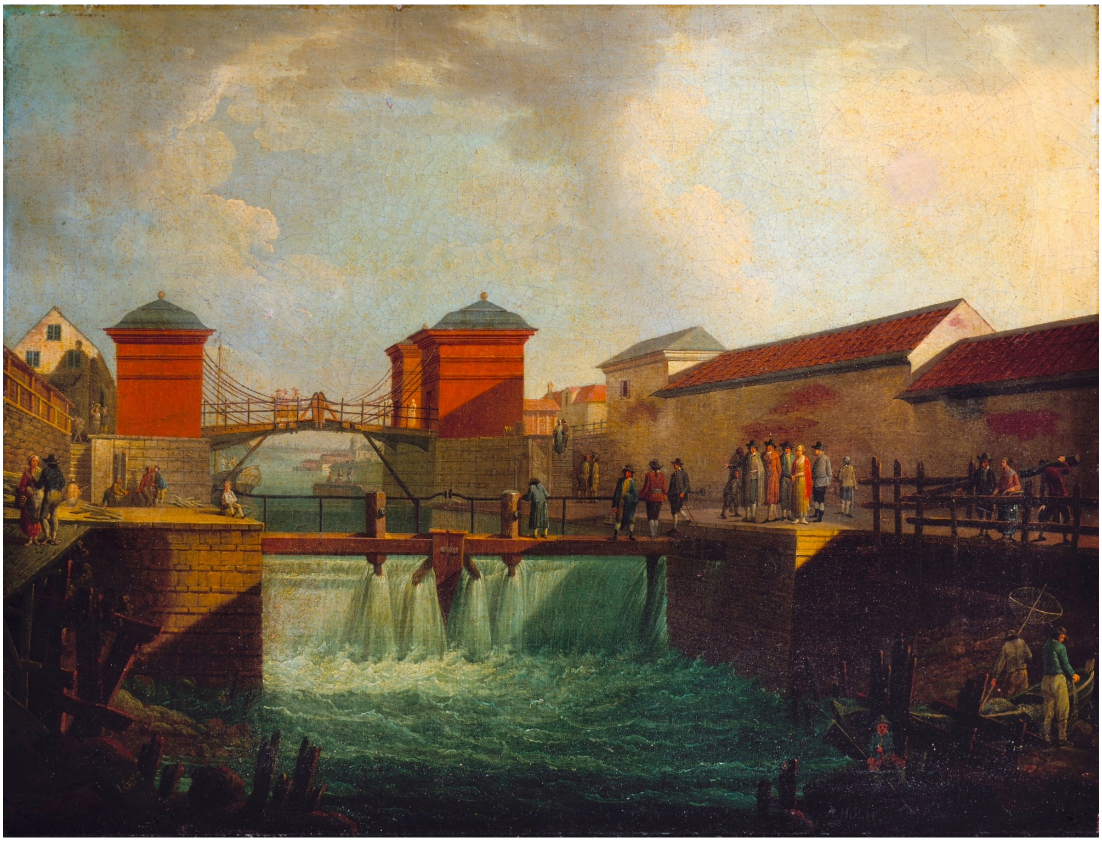

Figure 1. The Stockholm sluice. Painting by Anders Holm 1780. (City Museum of Stockholm; see also www.stockholmskallan.se.)

What is so interesting with this painting? The interesting thing is the remarkable circumstance of the water overflowing the lock gate, and the exceptionally large water level difference between the lake and the sea. This raises a number of questions. What day or period of days in the year 1780 does the painting illustrate? What is the water level difference? What is the level of the lake and what is the level of the sea relative to normal? What is the climatic background producing the effect shown in the painting? Some additional questions could also be put. What time during the day is it? What is the weather situation? What is the position of the sun? In this publication we will try to answer all these questions. The purpose of this is two-fold: to analyse and understand what the painting shows, and to investigate how accurate and realistic the painting is.

2. People and water level difference

At the Stockholm sluice water level observations started in 1774, both in the lake and in the sea; see Ekman (2009). The sea level observations constitute the longest sea level series in the world. For the year 1780, however, the sea level data are missing. Only the lake level data are preserved. Thus the water level difference cannot be determined from archived data.

To estimate the water level difference between Lake Mälaren and the Baltic Sea shown by the painting we will now use the painting itself. The height difference of the water at the lock gate can be estimated using the height of the people (excluding children) standing at the lock gate. There are 8 persons standing to the right, one person on the lock gate itself, and a few persons to the left. Only the persons to the right are standing upright and are located precisely at the lock gate, so we will concentrate on these. Of these persons there are 7 men and 1 woman. To be able to calibrate the height difference of the water against the height of the people we need to know the average height of people here at the end of the 1700s.

It is known that Scandinavian people were shorter in earlier centuries and have gradually become taller since the agrarian and industrial revolutions in the 1700s and 1800s; see e.g. Olsson (1986). The average height of people before our own time can be estimated either from modern measurements of dated skeletons or from archived measurements of heights of persons when they lived. The latter method is particularly useful in Sweden where the military have measured the heights of soldiers systematically since the middle of the 1700s. From such data analysed by Sandberg & Steckel (1980) it can be concluded that the average height of men around 1780 in the part of Sweden where Stockholm is situated was approximately 168 cm. From measurements of skeletons it is known that women have constantly been very close to 10 cm shorter than men; hence the average height of women around 1780 in the same area was approximately 158 cm. Thus the average height of the 8 persons standing at the lock gate should be 167 cm.

Now, the water level difference at the lock gate on the painting is about 1.35 times the average height of the 8 persons at the lock gate. Consequently the water level difference should amount to

$$\Delta H \approx 225 \text{ cm}$$

This is a very high value; the normal value at that time was 48 cm (see Section 3). The main explanation of the difference must be a very high water level in the lake. This is confirmed by the overflow of the lake water at the lock gate. (A minor contribution to the difference might also come from a low water level in the sea.) The lock gate in the end had to be sawn to pieces to prevent the sluice as a whole from being damaged.

3. Lake level and sea level

As mentioned in Section 2 the lake level observations at the Stockholm sluice from 1780 are still preserved, while the sea level observations from that year unfortunately are gone. The observations, commencing in 1774, were made at water level scales cut into the stone wall of the sluice. Later on separate wooden scales were put up. They were for various reasons a few times raised or lowered in relation to the original scales. Moreover, in 1851 the water level readings were moved to the new sluice recently built, and in 1889 the sea level readings were moved further to the mareograph established close to the sluice. Thus the zero point of the water level scales have been changed several times; an overview of these changes is given by Ekman (2003).

The archived water level data show that in late spring 1780 the lake level was very high. During the two-week-period May 21 – June 5 the mean lake level was 17 feet 1/2 inch on the sluice scale. On June 4 and 5 the lake level reached its maximum value, 17 feet 4 inches. Converting this into cm through 1 Swedish foot = 29.69 cm we get a maximum lake level of 515 cm. Applying a zero point correction of - 9 cm (Ekman, 2003) we obtain a maximum lake level of 506 cm in relation to "modern mareograph zero". In the same way we obtain a maximum mean lake level during two weeks of 497 cm relative to the same zero. To compare these values with normal lake level at that time we first have to briefly explain the special character of the lake we are dealing with here.

Lake Mälaren originally was a part of the Baltic Sea. Due to the postglacial land uplift that part was gradually cut off from the Baltic Sea, at the locality of Stockholm, and turned into Lake Mälaren. This process started nearly 1000 years ago, but due to erosion of its outlets the lake level has continued to be close to the sea level. Lake Mälaren thus has formed an intermediate between lake and sea, its level showing an apparent fall in approximately the same way as the level of the Baltic Sea (until 1943 when the lake became artificially regulated).

Normal lake level in Lake Mälaren, therefore, has to be determined through a linear regression of the lake level during a reasonable time span, in the same way as normal sea level in the Baltic Sea has. Such a linear regression was performed by Lilienberg (1891). Although his data handling suffers from certain weaknesses the result is still useful for our purposes. Lilienberg's lake level regression line may be converted into cm and then transformed to "modern mareograph zero", using a comparison between the regression lines for the Baltic Sea by himself and by Ekman (2003). In this way we find a normal lake level at 1780 of 335 cm. Hence the maximum lake level above normal lake level is H_l = 506 - 335 cm, i.e.

H_l = 171 cm (June 4 – 5)

Correspondingly the maximum mean lake level during two weeks above normal lake level is

H_l = 162 cm (May 21 – June 5)

The lake level for each day during this period is given in Table 1. Before May 21 the level had been rising from about normal at the beginning of March. After June 5 it fell continuously, reaching normal at the end of August.

Moreover, from Ekman (2003) we find a normal sea level in the Baltic Sea at 1780 of 287 cm. This makes the normal water level difference between the lake and the sea ΔH_n = 335 - 287 cm, i.e.

ΔH_n = 48 cm

Hence the maximum lake level above normal sea level amounts to H_{ls} = 171 + 48 cm, i.e.

H_{ls} = 219 cm (June 4 – 5)

Table 1. Levels of Lake Mälaren (in cm) above normal lake level (H_l) and normal sea level (H_{ls}), respectively, during the high water period May 21 – June 5, 1780.

Date		H_l	H_{ls}
May	21	163	211
	22	159	207
	23	154	202
	24	157	205
	25	160	208
	26	160	208
	27	161	209
	28	168	216
	29	163	211
	30	165	213
	31	161	209
June	1	160	208
	2	160	208
	3	156	204
	4	171	219
	5	171	219

Correspondingly the maximum mean lake level during two weeks above normal sea level amounts to

$$H_{ls} = 210 \text{ cm} \qquad \text{(May 21 – June 5)}$$

These are the heighest levels ever observed in Lake Mälaren; the levels for each day are again given in Table 1.

The dates connected to the lake levels of Table 1 are the only realistic days in the year 1780 when the painting could have been made, or at least the only realistic days that the painting could be supposed to illustrate. Thus we can say, so far, that the painting shows the Stockholm sluice within approximately one week before or after May 30, 1780.

Now we can apply the water level difference in Section 2 estimated from the painting, i.e. the difference between the lake level and the sea level at the time stated above. If the painting shows the maximum lake level, the sea level relative to normal sea level becomes $H_s \approx 219 - 225$ cm, i.e.

$$H_s \approx - 6 \text{ cm}$$

If the painting more generally shows the maximum mean lake level during two weeks, the sea level relative to normal sea level becomes

$$H_s \approx - 15 \text{ cm}$$

These figures make sense, indicating that the water level difference in the painting is reasonably correct; see also next section.

Putting all the above results together we find that the water level difference shown in the painting, 2.2 m, is created by three components added together: The lake level in the painting is 1.6 m above normal lake level, the normal lake level is 0.5 m above normal sea level, and the sea level in the painting is 0.1 m below normal sea level.

4. Climatic background to the lake and sea levels

We can now ask ourselves: What were the climatic conditions creating the extremely high lake level shown in the painting? Such a high lake level at this time of the year should primarily be caused by a considerable melting away of snow in the area around the lake supplying it with water. This would require two things: A large amount of snow and a rapid melting of it.

There were meteorological observations made in Stockholm at that time, but Stockholm is situated at the outlet of Lake Mälaren. A station more relevant for the supply of Lake Mälaren with water, in our case from melted snow, would be Uppsala on the northern side of the lake, where meteorological observations have been made since 1722. These data have been scrutinized and homogenized by Bergström & Moberg (2002); monthly mean temperatures have been published by Moberg & Bergström (1997). In Table 2 we give monthly mean temperatures for the period November 1779 to June 1780. We also give approximate descriptions of precipitation; the information available does not allow any exact statements.

Table 2 reveals a fairly cold winter with plenty of snow. This is followed by a remarkable spring. First we have a reasonably normal March with a mean temperature above zero, which should lead to a partial melting away of snow. During this month the lake level rose considerably. Then, contrary to normal, April 1780 shows a mean temperature below zero; this turns out to be the second coldest April month during the almost 300 years of temperature measurements at Uppsala. A note in the weather journal is illustrative: "The Dalälven river, that at the end of the last month had become free if ice allowing travellers to row across it, frose again this month so strongly that one could drive across it on the ice." During this month the lake level did not rise at all. In May, suddenly, it became warm, which should lead to a complete melting away of remaining snow. During this month again the lake level rose considerably.

Table 2. Temperature (in °C) and approximate precipitation at Uppsala November 1779 – June 1780.

Year	Month	Temp.	Precipitation
1779	November	+ 0.7	Some rain
	December	- 6.1	Much snow
1780	January	- 7.2	Much snow
	February	- 5.8	Some snow
	March	+ 2.1	Fairly dry
	April	- 0.6	Some snow
	May	+ 9.4	Much rain
	June	+ 14.1	Some rain

The extremely high lake level shown in the painting can now be fairly well understood. A snowy winter followed by a very cold spring, and then sudden warmth, probably caused a delayed and rapid melting away of snow, with a peak in May, 1780.

Turning to the sea level the dominating factor governing sea level at Stockholm is persistent winds transporting sea water from the North Sea into the Baltic Sea, or out of the Baltic Sea to the North Sea. Persistent (south)westerly winds will cause a high sea level in the Baltic, while persistent (north)easterly winds will cause a low sea level in the Baltic. Wind observations close to the Baltic entrance, at Lund, have been made since 1740; these data have been treated by Jönsson (1998). During the period of interest here winds tended to be northerly in the winter months, westerly in March, easterly in April and again westerly in May. This would imply a sea level slightly above normal towards the end of May.

Another factor governing sea level is the local air pressure, high air pressure causing a lower sea level and low air pressure causing a higher sea level. Air pressure observations at Stockholm have been made since 1756; these data have been thoroughly treated by Moberg et al (2002). They show that the air pressure during the days in question at the end of May and the beginning of June 1780 was mostly slightly above normal. (An exception is June 4 when the air pressure was somewhat low.) This would imply a sea level slightly below normal around the end of May.

In total, winds and air pressure indicate a sea level around the end of May 1780 not very far from normal. This is in reasonable agreement with our calculations in Section 3, based on lake level data combined with the water level difference estimated from the painting.

5. Cloudiness and temperature

The upper part of the painting shows a sky with scattered clouds. The sun is shining from somewhere behind the viewer. Since we are viewing approximately west, the sun should be somewhere in the east. This means that the painting shows a morning scene with scattered clouds.

Just to the left of the lock gate on the painting there is a person basking in the sunshine. This requires a sufficiently high morning temperature (and relatively weak winds).

Let us now take a look in the daily weather journal for the year 1780 of the Stockholm observatory; see also the modern treatments of these data by Moberg et al (2002, 2003). In Table 3 we give daily morning temperatures and morning cloudiness from the weather journal for the period May 21 – June 5.

Table 3 shows that neither the beginning nor the end of this period fit the morning temperature conditions in the painiting. These days are too cold (and also too windy in connection with low air pressures passing). In between, however, we find a sufficiently warm period with a highest morning temperature of 14°C at May 30. Furthermore we find that among the sufficiently warm mornings there are only two with scattered clouds as in the painting, namely May 30 and June 2.

Altogether we can now fix a probable date of the painting: May 30. An alternative date could be June 2, but that day the lake level is lower. We may add here that these mornings have weak to moderate westerly winds, a favourable wind direction for the sun-basking person turning his face towards the sun in the east.

Table 3. Morning temperature (in °C) and morning cloudiness at Stockholm during the period May 21 – June 5, 1780.

Date		Temp.	Cloudiness
May	21	1	Cloudy
	22	2	Scattered cluds
	23	7	Cloudy
	24	10	Clear
	25	10	Cloudy
	26	11	Clear
	27	10	Clear
	28	12	Clear
	29	12	Cloudy
	30	14	Scattered clouds
	31	13	Cloudy
June	1	11	Clear
	2	13	Scattered clouds
	3	12	Clear
	4	11	Clear
	5	5	Cloudy

6. Shadows and the position of the sun

In the painting the sun is shining from somewhere behind the viewer. Buildings and people cast shadows. Especially interesting is the shadow on the wall of the house to the far left. This shadow is obviously cast by one of the towers at the sluice bridge. To investigate the direction of the tower shadow and, thereby, the position of the sun in the sky, we need a contemporary detailed map of Stockholm. Such a map is the one by Brolin (1771).

From Brolin's map we find that the direction of the sluice, expressed as its azimuth counted from north towards east, is 114°. Concerning the direction of the line from the shadow to the sluice tower, there are four towers to choose between. The positions of the towers on the map and the approximate direction of other shadows in the painting make it clear that the tower casting its shadow is the tower seen to the left in the painting. The azimuth of the line between the shadow on the wall and the tower in question amounts, according to the map, to 93°. Hence the azimuth A of the sun at this instant amounts to the same quantity,

$$A = 93°$$

Knowing the sun's azimuth, the altitude (height angle) h of the sun above the horizon can be computed by applying spherical trigonometry to the fundamental astronomical triangle. The spherical law of cosines yields

$$\sin\delta = \sin\varphi \sin h + \cos\varphi \cos h \cos A \qquad (1)$$

(see e.g. Smart, 1962). Here φ is the latitude of the place, and δ is the declination of the sun. For Stockholm we have φ = 59.3°, and for the end of May we have δ = 22° (from astronomical tables). To satisfy equation (1) it then turns out that the sun's altitude has to be

$$h = 28°$$

Now, knowing both the azimuth and the altitude of the sun, its hour angle t, counted along the equator from south towards west, can be computed. The spherical law of sines yields

$$\sin t = -\frac{\cos h \sin A}{\cos\delta} \qquad (2)$$

Inserting values from above we obtain t = - 72° = - 4 h 50 m. Adding 12 h we obtain the time T during the day,

$$T = 7\text{ h }10\text{ m}$$

Hence the painting should illustrate the situation soon after 7 o'clock in the morning. (This time is the so-called true solar time, the time a correct sun dial would show.) We may remark here that Holm is known for being fond of painting morning scenaries.

7. Conclusions

A detailed geophysical and astronomical analysis of the painting of the Stockholm sluice by Anders Holm in 1780 has been performed. The analysis reveals that the painting probably shows the situation on May 30 at about 7 10 a.m. local time. The azimuth of the sun is 93°, close to due east, and its altitude above the horizon 28°. The air temperature is 14°C, allowing a nice stay in the sun. The level of Lake Mälaren is about 225 cm higher than the level of the

Baltic Sea, the lake level being 165 cm above normal lake level, an exceptional state of the lake. This is mainly caused by a snowy winter followed by a very cold April and a warm May, resulting in a delayed and rapid melting away of snow.

It is of course possible that the painting is not intended to show a specific moment but rather to illustrate the situation in general during this extreme high-water period of the lake. However, our investigation reveals that, whether Holm intended to paint a specific moment or not, his painting of the Stockholm sluice is very accurate and realistic. In fact, it is so accurate and realistic that it agrees almost precisely with the hydrological, meteorological, oceanographic and astronomical conditions for 1780, May 30, 7 10 a.m.

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ISSN 1798-1883 (print)
ISSN 1798-1891 (online)