Small Publications in Historical Geophysics

No. 12

The World's Longest Sea Level Series and a Winter Oscillation Index for Northern Europe 1774 - 2000

Martin Ekman

Summer Institute for Historical Geophysics
Åland Islands

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1. Introduction

Sea level observations have been performed at Stockholm since 1774. This constitutes the longest sea level record in the world; annual mean sea levels have been published by Ekman (1988). The oldest sea level record, starting in 1700, is the one from Amsterdam, but this was discontinued a long time ago (van Veen, 1954; Spencer et al, 1988). Another old sea level record, starting in 1768, is from Liverpool, but this is a high water record only and suffers from large gaps (Woodworth, 1999).

In a series of papers the author and others have shown that the Stockholm sea level observations, originally made for handling a sluice, contain a wealth of scientific information. For studies of postglacial rebound, first made already by Nordenskiöld (1858), see Ekman (1988, 1996) and Lambeck et al (1998). For studies of global sea level rise, first made by Thorarinsson (1940) and Mörner (1973), see Ekman (1988, 2000) and Woodworth (1990). For studies of sea level variations, see Ekman & Stigebrandt (1990) and Ekman (1996a, 1996b). For studies of climate changes, see Ekman (1997, 1998, 1998a, 1999). In the two last-mentioned papers the author also argued that there should be a relation between the Stockholm sea level and the North Atlantic Oscillation (NAO), at least during winter seasons. Recently Andersson (2002) showed that this is indeed the case and suggested that the Stockholm sea level series in itself could be used as a seasonal climate index, especially for winters.

The importance of the Stockholm sea level series is not only due to its unique length. It is also due to its unique oceanographic position in the central Baltic Sea, with practically no tides but considerable wind-driven sea level variations of a special kind.

The general behaviour of the sea level variations in the Baltic Sea was first studied by Colding (1881) and Witting (1918), and has been closely investigated by Samuelsson & Stigebrandt (1996); cf. also Ekman (1996a). They found that variations on a time scale exceeding 1 month are mainly externally driven variations, with maximum amplitudes in the north and minimum amplitudes at the Baltic entrance in the south. More rapid external variations are filtered out due to the choking effect of the narrow and shallow Baltic entrance. They also found that variations on a time scale less than 1 month are mainly internally driven variations, with maximum amplitudes in the far north and the far south, and a nodal line close to Stockholm in the central part of the Baltic. Thus nature has given the Stockholm sea level remarkable properties: Short-term sea level variations are nearly eliminated, while long-term sea level variations are those of the North Sea in magnified form. These long-term variations are mainly governed by the dominating winds over the North Sea and the Baltic entrance.

Because of the considerable importance of the Stockholm record, both as a sea level series and as a kind of atmospheric circulation index, we will here publish all monthly (and annual) mean sea levels from 1774 up to 2000. We will also give relevant historical information to help the reader in understanding and judging the quality of these data. For the first 50 years the Stockholm series contains some gaps, where the original data are missing. The largest of these gaps will be filled through a transformation of mean sea levels from Copenhagen, where sea level data exist for a few decades around 1800. Finally, based on the complete set of Stockholm monthly mean sea levels, a winter climate oscillation index for northern Europe will be presented. It will also be analysed for climate changes.

2. History of sea level observations

The foundation of Stockholm in the middle of the 13th century was mainly a consequence of the postglacial land uplift. At that locality a part of the Baltic Sea was gradually being cut off by the land uplift and turned into a lake, Mälaren, the outlets of which caused problems for the important shipping. In 1642 it became necessary to build a sluice with lock gates here (the construction being made by Dutch experts). This sluice was replaced in 1755 by a larger and deeper one ("Polhem's sluice"). This in its turn was replaced in 1851 by a still somewhat deeper sluice ("Ericson's sluice"). We refer to Nordberg (1935) and Eklund (1981) for details.

At the 1772 session of the Swedish parliament there were complaints that the level of the lake was often too high, causing flooded fields. By order of King Gustaf III a hydrographic investigation of the outlets of the lake was undertaken in the next year; see Brolin (1773). The following year, 1774, systematic observations of the water levels started on both sides of the sluice, i.e. both in the lake and in the sea; a picture of the sluice is shown in Figure 1.

Although there was an ambition to keep the lake not too high, it was equally important to keep it not too low. In the latter case the sea level could at certain events get higher than the level of the lake, thereby making the use of the sluice difficult. These events were noted together with the water level readings by the special word "uppsjö", approximately meaning "sea higher". They now provide a valuable possibility to check the zero levels of the gauges, as will be seen below.

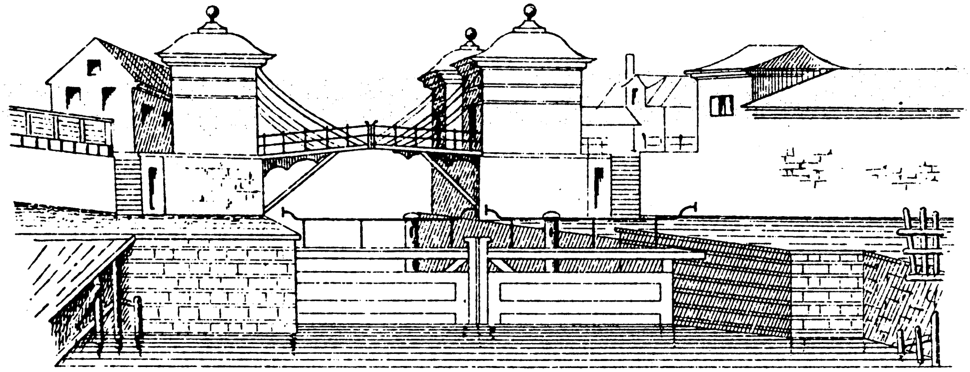
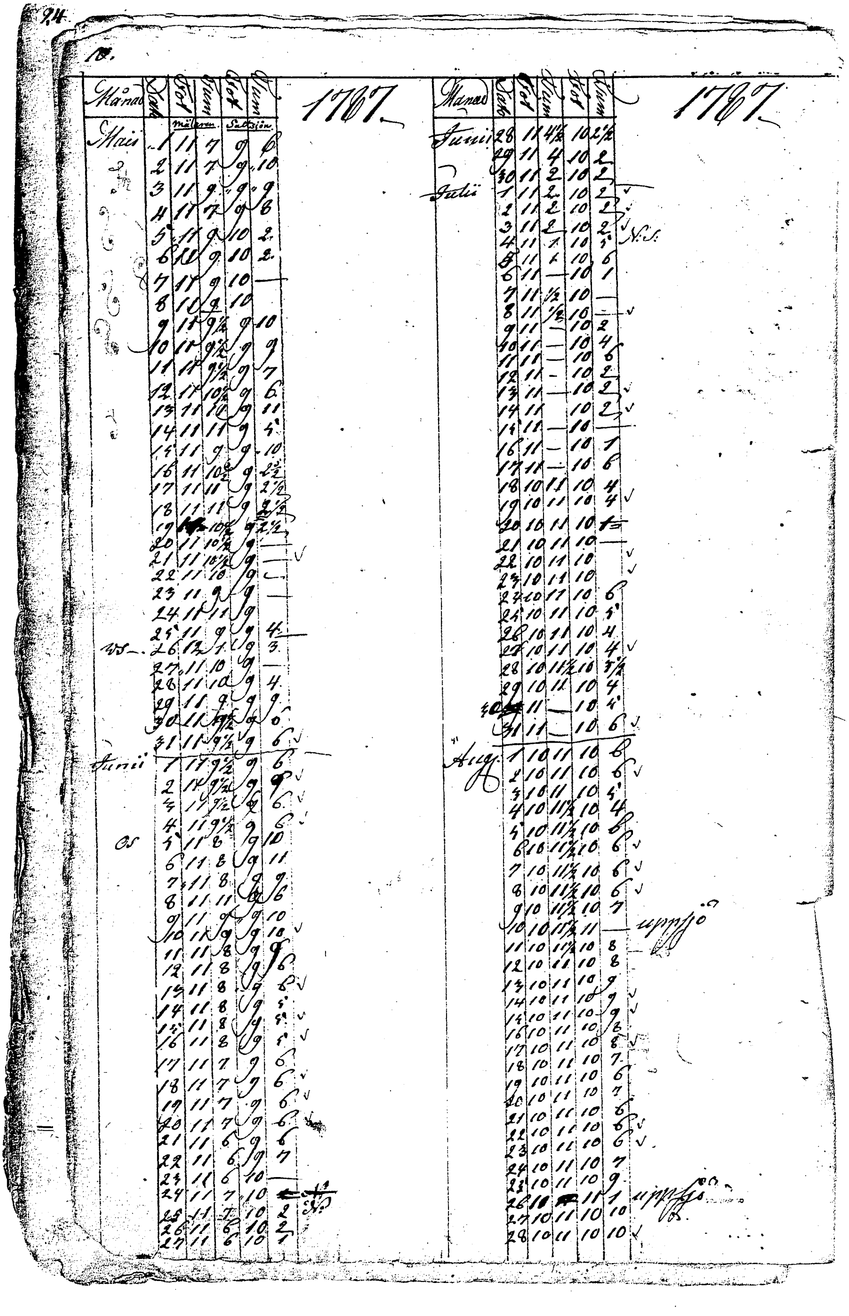


Figure 1. The Stockholm sluice in 1780. (From Lilienberg (1891), after a painting by A. Holm.)

The water level readings were collected in water level books and other documents, now preserved in the City Archives of Stockholm; an example is shown in Figure 2. Various (sometimes incorrect) tables and other relevant published information may be found in Erdmann (1847, 1853), Nordenskiöld (1858), Forssman (1874), Lilienberg (1891), and Rosén (1906).

In 1849 the Royal Swedish Academy of Sciences initiated sea level observations at the lighthouse Grönskär, on a solid rock distant in the Stockholm archipelago. These observations were performed with great care by the lighthouse keeper. His water level books are stored in the Archives of the Swedish Meteorological and Hydrological Institute. Some (incomplete) tables and other relevant information have been published by Erdmann (1856), Forssman (1874), Fagerholm (1879) and Bergsten (1930). Comparisons between the Stockholm and Grönskär data provide an important additional means for checking the zero level of the Stockholm gauge.

In 1889 the Nautical-Meteorological Bureau - a predecessor of the Swedish Meteorological and Hydrological Institute (SMHI) - established a continuously recording mareograph in the bedrock of a small island in Stockholm (Skeppsholmen) close to the sluice; see Rosén (1899). This mareograph has since then recorded the Stockholm sea level; today it is operated by SMHI.



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18.

1787

Månad	Dato	Mälaren Fot	Mälaren Tum	Saltsjön Fot	Saltsjön Tum
Mai	1	11	7	9	6
	2	11	7	9	10
	3	11	9	9	9
	4	11	7	9	8
	5	11	9	10	2
	6	11	9	10	2
	7	11	9	10	—
	8	10	9	10	
	9	11	9½	9	10
	10	11	9½	9	9
	11	11	9½	9	7
	12	11	10½	9	6
	13	11	10	9	11
	14	11	11	9	5
	15	11	9	9	10
	16	11	10½	9	2½
	17	11	11	9	2½
	18	11	11	9	2½
	19	[illegible]	10½	9	2½
	20	11	10½	9	—
	21	11	10½	9	—
	22	11	10	9	—
	23	11	9	9	—
	24	11	11	9	
	25	11	9	9	4
	26	12	1	9	3
	27	11	10	9	—
	28	11	10	9	4
	29	11	9	9	9
	30	11	9½	9	0
	31	11	9½	9	6
Junii	1	11	9½	9	6
	2	11	9½	9	9
	3	11	9½	9	6
	4	11	9½	9	6
	5	11	8	9	10
	6	11	8	9	11
	7	11	8	9	9
	8	11	11	9	6
	9	11	9	9	10
	10	11	9	9	10
	11	11	8	9	9
	12	11	8	9	6
	13	11	8	9	6
	14	11	8	9	5
	15	11	8	9	5
	16	11	8	9	5
	17	11	7	9	6
	18	11	7	9	6
	19	11	7	9	6
	20	11	7	9	6
	21	11	6	9	6
	22	11	6	9	7
	23	11	6	10	—
	24	11	7	10	
	25	11	7	10	2
	26	11	6	10	2
	27	11	6	10	1

1787

Månad	Dato	Fot	Tum	Fot	Tum
Junii	28	11	4½	10	2½
	29	11	4	10	2
	30	11	2	10	2
Julii	1	11	2	10	2
	2	11	2	10	2
	3	11	2	10	2
	4	11	1	10	5
	5	11	1	10	6
	6	11	—	10	1
	7	11	½	10	—
	8	11	½	10	—
	9	11	—	10	2
	10	11	—	10	4
	11	11	—	10	6
	12	11	—	10	2
	13	11	—	10	2
	14	11		10	2
	15	11	—	10	—
	16	11	—	10	1
	17	11	—	10	6
	18	10	11	10	4
	19	10	11	10	4
	20	10	11	10	1
	21	10	11	10	—
	22	10	11	10	
	23	10	11	10	
	24	10	11	10	6
	25	10	11	10	5
	26	10	11	10	4
	27	10	11	10	4
	28	10	11½	10	3½
	29	10	11	10	4
	30	11	—	10	4
	31	11	—	10	6
Aug.	1	10	11	10	6
	2	10	11	10	6
	3	10	11	10	5
	4	10	11½	10	4
	5	10	11½	10	6
	6	10	11½	10	6
	7	10	11½	10	6
	8	10	11½	10	6
	9	10	11½	10	7
	10	10	11½	11	—
	11	10	11½	10	8
	12	10	11	10	8
	13	10	11	10	9
	14	10	11	10	9
	15	10	11	10	9
	16	10	11	10	8
	17	10	11	10	8
	18	10	11	10	7
	19	10	11	10	6
	20	10	11	10	7
	21	10	11	10	6
	22	10	11	10	6
	23	10	11	10	6
	24	10	11	10	7
	25	10	11	10	9
	26	10	[illegible]	11	1
	27	10	11	10	10
	28	10	11	10	10

Figure 2. Water level observations at the Stockholm sluice during a part of 1787. The columns contain (from left to right) date, lake level in feet and inches, and sea level in feet and inches.

The sea level observations at the Stockholm sluice were made for three different purposes. The first purpose was to know the depth of the water above the sill of the sluice. The second purpose was to control the difference in the water level between the lake and the sea. The third purpose, added somewhat later, was the scientific determination of the rate of the land uplift. This led to incompatible demands on the handling of the zero level of the sluice gauge. The first purpose would require that the zero level was changed when the sill of the sluice was rebuilt. The second purpose would require that the zero level was changed only in the same way in the sea as in the lake. The third purpose, finally, would require that the zero level was not changed at all (or changes corrected for).

In reality the following changes of the zero level have been made or have occurred. Changes of the applied unit of length are also stated here.

1774. The sea level observations started on January 1. The readings were made, in Swedish feet and inches, from a scale that was cut into the stone wall of the sluice (with its zero 1 foot above the bottom).

1837. The separate gauge by now used for the readings was raised 4 ½ inches = 11 cm above the scale in the stone wall. This was due to adding a layer to the sill of the sluice. (A corresponding change of the gauge in the lake was not made until 9 years later.) The stated change of the sea level gauge is confirmed by comparing the sea level readings with the lake level readings at the events of "uppsjö", and these comparisons indicate that the change occurred around November 1.

1851. The observations were moved to the gauge of the new and deeper sluice on September 1, and from now on made in feet and decimal inches (with its zero at the sill). The new gauge was nearly 5 feet 4 (duodecimal) inches = 158 cm lower than the old one, the difference being determined by several contemporary readings at the old and the new gauge during calm sea surface. (This is also confirmed by comparions with Grönskär in the Stockholm archipelago.)

1868. According to repeated levellings a local subsidence of the whole sluice by (2 ½ -) 3 cm occurred, probably caused by explosions for a railway tunnel close to the sluice. Comparisons with Grönskär confirm this, and indicate that most of it occurred around October 1.

1873. The gauge was raised 5 cm since it was said to be lower than the gauge in the lake. Again, comparisons with Grönskär confirm this, and indicate that it occurred around December 1.

1889. Although the water level observations at the sluice continued, the mareograph close to the sluice had now come into operation. From January 1 that year and onwards the mareograph data from SMHI, given in cm, are used. At first the mareograph had an inverted scale but this was later changed to the present one. The zero level of the mareograph is (153 ½ -) 154 cm higher than that of the sluice gauge, a value determined both by levellings and from overlapping sea level observations.

Earlier discussions of the above problems, in Lilienberg (1891), SMHA (1932) and Åse (1969), are based on insufficient data. Lilienberg (1891), who seems to have been the last person before the author to have had the original data in his hands, did not fully utilize the information on "uppsjö", and was obviously unaware of the Grönskär data. The later papers are based on Lilienberg, and suffer from the same weaknesses (although they contain comparisons with a few other but less useful stations).

3. Monthly and annual mean sea levels

The observations of the Stockholm sea level have been made with the following approximate frequencies (apart from the gaps considered below):

1774 - 1804, 1812 - 1841	Weekly
1805 - 1811, 1842 - 1888	Daily
1889 -	Hourly

Because of the very special oceanographic conditions in the central part of the Baltic Sea, explained in Section 1, even weekly observations are sufficient to produce a reliable monthly mean. This is contrary to most other places in the world.

The calculation of monthly (and annual) means of the sea level is in principle quite straight-forward. However, for the older data, i.e. the sluice data, there are a number of complications that need to be handled.

First, the Swedish feet and (duodecimal) inches from 1774 January 1 to 1851 September 1 as well as the same feet and decimal inches from 1851 September 1 to 1889 January 1 have to be converted into cm. This has been done using the relation 1 Swedish foot = 29.690 cm.

Second, the resultant values in cm have to be corrected for the changes of the zero level of the gauge. This has been accomplished by adding the following constants, based on Section 2:

1774 January 1 - 1837 November 1	- 9 cm
1837 November 1 - 1851 September 1	+ 2 cm
1851 September 1 - 1868 October 1	- 156 cm
1868 October 1 - 1873 December 1	- 159 cm
1873 December 1 - 1889 January 1	- 154 cm

Third, during quite a number of months sea level readings were made at irregular intervals, i.e. not always once a week or once a day throughout the whole month. This has been taken care of, either by interpolating missing values or by merging groups of values into single ones, before calculating the monthly mean sea level.

Fourth, for some months (only in the beginning) there is, instead of sea level readings, a note that sea level has varied between two specified levels. Then the average of these two levels has been used as a monthly mean sea level.

Fifth, in a few (early) cases there are one or two single months missing in a year. These monthly mean sea levels have then been interpolated or extrapolated; see below.

Sixth, for longer periods of missing data, monthly means have, when possible, been reconstructed in a special way, transforming mean sea levels from Copenhagen to Stockholm. This method will be described in Section 4.

Finally it should be mentioned that in a few cases there is, instead of a reading of the sea level, a note on its relation to the lake level, which then has been used to obtain the relevant sea level. Also, in some rare cases obvious misreadings (of 1 foot) have been corrected.

For the mareograph data the only point worth noticing is that some occasional missing months, or parts thereof, have been accurately transferred from neighbouring stations.

The resultant monthly and annual mean sea levels are listed in Table 1. (A few isolated groups of months in the 1780s and 1790s with sparse or doubtful data have been ignored.) All values are given in cm above modern "mareograph zero", a level fixed in the crust at the height - 230.5 cm in the old Swedish height system RH 1900, or at the height - 194.5 cm in the present Swedish height system RH 1970, corresponding to - 195.5 cm in the Nordic height system NH 1960. This sea level scale is equal to the one applied by SMHI; to convert to that used by PSMSL (revised local reference record) one should add 490.0 cm to all values.

Table 1. Monthly and annual mean sea levels at Stockholm 1774 - 2000, in cm. Values before 1889 according to the author; values after 1889 mainly according to SMHI. Also available as a computer file from the Permanent Service for Mean Sea Level (PSMSL).

	J	F	M	A	M	J	J	A	S	O	N	D	
1774	293	293	278	264	264	283	281	263	249	285	295	300	279.0
1775	298	281	302	308	308	295	290	307	312	305	307	296	300.8
1776	278	273	273	283	285	273	286	287	312	293	288	288	284.9
1777	277	277	283	278	280	273	300	306	311	285	322	303	291.3
1785	264	259	273	280	284	286	311	294	298	310	310	280	287.4
1786	252	261	251	246	260	283	*293*	*289*	*297*	*285*	*266*	*259*	*270.2*
1787	*274*	*286*	*270*	*269*	273	280	295	307	285	278	288	289	282.8
1788	*293*	*272*	*264*	267	277	283	285	294	282	291	299	303	284.2
1789	297	290	259	259	258	256	271	285	290	278	258	285	273.8
1790	318	331	305	251	234	269	294	292	312	292	275	295	289.0
1791	292	290	293	266	262	277	280	287	290	280	*268*	*280*	280.4
1801	303	303	299	281	266	283	293	272	273	258	293	302	285.5
1802	286	275	280	282	288	283	292	285	290	296	264	277	283.2
1803	235	253	266	271	280	294	278	274	297	287	277	275	273.9
1804	270	264	244	243	259	284	289	286	280	251	233	253	263.0
1805	264	256	274	238	244	288	280	275	288	273	269	306	271.3
1806	312	268	268	256	258	291	298	281	278	276	277	296	279.9
1807	309	299	279	266	270	280	293	273	290	291	291	294	286.3
1808	305	298	258	266	272	273	265	272	268	273	267	268	273.8
1809	245	260	266	251	261	281	276	268	270	271	276	269	266.2
1810	270	281	291	256	267	276	278	280	278	263	264	276	273.3
1811	263	268	272	268	261	269	271	280	276	272	272	305	273.1
1812	283	*248*	*245*	*250*	*246*	*256*	*276*	*274*	*277*	*280*	*281*	*275*	*265.9*
1813	*258*	*278*	*278*	*267*	*248*	*258*	*266*	*280*	*271*	*271*	*280*	*264*	*268.3*
1814	*271*	*234*	*222*	*237*	*239*	*245*	*261*	*259*	*262*	*258*	*265*	*280*	*252.8*
1815	*257*	*244*	*263*	*263*	*253*	*256*	*266*	*282*	*279*	*254*	*287*	*271*	*264.6*
1816	*275*	*281*	*263*	242	244	*255*	*252*	*280*	*270*	*276*	*273*	*277*	*265.7*
1817	*282*	*314*	*291*	*278*	*269*	*261*	*270*	*271*	*254*	*262*	*279*	*262*	*274.4*
1818	*279*	*275*	*280*	*266*	*245*	*260*	*277*	*274*	*269*	*247*	*256*	*263*	*265.9*
1819	*273*	*258*	*271*	266	242	*267*	*278*	*261*	*266*	*267*	258	240	*262.3*
1820	250	254	*247*	260	258	*260*	*276*	*283*	*275*	*270*	261	260	*262.8*
1821	*255*	*278*	*258*	*252*	*255*	*261*	*272*	*278*	*280*	*274*	*299*	*302*	*272.0*
1822	*309*	*296*	*311*	*274*	*251*	*270*	*277*	*277*	*285*	*265*	*272*	*260*	*278.9*
1823	*231*	*230*	*239*	*252*	*267*	*259*	*270*	*266*	*279*	*263*	*286*	*295*	*261.4*
1824	*287*	*271*	*260*	*241*	*265*	*255*	*276*	*276*	*264*	*267*	*301*	*312*	*272.9*
1825	308	291	253	266	251	267	270	272	273	278	306	266	275.1
1826	241	254	249	265	249	248	255	259	265	262	257	248	254.3

1827	275	248	270	253	239	245	273	272	258	241	262	274	259.2
1828	259	256	257	250	250	260	272	275	262	267	256	276	261.7
1829	243	240	254	237	253	250	266	262	265	265	270	236	253.4
1830	235	236	266	272	249	255	255	270	253	267	277	248	256.9
1831	246	238	230	226	248	250	250	251	252	254	284	267	249.7
1832	256	257	245	245	257	249	282	272	278	278	258	261	261.5
1833	255	258	226	234	248	259	262	279	267	246	274	304	259.3
1834	284	273	286	268	263	270	261	250	261	276	290	283	272.1
1835	287	299	274	266	255	258	266	265	241	253	255	278	266.4
1836	281	288	283	264	247	262	283	277	271	268	266	261	270.9
1837	266	253	256	241	246	246	258	262	254	259	287	266	257.8
1838	242	244	251	262	248	258	270	291	276	269	272	284	263.9
1839	304	280	258	259	261	265	269	277	272	263	241	217	263.8
1840	266	261	233	238	238	258	264	254	272	266	263	248	255.1
1841	240	235	236	236	247	266	265	264	242	256	261	270	251.5
1842	232	236	259	243	237	258	278	254	240	246	255	265	250.3
1843	284	263	240	240	220	240	262	253	253	272	261	279	255.6
1844	274	257	245	240	250	261	283	276	260	271	250	223	257.5
1845	240	242	236	240	235	240	250	252	257	269	267	281	250.8
1846	270	263	269	244	241	260	267	248	246	246	233	254	253.4
1847	232	252	242	240	235	247	247	242	262	249	268	259	247.9
1848	209	237	232	237	242	244	264	279	273	238	265	276	249.7
1849	253	285	280	224	221	262	270	266	249	248	262	224	253.7
1850	216	264	271	226	240	248	259	249	256	255	272	272	252.3
1851	265	250	241	233	242	271	268	257	253	255	265	260	255.0
1852	278	264	244	237	231	242	246	244	248	270	252	268	252.0
1853	276	232	224	226	234	231	256	265	252	264	250	233	245.3
1854	228	268	263	258	249	242	248	247	267	274	264	278	257.2
1855	276	226	232	240	240	232	240	257	258	263	241	253	246.5
1856	250	258	238	234	239	249	266	254	255	244	254	274	251.3
1857	256	237	241	214	221	238	259	252	239	251	235	266	242.4
1858	271	252	248	265	249	239	253	243	249	261	253	246	252.4
1859	257	265	283	270	232	237	257	258	254	246	255	244	254.8
1860	251	252	235	235	237	246	255	255	263	266	244	229	247.3
1861	234	245	255	237	263	237	244	272	270	239	248	261	250.4
1862	241	237	226	235	237	252	274	260	241	253	250	231	244.8
1863	262	288	247	246	248	244	261	267	264	254	267	276	260.3
1864	254	254	241	240	233	251	257	274	260	249	239	221	247.8
1865	257	233	222	226	236	254	250	251	256	235	250	249	243.3
1866	275	293	231	222	239	239	258	260	256	235	270	275	254.4
1867	249	256	228	249	226	243	258	251	243	256	272	265	249.7
1868	241	283	264	241	250	255	249	235	253	244	258	244	251.4
1869	237	265	236	221	235	251	252	254	262	268	278	251	250.8
1870	243	215	231	228	248	247	256	232	254	246	248	231	239.9
1871	228	207	241	252	236	236	238	253	240	230	232	242	236.3
1872	244	213	223	232	232	234	240	243	252	250	252	245	238.3
1873	262	235	225	215	239	242	248	255	252	262	252	285	247.7
1874	285	273	239	245	228	246	245	255	256	254	261	246	252.8
1875	224	225	206	228	238	243	233	231	238	230	221	223	228.3

1876	231	228	244	231	222	237	248	246	257	241	234	216	236.3
1877	220	244	238	221	223	233	251	253	255	251	265	245	241.6
1878	247	249	262	227	222	252	251	238	255	257	248	247	246.3
1879	240	220	233	213	223	237	254	243	250	253	252	238	238.0
1880	253	240	239	217	231	230	235	236	226	239	258	283	240.6
1881	256	224	220	228	229	237	243	260	240	226	235	241	236.6
1882	261	253	262	225	228	240	234	250	234	204	224	210	235.4
1883	217	213	224	213	219	233	238	250	243	242	254	264	234.2
1884	258	257	214	201	227	234	234	231	222	248	249	251	235.5
1885	223	225	236	214	219	241	235	238	245	249	230	254	234.1
1886	255	207	191	216	215	223	250	246	238	225	215	255	228.0
1887	220	227	231	225	226	232	240	250	243	245	238	260	236.4
1888	231	226	198	206	229	224	234	238	228	250	236	256	229.7
1889	235	253	221	220	206	222	238	256	243	234	230	231	232.4
1890	247	232	230	230	220	245	249	243	238	264	247	220	238.7
1891	220	232	240	210	222	220	231	245	244	240	226	243	231.1
1892	245	241	204	225	233	236	249	243	243	233	218	240	234.2
1893	222	223	243	234	219	235	232	242	263	260	261	252	240.4
1894	236	273	246	210	219	228	236	244	243	224	239	245	236.9
1895	231	207	224	234	215	221	246	244	253	252	246	238	234.2
1896	232	246	236	226	231	233	246	239	230	233	230	219	233.4
1897	210	225	223	226	227	227	242	234	242	239	226	242	230.2
1898	248	265	234	219	218	228	256	245	247	222	232	265	240.0
1899	263	242	242	243	222	233	226	244	252	254	268	251	245.0
1900	214	211	214	213	231	226	237	236	236	258	229	243	229.0
1901	229	234	209	218	205	226	222	225	218	226	238	247	224.6
1902	258	234	220	204	218	222	242	250	243	229	228	217	230.4
1903	239	269	249	253	230	223	239	261	254	236	244	229	243.6
1904	218	222	200	214	229	232	248	248	226	227	243	256	230.1
1905	249	255	212	218	221	217	239	246	244	244	223	246	234.4
1906	244	245	251	224	213	230	240	243	232	220	218	251	234.2
1907	236	226	240	218	228	223	238	258	251	225	208	215	230.3
1908	225	256	207	201	217	218	220	235	242	218	214	233	223.7
1909	229	228	205	208	219	228	240	252	234	229	239	234	228.8
1910	257	239	225	219	224	218	238	231	220	225	232	218	228.8
1911	240	239	233	221	221	216	236	226	247	231	248	221	231.6
1912	215	221	219	231	226	236	217	237	245	228	237	263	231.2
1913	238	228	254	228	211	233	236	241	214	211	248	279	235.2
1914	250	252	231	221	233	220	224	230	229	225	207	241	230.2
1915	222	214	215	225	221	226	232	239	238	204	216	235	223.9
1916	247	242	198	215	215	223	231	238	231	236	224	224	227.0
1917	214	207	200	219	214	212	218	215	236	249	246	266	224.8
1918	242	229	207	198	188	229	235	233	247	240	222	225	224.5
1919	218	205	200	217	202	227	233	252	237	240	202	228	221.7
1920	237	234	234	214	226	222	226	237	225	198	206	195	221.1
1921	241	230	229	228	210	227	239	239	238	240	231	232	232.0
1922	246	205	230	208	221	234	234	239	228	214	229	244	227.6
1923	237	227	185	186	216	241	235	249	240	252	260	235	230.3
1924	213	223	213	219	212	221	240	223	226	224	226	222	221.8

1925	256	245	214	211	204	227	220	230	244	240	228	232	229.2
1926	221	202	227	211	207	216	218	232	242	232	223	228	221.6
1927	235	219	211	225	233	237	227	228	232	241	236	202	227.2
1928	218	225	184	196	202	231	247	245	234	232	232	234	223.2
1929	211	181	199	213	214	226	235	227	232	243	233	233	220.4
1930	234	208	207	196	200	208	227	237	210	225	258	225	219.4
1931	227	201	206	204	203	219	234	226	229	236	224	225	219.6
1932	247	232	207	214	207	215	221	228	233	240	221	226	224.1
1933	211	221	199	224	207	202	222	238	216	209	210	199	213.3
1934	215	236	222	183	211	221	222	230	216	242	235	218	220.8
1935	206	235	213	221	200	213	234	232	228	247	228	229	223.7
1936	228	211	192	209	196	208	216	224	217	224	231	238	216.1
1937	222	193	199	194	200	210	225	219	228	212	218	208	210.6
1938	217	233	237	246	214	223	228	209	217	230	238	212	225.3
1939	207	230	209	207	196	213	222	211	195	189	197	217	207.7
1940	213	184	204	197	190	203	213	234	244	215	217	226	211.6
1941	190	187	198	189	191	200	213	222	226	211	195	223	203.7
1942	208	184	184	193	199	216	224	213	218	236	229	237	211.8
1943	215	238	227	235	221	216	226	235	220	225	215	219	224.3
1944	249	238	220	203	221	216	214	207	220	214	216	219	219.8
1945	221	210	225	228	215	224	226	224	213	222	209	222	219.8
1946	216	231	202	224	203	216	216	225	227	212	200	197	213.9
1947	180	164	189	215	196	204	211	205	204	222	218	220	202.3
1948	222	206	208	207	200	211	220	221	229	243	231	226	218.5
1949	237	237	218	213	213	222	218	234	203	214	218	239	222.0
1950	220	209	218	219	201	217	221	209	227	242	217	223	218.5
1951	208	181	187	210	195	196	218	209	210	192	194	250	204.1
1952	243	227	198	196	197	227	223	214	230	228	217	216	218.0
1953	204	220	208	213	200	204	214	232	234	219	210	218	214.7
1954	223	174	177	195	189	193	222	221	227	236	232	227	209.7
1955	221	214	196	201	220	207	207	202	214	226	223	244	214.5
1956	240	195	191	193	209	208	215	228	212	228	207	226	212.7
1957	212	222	195	191	201	206	213	219	231	238	224	223	214.6
1958	226	220	200	183	214	203	213	219	199	213	208	215	209.3
1959	232	207	202	203	188	208	209	203	212	204	198	177	203.6
1960	201	188	167	178	194	206	217	219	217	192	198	223	199.9
1961	197	211	229	220	207	222	238	234	223	200	219	221	218.4
1962	233	233	193	196	199	209	222	221	236	210	201	215	213.9
1963	192	188	184	175	186	190	207	207	202	230	220	210	199.1
1964	211	218	170	176	202	201	216	214	220	211	215	228	206.7
1965	216	206	193	192	186	195	223	215	212	203	217	213	205.8
1966	190	184	216	194	194	201	215	211	222	207	194	214	203.6
1967	216	202	237	219	205	206	210	215	210	232	227	235	217.7
1968	217	215	214	212	199	188	206	195	187	208	197	195	202.8
1969	183	189	164	192	189	193	210	191	206	217	249	202	198.8
1970	176	185	188	206	196	197	213	204	212	212	230	217	202.9
1971	205	208	195	187	186	192	214	201	207	218	232	231	206.2
1972	186	168	166	202	184	201	200	199	199	202	234	227	197.2
1973	196	219	208	215	196	199	205	207	209	199	228	238	209.8

1974	210	207	168	174	172	204	228	216	203	215	215	244	204.6
1975	252	208	190	191	190	198	197	202	204	207	193	220	204.2
1976	250	191	182	197	188	196	196	199	191	169	182	214	196.0
1977	193	183	192	201	191	191	212	191	204	204	235	202	199.8
1978	213	174	193	180	165	188	203	200	235	214	228	192	198.8
1979	178	186	190	175	192	186	221	208	218	199	198	217	197.3
1980	188	174	163	184	181	191	200	200	206	218	213	234	196.0
1981	234	224	186	181	183	201	207	212	196	214	236	234	208.9
1982	196	192	195	204	202	189	193	199	214	184	209	226	200.2
1983	253	223	200	194	183	193	200	200	210	233	234	215	211.4
1984	240	188	166	177	180	192	211	195	208	220	194	198	197.4
1985	182	187	173	187	183	196	204	205	220	210	214	208	197.3
1986	213	167	172	178	182	189	205	199	220	214	224	230	199.3
1987	187	198	168	175	192	194	201	213	216	199	199	205	195.4
1988	222	202	197	189	178	189	189	212	211	207	206	221	202.0
1989	237	246	221	192	199	194	200	214	198	211	206	212	210.8
1990	225	237	252	209	189	191	209	203	207	211	203	199	211.0
1991	212	179	171	181	183	200	201	203	203	203	199	207	195.3
1992	227	211	207	192	193	174	190	208	204	185	208	208	200.5
1993	218	220	194	178	170	195	212	209	190	171	169	195	193.4
1994	205	185	194	191	174	207	189	187	194	202	197	219	195.4
1995	217	228	215	216	192	192	194	187	184	203	208	175	200.8
1996	165	155	155	168	181	192	205	181	169	184	215	194	180.4
1997	184	208	206	207	190	185	179	179	208	218	190	180	194.5
1998	201	214	214	171	181	193	212	216	200	191	213	199	200.3
1999	209	214	192	192	180	183	188	189	181	200	190	228	195.7
2000	217	227	217	182	174	199	211	202	180	177	193	204	198.5

Uncertain values due to interpolation or extrapolation (in 1786 and 1801) are printed in a somewhat deviating type and size in Table 1. Mean sea levels transformed from Copenhagen according to below are denoted by italics, to allow them to be separated from the ones actually observed in Stockholm.

Annual means, except for the ones transformed from Copenhagen, have been published earlier (Ekman, 1988). The annual means published here are mostly identical within a cm (with the exceptions of 1787, 1802, 1837 and 1838, which have been changed by about 5 cm). The monthly means, on the other hand, have not been published earlier, although preliminary ones from 1825 onwards have been used in some papers. The general conclusions in earlier papers based on the preliminary means are still valid. The important improvement achieved here is the extension of the monthly means back in time to 1774.

4. Reconstruction of missing mean sea levels

For the first 50 years the Stockholm sea level series contains some gaps, where original data are missing. The largest of these gaps is 1812 - 1824, although this period does contain a few short periods of data. The gap has been filled by transformation of monthly mean sea levels from a station in another part of the Baltic Sea. That station is Copenhagen (København), from which sea level data exist for some decades around 1800.

The Copenhagen sea level observations were performed daily at the dock of the Christianshavn harbour. (The daily frequency here partly compensates for the fact that Copenhagen is not on the Baltic nodal line for short-term variations.) These data are kept in the Danish National Archives. Reliable data exist for the years 1812 - 1832, during which time the zero point has been possible to check against another sea level scale in Copenhagen (at Nyholm). Monthly means for some of the years have been calculated and published by Simonsen (1949); for the rest of the years they have been calculated from the original data by the author. The readings are given in Danish feet and inches (the Danish foot being equal to the Prussian foot used in northern Germany). Thus they need to be converted into cm; this has been done using the relation 1 Danish foot = 31.385 cm (i.e. 6 % longer than the Swedish foot).

As can be seen, the missing years 1812 - 1824 in the Stockholm sea level data are completely covered by the Copenhagen data. This calls for a method to transform the Copenhagen monthly (and annual) mean sea levels to Stockholm. When transforming the Copenhagen sea level data to Stockholm there are three major effects to deal with. The first one is the differing amplitudes of long-term sea level variability at the two sites, the second one is the differing rates of land uplift, and the third one is the differing zero points of the gauges. (In addition a seasonal correction needs to be made.)

Sea level variations in the Baltic Sea on time scales one month or longer obey a certain geographical pattern, as shown by Ekman (1996a). From his analysis, based on the 100-year-period 1892 - 1991, it can be concluded that long-term sea level variations at Stockholm are in general 1.58 times those at Copenhagen. (It is important to note that this rule does not at all hold for variations shorter than one month; see Samuelsson & Stigebrandt, 1996.) Thus, a deviation of a monthly or annual mean sea level from normal sea level at Copenhagen will correspond to a deviation at Stockholm that is approximately 1.58 times larger.

The land uplift rates along the coasts of the Baltic Sea are well known; see the mareograph results of Ekman (1996), also based on the 100-year-period 1892 - 1991. From his figures it can be concluded that the land uplift difference between Stockholm and Copenhagen amounts to 0.42 cm/yr. Hence, the regression line defining normal sea level is that much steeper at Stockholm than at Copenhagen.

Finally we have the zero point difference. This has to be found out from overlapping sea level observations at Copenhagen and Stockholm, which exist for the 8 years 1825 - 1832. (Here one also has to take into account a small effect due to mean sea level during this time span being lower than normal.)

Thus, according to above we have the following formula for calculating Stockholm mean sea levels, H_S, from Copenhagen ones:

$$H_S = H_K + \Delta H_0 + \Delta U(t_0 - t) + (m-1)(H' - H) + s \qquad (1)$$

Here H_K is the Copenhagen sea level, ΔH_0 the zero point difference for the epoch t_0, ΔU the land uplift difference, t the year, m the "amplitude" factor, H' the Copenhagen sea level transferred to Stockholm by the first three terms in (1), and H the "normal" Stockholm sea level from linear regression with respect to time. (The last term s denotes a seasonal correction to be explained later.) The numerical constants are $\Delta H_0 = 266$ cm, $t_0 = 1829$, $\Delta U = 0.42$ cm/yr, and $m = 1.58$.

A test of formula (1) was made using the 8 common years 1825 - 1832, containing nearly 100 months. Starting from the Copenhagen mean sea levels, the Stockholm ones were predicted according to (1) and then compared with the observed Stockholm mean sea levels. In a first run the test was made without the additional term s in (1). The result was good but showed a seasonal effect that should not be there. The reason for this is probably that the amplitude factor m is mainly a wind factor, winds being the main cause for long-term Baltic sea level variations. However, the seasonal sea level variation is also due to temperature and, therefore, overestimated by only using the wind-induced amplitude factor (cf. Ekman, 1996a). Hence, the seasonal effect from the first run of the test was now added as a correction term s in (1), the numerical value of which is $s = 4$ cm for January - April, $s = 0$ cm for May, $s = -4$ cm for June - October, and $s = 0$ cm for November - December.

With the complete formula (1) a second and final run of the test was performed. From the discrepancies between predicted and observed figures we found a prediction standard error for monthly mean sea levels of 5 cm. The standard deviation of observed monthly means from normal sea level is about 15 cm at Stockholm. Consequently, the prediction will increase the standard deviation only from 15 to 16 cm. We conclude that predicted monthly means obtained through (1) are quite useful.

In principle it would have been possible to transform sea level data also from Swinemünde after 1811 (Seibt, 1890). However, being located at the southern coast of the Baltic, Swinemünde is heavily affected by the internal short-time variations of the Baltic sea level. Hence, Copenhagen is, in our context, clearly preferable.

The possibility to fill earlier gaps in the Stockholm series is very limited. The earlier Copenhagen data have no zero point control, and a similar test as above for the common years 1785 - 1791 shows the Copenhagen data to be unreliable. The discrepancies between predicted and observed Stockholm sea levels are in this case no longer normally distributed; consecutive months may have a systematic discrepancy of a couple of decimetres, with the predicted values being the unrealistic ones. The only additional transformation of Copenhagen sea levels to Stockholm that we have allowed ourselves to make, is for parts of the years 1786, 1787 and 1788, when there are minor gaps imbedded in a period of small discrepancies, and for a similar short part of 1791.

It should, of course, be born in mind that mean sea levels transformed from Copenhagen must not be used for calculations of those phenomena that were already taken into account when producing the transformation formula. However, the transformed mean sea levels will be most useful for the climatic investigations to which we now turn.

5. A winter climate oscillation index

Of particular interest among the monthly mean sea levels are those for the winter months. Using the Stockholm sea level series in its preliminary and less complete form, Ekman (1997, 1999) and Andersson (2002) have demonstrated the central role played by winter climate, especially winds, for the Baltic Sea level (partly noted from other data already by Lisitzin (1958)). The role of winters here is mainly due to the fact that winds tend to be stronger and more persistent during late autumn and winter, and wind stress is proportional to the square of the wind velocity. Ekman (1999) pointed out that there should be a winter relation between the Stockholm sea level and the North Atlantic Oscillation (NAO). This was confirmed by Andersson (2002), who also suggested that the Stockholm sea level series in itself could be used as a climate index. Andersson found, based on data from the 1900s, a winter correlation as high as 0.9 between the Stockholm sea level and several south-north air pressure differences, both across the North Sea and across Europe as a whole. These air pressure differences govern the well-known west-east wind field over northern Europe.

Using the recalculated and complete set of monthly mean sea levels in Table 1 we now construct a winter oscillation index for northern Europe for the years 1774 onwards. The principle is quite simple: The index is the difference between winter mean sea level and normal sea level. This requires, however, that we specify what we mean by these concepts.

To define normal sea level we first correct the annual means for the small lunar nodal tide of period 18.6 years (Proudman et al, 1960). Then we perform a regression of these annual mean sea levels. It is already known that the long Stockholm sea level series cannot be properly described by a linear trend, but requires two such trends. (Alternatively one could use a second degree curve but this would be less realistic from a geophysical point of view.) The first trend is basically due to the postglacial land uplift whereas the second one is due to the land uplift together with the global sea level rise occurring since the late 1800s. These two significantly different trends have been determined by Ekman (1988, 1999) as - 0.493 cm/yr for 1774 – 1884 and - 0.392 cm/yr for 1885 – 1984. As they are determined independently of each other, the inflexion point at 1885 does not necessarily coincide with the intersection of the regression lines. In fact, the intersection happens to be around 1865, leaving at 1885 a jump of 2 cm in the normal sea level. Therefore, a new regression was tried, with the inflexion year 1865. It turned out successful for our purpose; we obtained the same trends (within 0.01 cm/yr), but now the inflexion point and the intersection agreed within half a cm. Hence, normal sea level is here defined 1) for 1774 – 1864 by a regression line corresponding to the apparent land uplift 0.489 cm/yr, determined from the mentioned years except those transformed from Copenhagen, and 2) for 1865 - 2000 by a regression line corresponding to the apparent land uplift 0.389 cm/yr, determined from the mentioned years except the unusual ones after 1988 (see below).

Winter mean sea level is defined as the average of the monthly means for January, February and March, corrected as above for the small lunar nodal tide. These three months stand out as having the largest interannual variations in monhly mean sea level and the highest correlation with the atmospheric circulation; see Ekman (1996b, 1999) and Andersson (2002).

Our winter oscillation index, ΔH, is thus the difference (in cm) between the winter mean sea level, H_W, and the normal sea level, H, as described above:

$$\Delta H = H_W - H \tag{2}$$

where

$$H_W = (H_J + H_F + H_M)/3 - 0.7\cos(115° - 19.34°(T - 2000)) \tag{3}$$

$$H = 277.4 - 0.489(T - 1800) \qquad \text{before 1865} \tag{4a}$$
$$H = 193.5 - 0.389(T - 2000) \qquad \text{after 1865} \tag{4b}$$

The resultant numerical values are presented in Table 2, giving the winter oscillation index for the years 1774 - 2000. The index is also graphically illustrated in Figure 3. Large positive values mean large south-north air pressure differences and dominating westerly to southwesterly winds over central and northern Europe, large negative values mean large north-south air pressure differences and dominating easterly to northeasterly winds over the same area.

As can be seen from Table 2, the winter oscillation index spans between the extreme values 39.9 and - 37.0, with a general average of - 1.5. To get a quick impression of the character of the index, let us take a look at the years with the most extreme values. We compare them with, in turn, the winter wind direction at the Baltic entrance (Jönsson, 1998), the winter temperature at Stockholm (Moberg & Bergström, 1997) and the ice extent in the Baltic Sea (Seinä & Palosuo, 1996). The results are given in Table 3. Index values above 30 coincide with winter winds around WSW, winter temperatures about 5°C above normal, and about 15 % ice cover in the Baltic Sea. Index values below - 30 coincide with winter winds around ENE, winter temperatures from normal to 4°C below, and 40 - 100 % ice cover in the Baltic Sea.

Table 2. North European Winter Oscillation (NEWO) index 1774 - 2000, based on the deviation of winter (January - March) mean sea level from normal sea level at Stockholm (in cm). Also available as a computer file from the Permanent Service for Mean Sea Level (PSMSL).

1774	-1.4	1823	-33.1	1858	7.3
1775	4.7	1824	6.9	1859	19.2
1776	-14.0	1825	19.0	1860	-2.4
1777	-9.4	1826	-16.3	1861	-3.1
		1827	0.7	1862	-12.3
1785	-19.9	1828	-5.7	1863	19.4
1786	-29.8	1829	-16.8	1864	4.1
1787	-7.1	1830	-16.3	1865	-8.1
1788	-6.7	1831	-23.6	1866	21.4
1789	-0.3	1832	-8.6	1867	-0.3
1790	36.3	1833	-14.7	1868	18.4
1791	10.6	1834	20.2	1869	1.9
		1835	26.1	1870	-14.2
1801	(24.1)	1836	23.7	1871	-18.4
1802	3.2	1837	-1.6	1872	-16.9
1803	-25.2	1838	-13.8	1873	-2.8
1804	-16.5	1839	21.7	1874	22.5
1805	-10.5	1840	-5.1	1875	-24.6
1806	8.3	1841	-20.8	1876	-8.2
1807	22.0	1842	-14.8	1877	-8.1
1808	14.0	1843	6.0	1878	11.1
1809	-15.3	1844	3.0	1879	-9.9
1810	8.9	1845	-15.6	1880	3.7
1811	-3.6	1846	13.1	1881	-6.4
1812	-12.2	1847	-11.7	1882	19.6
1813	0.8	1848	-27.2	1883	-20.5
1814	-27.9	1849	19.9	1884	5.0
1815	-15.3	1850	-2.1	1885	-9.6
1816	3.3	1851	-0.1	1886	-19.6
1817	26.2	1852	10.2	1887	-10.9
1818	8.8	1853	-7.6	1888	-18.4
1819	-1.4	1854	1.7	1889	-0.2
1820	-18.0	1855	-6.4	1890	-0.1
1821	-4.1	1856	-2.0	1891	-5.6
1822	38.2	1857	-5.6	1892	-6.0

1893	-6.7	1929	-24.7	1965	-2.4
1894	16.3	1930	-5.2	1966	-10.4
1895	-14.4	1931	-9.6	1967	11.4
1896	3.3	1932	7.8	1968	8.7
1897	-14.4	1933	-9.7	1969	-27.4
1898	15.9	1934	4.5	1970	-22.8
1899	16.1	1935	-1.3	1971	-2.9
1900	-19.1	1936	-8.1	1972	-31.4
1901	-7.9	1937	-13.2	1973	3.2
1902	6.4	1938	11.7	1974	-8.7
1903	21.7	1939	-1.6	1975	13.7
1904	-16.8	1940	-15.9	1976	5.2
1905	8.8	1941	-24.2	1977	-12.9
1906	16.9	1942	-23.2	1978	-7.8
1907	4.2	1943	11.5	1979	-16.4
1908	-0.1	1944	20.6	1980	-25.9
1909	-8.3	1945	3.9	1981	13.8
1910	11.0	1946	1.3	1982	-6.1
1911	8.6	1947	-37.0	1983	25.3
1912	-10.0	1948	-2.2	1984	-2.1
1913	12.0	1949	16.6	1985	-19.4
1914	16.7	1950	1.7	1986	-15.8
1915	-10.2	1951	-21.3	1987	-15.3
1916	2.6	1952	9.9	1988	8.3
1917	-18.9	1953	-1.4	1989	36.4
1918	0.6	1954	-20.2	1990	39.9
1919	-17.1	1955	-0.7	1991	-9.9
1920	10.8	1956	-1.7	1992	18.3
1921	10.0	1957	0.0	1993	14.6
1922	3.6	1958	6.1	1994	-0.6
1923	-6.5	1959	5.0	1995	25.2
1924	-6.3	1960	-23.1	1996	-35.9
1925	15.8	1961	4.2	1997	5.5
1926	-5.5	1962	11.7	1998	15.9
1927	-0.2	1963	-19.9	1999	11.9
1928	-12.8	1964	-7.9	2000	27.0

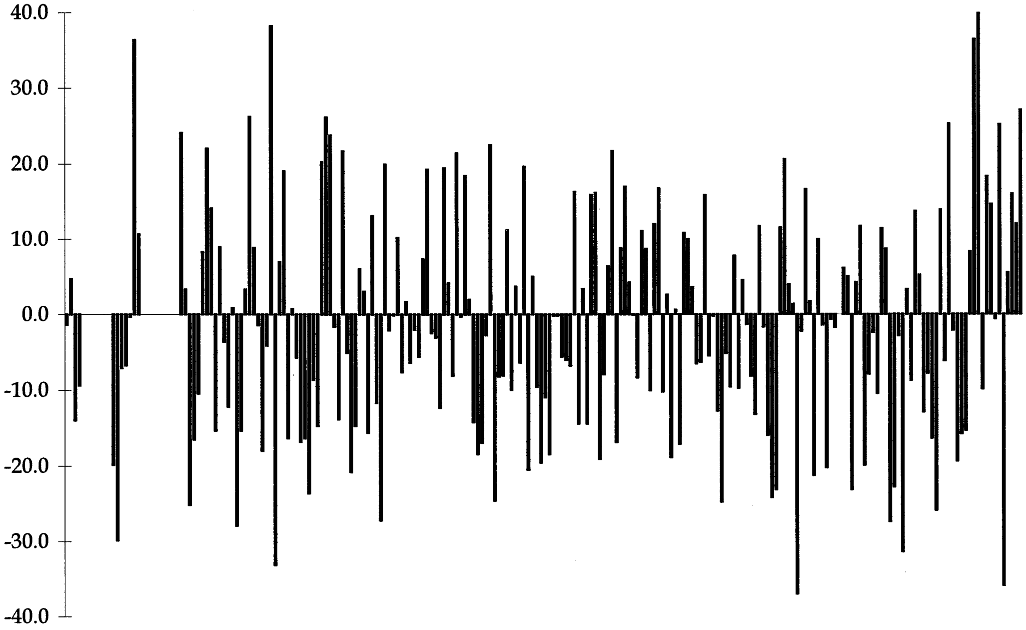

Figure 3. North European Winter Oscillation index 1774 - 2000; data according to Table 2.

Table 3. Extreme values of the North European Winter Oscillation index and corresponding main wind directions (Baltic entrance), temperature deviations from average (Stockholm, °C), and maximum ice extents (Baltic Sea, %).

1790	36.3	WSW	4.2	17
1822	38.2	WSW	4.9	18
1989	36.4	WSW	5.5	12
1990	39.9	SW	5.7	16
1823	-33.1	E	-0.5	43
1947	-37.0	ENE	-3.8	100
1996	-35.9	ENE	-1.1	62

The winter oscillation index basically measures the integrated effect of wind direction, wind speed and wind persistence over the North Sea and the Baltic entrance. Thus the primary relation should be between the index and the air pressure difference causing the geostrophic wind field there. Andersson (2002), using data from 1902 - 1997, found an optimal correlation in two geographical cases: across the North Sea, between De Bilt at its southern coast and Oksøy at its northern one (0.89); across the whole of Europe, between Gibraltar in the far south and Haparanda in the far north (0.88).

Using air pressure data from the above stations, now from 1902 - 2000, we can, through linear regression, determine relationships between the winter oscillation index ΔH and the air pressure differences across the North Sea, Δp_N, and across the European continent, Δp_E, respectively. (For information on the air pressure data see Alexandersson et al (1998) and Jones et al (1997).) The results are (in hPa)

$$\Delta p_N = 0.240\,\Delta H + 3.0 \tag{5}$$

$$\Delta p_E = 0.421\,\Delta H + 10.4 \tag{6}$$

Under the reasonable assumption that (5) and (6) hold also for earlier centuries, the index can be used to estimate the south-north air pressure distribution for any winter back to 1774. As an example we have done so for the extreme winters of Table 3; see Table 4. In general, the index should be

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Table 4. Extreme values of the North European Winter Oscillation index and corresponding estimated air pressure differences (hPa) across the North Sea (De Bilt - Oksøy) and across Europe (Gibraltar - Haparanda). For the modern years we have included the actually measured pressure differences (in italics) as a comparison.

1790	36.3	11.7		25.7	
1822	38.2	12.2		26.5	
1989	36.4	11.7	*10.5*	25.7	*24.3*
1990	39.9	12.6	*12.6*	27.2	*27.1*
1823	-33.1	-4.9		-3.5	
1947	-37.0	-5.9	*-6.4*	-5.2	*-3.1*
1996	-35.9	-5.7	*-6.1*	-4.7	*-6.9*

---

useful for studies of a variety of winter climate-related phenomena from 1774 onwards, and could also be compared with old meteorological data where available.

It may be mentioned that Andersson (2002) and Wakelin et al (2003) found a time-dependence in the correlation between the Baltic/North Sea level and the NAO air pressure difference. However, such a time-dependence should be much smaller in our case because of the better geographical correspondence between the sea level and the air pressure differences above.

6. Winter climate changes

From Tables 3 and 4 it appears that extreme values of the winter oscillation index only occur at the beginning and the end of the time period 1774 - 2000. Also from Table 2 and Figure 3 one gets the impression that large positive or negative index values are more frequent at the two ends of the time period. This calls for a closer investigation to judge whether this tendency is a real or a random phenomenon.

We divide the whole time period into three subperiods: one early period of about 60 years, 1774 - 1840, one central period of 100 years, 1841 - 1940, and one late period of 60 years, 1941 - 2000. For each of these we compute the standard deviation σ of the index. The standard deviations, together with the corresponding degrees of freedom f, are given in Table 5. It indicates that the index variability might be much smaller during the central period.

We now apply F-tests to the standard deviations squared, i.e. we determine probability levels α satisfying the confidence interval

$$F_{1-\alpha/2}(f_x, f_y) < \sigma_x^2 / \sigma_y^2 < F_{\alpha/2}(f_x, f_y) \tag{7}$$

where x and y denote time periods 1, 2 or 3. The interesting result is included in Table 5: The decrease in variability of the winter oscillation index from the early period 1774 - 1840 to the central period 1841 - 1940 is statistically significant at the 99 % level. The increase in variability from the central period 1841 - 1940 to the late period 1941 - 2000 is also statistically significant at the 99 % level. We conclude that both these changes are real changes in the winter atmospheric circulation pattern over Europe.

Table 5. Standard deviations of the North European Winter Oscillation index, degrees of freedom, and significance levels according to F-tests.

1774 - 1840	17.1	50	
			99 %
1841 - 1940	12.3	99	
			99 %
1941 - 2000	17.3	59	

A somewhat similar result was reached earlier by the author (Ekman, 1998a, 1999) using the variability of the annual means of the Stockholm sea level, which are heavily influenced by the winter means. However, the present result using the variability of the winter oscillation index is based on both more data and more relevant data. This has led to a significance as high as 99 %.

Finally we note that the modern extreme mild winter period starting in 1989, with dominating westerlies, is clearly reflected in our index. While the index average during the two hundred years 1774 - 1988 is - 2.3, the average during the last 12 years, 1989 - 2000, is no less than 12.4. It remains to be seen whether this will continue. However, it is noteworthy that a similar warm winter period occurred in the beginning of the 1700s according to Bergström & Ekman (2002). Their findings imply that the winter oscillation index might have been equally high during the years 1720 - 1745.

7. Concluding remarks

The sea-level-based winter oscillation index introduced here obviously is correlated with the North Atlantic Oscillation (NAO) index (Ekman, 1999; Andersson, 2002). For several European applications the present index, however, has two main advantages. First, it is geographically more relevant, i.e. it will describe climate and climate-related phenomena in most of Europe (central and northern) better than the NAO index. Second, it extends further back in time, by half a century compared to the already extended NAO index (Hurrell, 1995; Jones et al, 1997). On the whole, our winter oscillation index should be useful for various studies of winter climate and its impacts in central and northern Europe since 1774.

We have found statistically highly significant changes in the variability of the winter oscillation index since 1774, first a decrease and then later an increase again. These changes in the atmospheric winter circulation pattern over Europe needs to be understood and explained in a wider perspective on climate changes.

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