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SHORT COMMUNICATION

INSTRUMENTAL PRESSURE OBSERVATIONS FROM THE END OF THE 17TH CENTURY: LEIDEN (THE NETHERLANDS)

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ABSTRACT

We present a series of daily pressure readings taken in 1697–98 in Leiden (Netherlands) by W. Senguerd. The readings were reviewed, converted to modern units, and reduced to 0 °C. The 2 year series runs parallel with the Paris 1665–1713 and London 1697–1708 pressure series. Although the series covers a time span of 23 months only, it can be regarded as a useful addition to the very few pressure series that extend back into the 17th century. Copyright © 2005 Royal Meteorological Society.

KEY WORDS: early instrumental data; sea-level pressure; databases; historical climatology; Europe

The increased interest in climate change and variability has created a demand for more empirical data about past climate. The understanding that palaeodata are capable of answering only some of the questions raised has led to a resurgence of interest in historical data of high temporal resolution. One track in the reconstruction of the past climate on the basis of high temporal resolution data is the recovery and digitization of pre-1854 semi-instrumental (i.e. wind) and weather observations from ships. The first comprehensive attempts in that direction (García-Herrera *et al.*, in press; Woodruff *et al.*, in press) have resulted in databases of good spatial coverage of wind direction and wind force data over the world's oceans for 1750–1854, which extend well into the era of poor global coverage over land. The second track is the recovery or revisiting of the earliest instrumental land station data of temperature, and in particular of pressure, that exists in the world, i.e. data taken in the early 18th century or even in the 17th century. Attempts in that direction have resulted in the discovery of pressure data taken by William Derham in Upmister (20 km east-northeast of central London) from February 1697–December 1708 (Slonosky *et al.*, 2001). Together with the earlier recovered pressure data from Paris (1665–1713) taken by Louis Morin (Legrand and LeGoff, 1992), this provides insight into the atmospheric circulation over Europe for the 11 years that the series overlap (Slonosky *et al.*, 2001).

Against this background, we present here another systematic pressure series that extends into the 17th century. The observations were made in Leiden, a town 35 km southwest of Amsterdam and situated 10 km from the North Sea coast. The series is daily and covers the 23 month period February 1697–December 1698. Its existence implies an independent third station in the 17th century daily pressure network over Europe. The location of Leiden (52°9′N, 4°30′E) with respect to Paris and London is optimal for circulation studies, as the three stations form an almost regular triangle with sides of about 400 km.

The readings were taken by Wolferd Senguerd (1646–1724), who was professor in natural philosophy at Leiden University from 1675 (founded in 1575), in a house in Leiden whose exact location is unknown. In

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Table I. Instruments used by Senguerd during his observations (1 February 1697–31 December 1698) in Leiden. Dates printed in italics indicate a late start or an early end of the instrument readings. The last column indicates the approximate conversion from the Senguerd thermometer scales to Celsius

	Instrument	Type	Observation period	Tube length (cm)	Temperature unit
North room	Barometer B	Stick	1 Feb 1697–*30 Apr 1698*	105	—
	Thermometer B	Air	1 Feb 1697–31 Dec 1698	52	1 °C = 4.2 units
	Thermometer C	Liquid	*1 Apr 1697*–31 Dec 1698	41	1 °C = 5.2 units
South room	Barometer A	Stick	1 Feb 1697–31 Dec 1698	127	—
	Thermometer A	Air	1 Feb 1697–31 Dec 1698	136	1 °C = 3.7 units
	Thermometer D	Air	*1 Jan 1698*–31 Dec 1698	220	1 °C = 2.2 units

total, two barometers and four thermometers were used (Table I). Half of the instruments were in a room at the north of the building; the others were in a south-facing room. The south-facing room was mostly closed; the instruments in the north-facing room were placed near a door that was opened regularly. The motivation behind this was the idea at the time that the motions in liquids in the instruments were partly determined by their exposure to the open air (Geurts and Van Engelen, 1992). Both rooms were probably at ground floor level. This implies that the instruments were at about 2 m above mean sea level, as the Leiden area is roughly at sea level. The observations ran from 1 February 1697 till 31 December 1698, with no single day missing. Senguerd possibly continued the observations after this, but, if so, these data are probably lost. The meteorological readings consist of pressure, temperature, wind direction, wind strength, and weather. The routine observation time refers probably to the morning, as additional observations took place in the afternoon or the evening. The observations, together with a scientific introduction that includes a detailed description of the dimensions of the instruments and their locations in Senguerd's house, were published in Latin in a scientific treatise under Senguerd's Latinized name Senguerdius (1699).

The pressure, in old-style Rhineland inches divided into 12 lines (1 Rhineland inch equals 26.1518 mm; one line equals 2.18 mm), was recorded from two mercury stick barometers, indicated in Senguerd's Latin introduction to his tables (Senguerdius, 1699) as barometers A and B. From 1 May 1698, only the readings of barometer A were published. The reported values were given in integer values of Rhineland lines, indicating a truncation error of 1.09 mm at most. Apart from an obvious misprinting of the pressure for barometer A (on 27 March 1698), differences between A and B are at most 2 Rhineland lines (4.36 mm). A difference of 2 lines happens for only 7 days in the series, all of them before July 1697; for all other days in the series the differences amount to 1 line at most (23% of the days). No corrections for height, temperature or gravity were applied to the data.

Temperature was recorded with three air thermometers and, from 1 April 1697, additionally from a liquid alcohol thermometer. The liquid thermometer was called thermometer C by Senguerd, and the air thermometers as thermometers A, B, and D. For each thermometer, the temperatures are reported in integer values of an unspecified unit. The units differ among the four thermometers. The four temperature units have in common that they all refer to an inverted scale (cold = high value). The relative response of the thermometers to temperature rise was determined by us from a regression of the daily temperature readings of liquid thermometer C with those of air thermometers A, B and D. The results show that the scales of the thermometers in the south room (averaged over the two thermometers) are about 1.5 times coarser than for the thermometers in the north room. The reason for this difference is unclear. See Table I for details of the instruments, their dimensions, their relative responses to temperature rise, as inferred from the calibrations described below, and their operations.

The simultaneous presence of temperature and pressure readings opens up the possibility of reducing the pressures to 0 °C. The readings of thermometer C are the most logical choice for this, as a liquid thermometer is barometrically independent and is more likely to remain stable over the 2 year period than an air thermometer. However, because the February–March 1697 readings of thermometer C are missing, readings from at least one of the three air thermometers have to be invoked for these 2 months. As thermometer D covers only 1698, the choice for this has to be made between thermometers A and B.

Table II. Comparison of monthly temperatures recorded by Senguerd (in his units) with the number of canal freezing days per month for the period of observation by Senguerd (1 February 1697–31 December 1698)

Month	Year	Number of canal freezing days	Thermometer[a] (Senguerd units)			
			B	C (liquid)	A	D
February	1697	28 (Jan: 31)[c]	121.8	—	116.2[b]	—
	1698	21 (Jan: 17)[c]	114.0	148.6	121.1[b]	108.8
March	1697	6	105.2	—	100.4	—
	1698	12	116.5	141.1	122.6	110.0
December	1697	10	112.7	147.0	120.5[b]	—
	1698	0	106.7	135.9	129.8[b]	112.7

[a] High values on all Senguerd thermometer scales indicate cold.
[b] Difference between 1697 and 1698 data inconsistent with the canal data.
[c] In brackets: number of canal freezing days for the preceeding January.

A proper reduction of the pressures to 0 °C requires an assessment of the quality and stability of the various thermometers. No parallel readings in the Netherlands are available to use for this purpose. However, the Netherlands is in the fortunate circumstances of having administrative records from 1634 about the transportation via the barge-canal between the cities of Leiden and Haarlem. These include accurate records of the days when the traffic was interrupted because of freezing of the canal (denoted here as canal freezing days). These days represent a physical proxy for temperature, which correlates well with the Dutch December–February (DJF) winter temperatures (De Vries, 1977; Van den Dool *et al*., 1978). Here, we tested the quality of the Senguerd thermometers using the number of canal freezing days stratified by month (Buisman and Van Engelen, 2005; De Kraker, personal communication), by investigating whether the signs of the trends from 1697 to 1698 for the individual winter months are consistent with the monthly mean thermometer data of Senguerd. The underlying assumption behind this approach is that a month with more freezing days was accompanied with a lower air temperature in Leiden, which seems reasonable as the canal passes through Senguerd's town. Table II presents the results of the comparison. It shows consistency between the canal data and the monthly mean temperatures of thermometers B and C (the latter being the liquid one), but inconsistency with thermometer A. For instance, December 1697 (10 canal freezing days) was apparently colder than December 1698 (no canal freezing), consistent with thermometer B (six units higher on its (inverted) temperature scale) and with thermometer C (11 units higher), but inconsistent with thermometer A (nine units lower). This result is supported by the high correlation between thermometers C and B (0.98) compared with their correlations with thermometer A (0.77 with C and 0.75 with B). Therefore, we chose thermometer B to augment the thermometer-C data in the February–March 1697 period.

The translation of the Senguerd units to Celsius requires the determination of a scale and a zero point, both for liquid thermometer C and air thermometer B. This is done in four steps. First, we verified that liquid thermometer C is barometrically independent, as it should be. This was done by considering the correlation between thermometer-C readings and barometer-A pressures, which yielded $r = 0.28$. Second, we estimated the Celsius equivalent to the Senguerd unit of thermometer C from the mean July minus mean December 1698 temperatures (57.4 units), assuming the real difference to be 11 °C, which is 1.5 °C below the 1971–2000 normal value. This results in a scaling factor of −0.19. The motivation for introducing the below-normal July–December value is that the number of canal freezing days (nil) for 1698 indicates a mild December (De Vries, 1977; Buisman and Van Engelen, 2005; De Kraker, personal communication), whereas documentary data indicate a cool 1698 summer in the Low Countries (Van Engelen *et al*., 2001). Third, the zero point of the thermometer-C scale was obtained from a comparison of the median of Senguerd's temperature distribution on days where he reported snowfall (12 days in total) with the median of the temperature distribution of the hours with snow in De Bilt 1991–95 (ww codes 71–75 only). The comparison indicates that the 149 Senguerd units on thermometer C correspond to −1.3 °C, so that

$$T(^{\circ}\mathrm{C}) = -0.19(T_{\mathrm{C}}(\mathrm{Seng.\ unit(C)}) - 149) - 1.3 \quad (1)$$

where the index to T refers to the thermometer and Seng. unit to the unit that is applied by Senguerd in that thermometer.

Finally, multiple linear regression analysis between the daily temperature observations of thermometer C against thermometer B and the reported pressure P (mm) of barometer A yields the conversion formula between the temperature readings T:

$$T_C(\text{Seng. unit(C)}) = 1.23T_B(\text{Seng. unit (B)}) - 1.38P(\text{mm}) + 1041 \quad (2)$$

The reliability of the conversions to Celsius (Equations (1) and (2)) was checked by comparing the result for the Senguerd 1697–98 DJF temperature (−1.27 °C) with the 1697–98 DJF estimate from the canal freezing days (−1.3 ± 0.7 °C; see Van den Dool *et al.* (1978)). These numbers compare surprisingly well, although two partly compensating effects may spoil the Senguerd data: the fact that his thermometers are indoors, and the fact that he observed in the mornings only. We estimated from modern data obtained from the synoptic station at Valkenburg airport, situated 6 km west of Leiden, that the latter may cause the Senguerd winter temperature to be too low by 1.0 °C at most. We note that a potential bias due to measuring indoors is partly compensated by our estimation procedures, in which the zero point of the units of Senguerd's indoor temperature was calibrated with the modern outdoor temperature during snowfall, and its scale with the annual variation of the outdoor air temperature.

For the pressure reduction to 0 °C, the barometer temperature is needed rather than the outdoor air temperature. In that sense, it is fortunate that Senguerd observed indoors, as it implies that the temperature reduction does not introduce an artificially increased variability in the day-to-day pressure. Although thermometers C and B were not in the same room as barometer A (Table I), it appears from the correlations between barometers A and B (0.99) and between thermometers B and D (0.96) that (perhaps helped by the fact that the north-facing room was regularly ventilated, whereas the south-facing room remained closed) the temperature variability of the thermometer C and B readings is also representative for that in the barometer-A room.

The actual pressure reduction to 0 °C proceeded in four steps. First, the temperatures, as expressed in Senguerd units of thermometer C, were estimated from the readings of thermometer B and the observed (uncorrected) pressure of barometer A according to Equation (2). Second, the temperature in Celsius was determined from the temperature in Senguerd units of thermometer C according to Equation (1). Third, the pressure expressed in millimetres was converted into hectopascals by means of multiplication by 1.33322. Fourth, the pressure was reduced to 0 °C using the formula of Kämtz (1832), which was generally used in the 19th century (Können *et al.*, 2003):

$$P(0\,^{\circ}\text{C}) = P(t)(1 - 1.62 \times 10^{-4}T(^{\circ}\text{C})) \quad (3)$$

The first step in this sequence is only required for February and March 1697, as readings from thermometer C are missing there. For these months inserting the values obtained via thermometer B is justified, as the difference between the monthly values averaged over the remaining 21 months in the Senguerd series between C and B is only 0.27 ± 0.10 °C. Note that in the calculation the barometric term in Equation (2) is really needed, as the response of thermometer B to 1 °C temperature rise is the same as a drop of 5 hPa.

Table III shows Senguerd's 17th century pressures for Leiden, together with those of London (Slonosky *et al.*, 2001) and Paris (Legrand and Le Goff, 1992). The Leiden values are much lower than modern climatology. An adjustment of 16.7 hPa is needed to bring the mean of barometer A to the 1971–2000 normal value of 1015.3 hPa of Valkenburg. This adjustment is large, but not unrealistic: the bias correction required for 17th century London data (9.5 hPa) is of comparable magnitude (Slonosky *et al.*, 2001). The most likely cause is trapped air in the barometer originating from outgassing of the mercury, which had been neither boiled nor distilled before its use. An accidental trapping of gases from the atmosphere during the construction of the barometers seems to be less likely, as the average value of the monthly mean differences of barometers A and B is negligible (−0.3 ± 0.2 hPa).

Adjusting the mean 1697–1698 pressures to the 1971–2000 normal automatically accounts for the systematic corrections (e.g. gravity and height) that are otherwise the standard requirement for pressure

Table III. Monthly mean pressures 1697–98 of Leiden from barometers A and B, monthly mean temperatures of Leiden, and the pressures of London (Slonosky *et al.*, 2001) and Paris (Legrand and Le Goff, 1992). To adjust the pressure data to the long-term means, 16.7 hPa, 9.1 hPa and 0.3 hPh have to be added to the Leiden (barometer A), London, and Paris data respectively

Year	Month	Leiden			London P (hPa)	Paris P (hPa)
		P_A (hPa)	P_B (hPa)	T (°C)		
1697	Feb	1001.0	1000.6	−2.5	1004.5	1012.8
1697	Mar	1005.9	1007.4	2.6	1004.9	1014.4
1697	Apr	1005.5	1006.4	3.5	1011.9	1015.5
1697	May	995.7	997.0	9.2	—	1013.9
1697	Jun	1000.2	1001.5	9.9	1007.1	1014.3
1697	Jul	996.3	995.0	12.2	1010.4	1019.3
1697	Aug	992.8	992.8	11.0	1004.9	—
1697	Sep	995.7	996.0	9.4	1006.3	1016.6
1697	Oct	1001.4	1001.4	5.3	1008.6	1018.5
1697	Nov	1005.4	1005.8	3.1	1012.2	1020.3
1697	Dec	997.7	998.1	−0.9	1002.3	1010.7
1698	Jan	1004.0	1004.1	−1.4	1007.4	1014.9
1698	Feb	998.6	998.6	−1.2	1000.5	1008.2
1698	Mar	1004.4	1004.6	0.2	1010.0	1019.3
1698	Apr	1001.8	1001.9	4.2	1009.1	1017.5
1698	May	997.7	—	5.6	1007.0	1015.8
1698	Jun	997.4	—	10.5	1009.1	1017.4
1698	Jul	991.3	—	12.1	1006.4	1017.5
1698	Aug	994.1	—	10.7	1007.9	1017.6
1698	Sep	990.3	—	9.3	1002.1	1012.8
1698	Oct	991.0	—	6.9	999.9	1011.9
1698	Nov	997.8	—	1.0	1000.2	1012.6
1698	Dec	1004.0	—	1.2	1005.9	1018.9

readings. For the Senguerd readings, we note that the gravity correction (+0.6 hPa), height correction (+0.2 hPa), and the time of observation correction (<0.2 hPa) are very small compared with the adjustment of 16.7 hPa applied here.

The quality of the Senguerd pressure series was checked by a comparison of its day-to-day standard deviation with that in the Valkenburg data. The comparison is shown in Figure 1. The figure implies that the variability in the Leiden pressures is realistic. Figure 2 shows the complete time series of the daily values of the Senguerd pressure series.

Figure 3 compares the monthly mean pressures of Leiden, Paris and London for the period under consideration. The difference with Paris in the summer months indicates prevailing westerly airflows, in accordance with the cool character of the 1697 and 1698 summers (Van Engelen *et al.*, 2001). For the 1697–98 winter the Leiden pressures are higher than Paris, indicating a persistent anomalous circulation pattern over Europe with a dominating easterly component in the airflow over the Netherlands. This anomalous circulation (also found by Slonosky *et al.* (2001) from the London–Paris difference) is consistent with the severity of the 1697–98 winter in the Netherlands, which was not matched till 1709 (Van den Dool *et al.*, 1978). Remarkable is the small London–Paris gradient with respect to Leiden–Paris. This may point toward a northerly component in the 1697 and 1698 summers and a southerly component in the 1697–98 winter airflow. From Senguerd's daily wind observations (not discussed further in this paper) we infer that the London data tend to lead here to an overestimation of the north and south wind components. This feature may be a manifestation of a data problem in the London pressures, which could, for these years, only be reduced crudely to 0 °C because of the lack of associated temperature readings (Slonosky *et al.*, 2001).

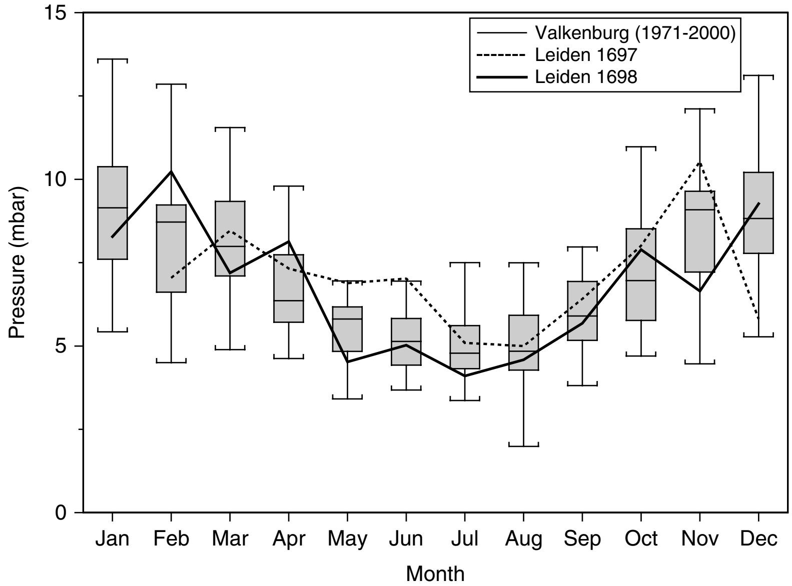

Figure 1. Standard deviation of the day-to-day air pressure difference series for each month of Leiden 1697 and 1698, compared with Valkenburg 1971–2000. The Valkenburg values are condensed in boxplots (each of them made up from the 30 values). A boxplot displays the variation of the standard deviation of the day-to-day differences of the Valkenburg 8 GMT air pressures 1971–2000 calculated per month. The lower and upper limits of the box represent the 25th and 75th percentiles (quartiles) respectively, and the horizontal line in the box represents the 50th percentile (median). The whiskers mark the full data range

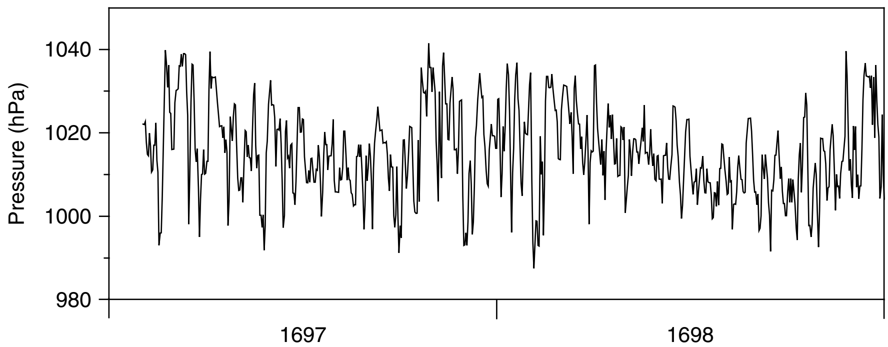

Figure 2. Daily pressures, 1697–1698, in Leiden, bias corrected

The Senguerd series represents a 17th century backward extension by 2 years of the otherwise almost uninterrupted two-century long Dutch daily pressure series, which starts with a series from 19 December 1705 till 1734 in Delft/Rijnsburg with observations by Cruquius (Van Engelen and Geurts, 1985), after which it continues through the entire 18th and 19th centuries by readings from Zwanenburg and Utrecht/De Bilt. We hope that this article stimulates others to undertake searches in their national archives for very old meteorological readings, particularly of pressure and/or wind, to review their contents, and to make them available via the Internet.

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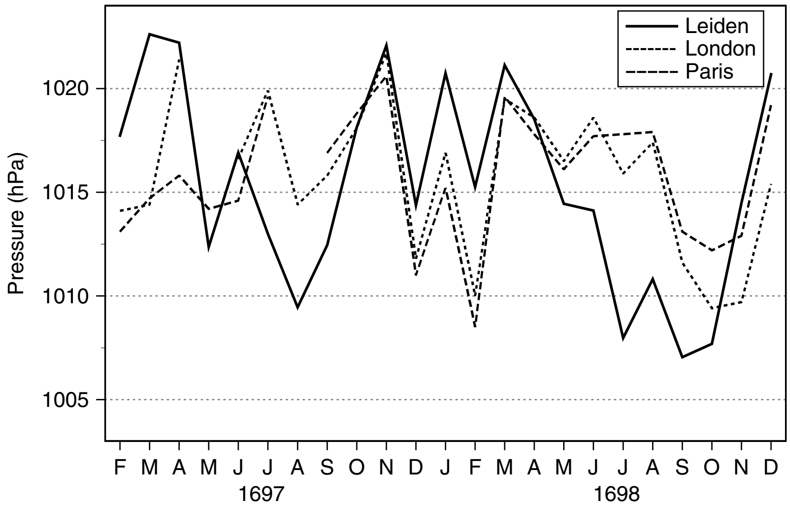

Figure 3. Leiden, Paris and London monthly pressures, 1697–1698, bias corrected. Note that May (London) and August (Paris) for 1697 are missing

Senguerd series. V. Slonosky kindly provided the Paris and London data; M. Carney helped us out in finding her present address. J. Vink digitized the data and provided the translation of the weather terms from Latin. The Senguerd series is available from http://www.knmi.nl.

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