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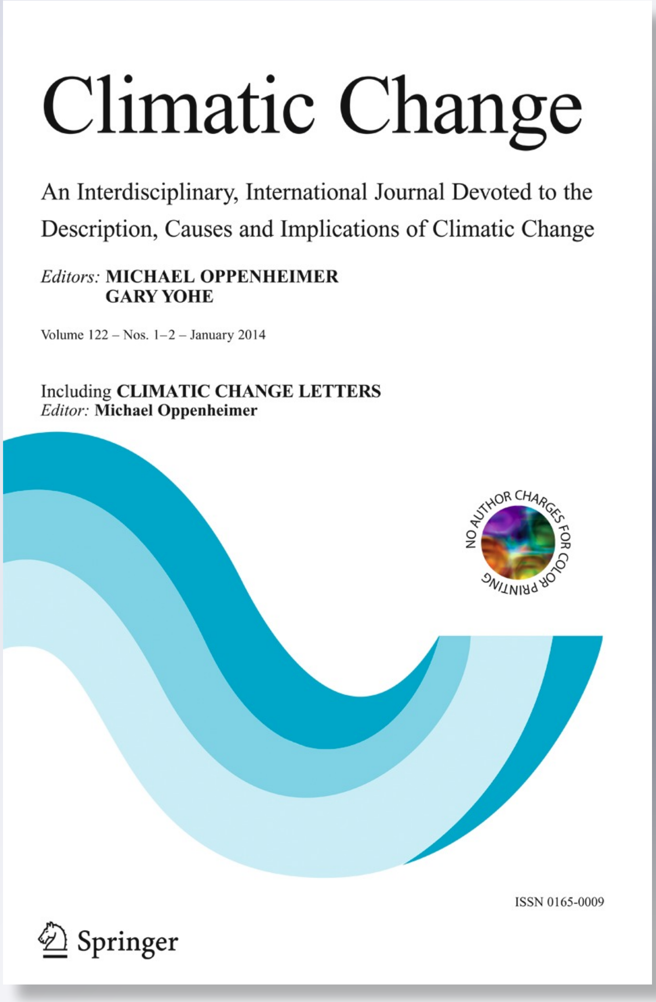

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Early hygrometric observations in Padua, Italy, from 1794 to 1826: the Chiminello goose quill hygrometer versus the de Saussure hair hygrometer

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Abstract The paper includes the reconstruction and analysis of rare historic records of relative humidity (RH). After having highlighted the story of the development of the hygrometer, the paper considers two instruments that in 1783 were submitted to the prize of the Theodoro-Palatina Academy of Sciences, Mannheim, for a new hygrometer with comparable readings. De Saussure proposed a hair wound on a cylinder connected to a pointer and Chiminello a goose pen fixed to a glass tube and filled with mercury. Chiminello won the prize for the corrections of the temperature dependence. In the Astronomic Observatory, Padua, two rare parallel series of RH observations were made in the same place, and at the same sampling time (tree readings a day) with a Chiminello and a de Saussure hygrometer, over the 1794–1826 period. A study was made to know these instruments and interpret the readings. A replica of the goose-quill hygrometer was built to verify in the lab instrumental performances and calibration problems. After having recovered the data, calibrated the instrument, transformed readings to modern units (%), corrected errors and homogenised the series, the paper compares the RH variability in Padua between early and recent instrumental measurements. It includes predictions of RH for two periods of the 21st century, concluding that no major modifications are expected. The paper highlights the importance of looking for metadata about early station sites, instruments and observers, in order to reconstruct early series as correctly as possible.

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1 Introduction

A large variety of hygrometers were invented, based on some physical principles (Middleton 1969; Frisinger 1983; Borchi and Macii 2007). The problem was to obtain comparable data. In the early period from the 15th to the 18th century, most instruments had only a qualitative response and/or a strong dependence on both temperature and relative humidity (See Online Resource 1).

For this reason the *Theodoro-Palatina Academy of Sciences*, Mannheim, launched a tender for the instrument able to provide the most comparable readings to be included as a standard in the international Network of weather observations (1781–1792) founded by the *Palatine Meteorological Society,* Mannheim (Hemmer 1783). The tender received two proposals. Horace-Bénédict de Saussure (1783) proposed a hair wound on a cylinder connected to a pointer (Fig. 1a), but the instrument was not appreciated. Objections were: "*a complicated instrument; the variable nature of the hair and the uncertainty in preparation; the uncertainty*

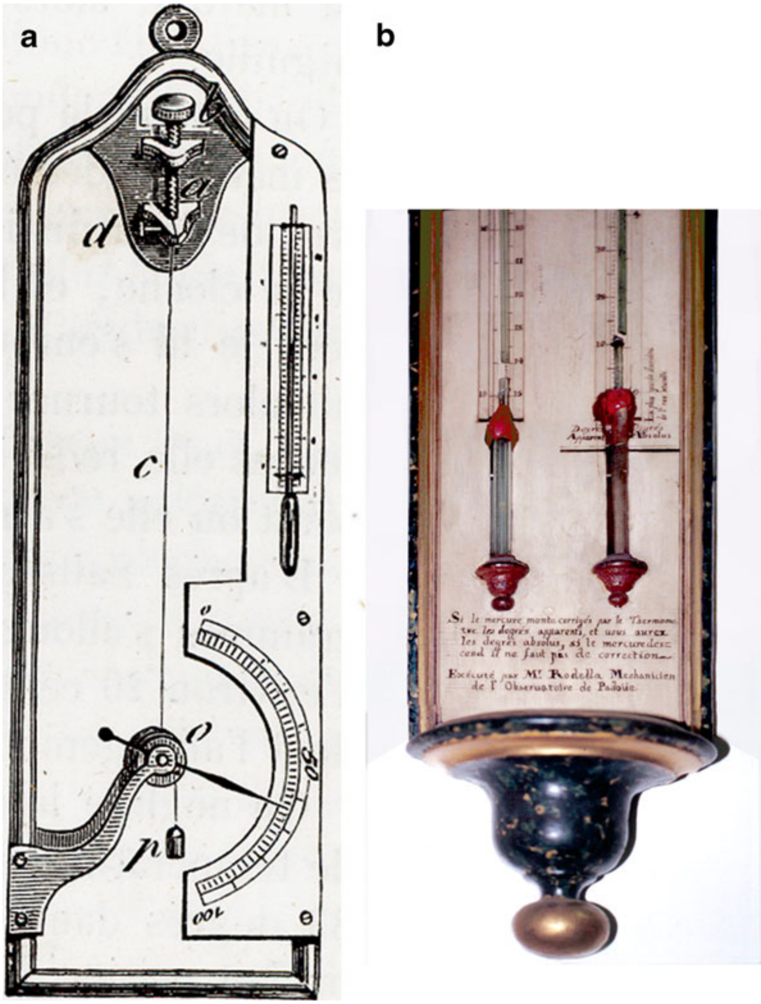

Fig. 1 **a** De Saussure hair hygrometer (Ganot 1860). **b** Chiminello goose quill hygrometer kept in the Museum of Physical Instruments of the Padua University

of dryness and dampness extremes; the weight that opposes the contraction of the hair; the danger of its being injured by dust and cobwebs; the limited extent of the scale; the rules for determining the absolute quantity of vapours in the atmosphere, while the attention should be directed only to the moisture and dryness which the air exhibits" (Smollett 1788). These severe comments were in part justified, although most of them could apply to the winner too. The hair hygrometer needed years to reach appreciation and was in common use from 1820 to 1980, when electronic capacitive and resistive sensors substituted it. Vincenzo Chiminello (1785) made the second proposal: an instrument inspired to a mercury-in-glass thermometer, but with the bulb sensitive to humidity (Fig. 1b). Chiminello considered that the ivory hygrometer developed by de Luc (1773–74) was the best existing instrument and the quill feather hygrometer developed by Retz (Retz 1779; Retz and Held 1786) the most practical solution (See Online Resource 1), but affected by temperature dependence and non-linearity. The quill hygrometer was not a novelty, but the key point was the attempt to reach the comparability of readings making corrections. Chiminello transformed readings into "absolute degrees" of a comparable scale. The methodology was appreciated; the quill hygrometer won the prize and was recommended for the observations of the Network.

In Padua, following the invitation of James Jurin (1723) to join the Network of the Royal Society, London (1724–35) Giovanni Poleni began a series of regular weather observations (Camuffo 2002). After Poleni died, Giuseppe Toaldo and Chiminello moved the observations to the Astronomic Observatory, nicknamed "*Specola*", and adhered to the Palatine Network. Chiminello added regular hygrometric observations, with the two instruments of the tender, i.e. his quill hygrometer and de Saussure hair hygrometer. After Chiminello was hit by an apoplectic fit in 1807, his assistant F. Bertirossi-Busata continued the record. When Chiminello died in 1813, the observations were continued by G. Santini, appointed director of the Specola. These instruments operated in parallel for over 30 years (1794–1826), in the same location, and with the same sampling times.

It is rare to find early instruments, especially hygrometers, and it is generally impossible to test their accuracy because sensors have degraded over time. This case study provides an exceptional possibility of knowing the above instruments, their construction and calibration, the methodology used to recover, homogenize and correct historic records of relative humidity measured at the Specola, how to transform early arbitrary units in modern % units, and how to distinguish indoor from outdoor readings. It stresses how careful one must be, while examining early instrumental data. Finally, the early records will be discussed and compared with the 1961–90 reference period and with the 2011–2040 near future and 2071–2100 far future scenarios.

2 The Chiminello goose quill hygrometer

The sensor was the hollow shaft of a goose feather filled with mercury. To increase sensitivity, the quill was carefully scratched and thinned to remove the hard and waterproof surface layer, impregnated with fatty acid. This was a critical operation because the surface layer provides mechanical strength to the fibrous structure and if scratching is not perfectly uniform or excessive, in the long term the quill is unable to resist the pressure exerted by the mercury column. Later, the quill was immersed in boiling and cold water. Finally, it was fixed to a glass tube using red sealing wax, and filled with mercury.

Chiminello fixed to the same frame his hygrometer, a cistern barometer, and a Réaumur thermometer: all having tube with the same diameter and length, except for the barometer that was a bit longer. All readings were in height units. This assembly constituted a compact weather station for indoor use; external air was monitored after long room ventilation, or with temporary external exposure in clear days. Three original instruments, built and signed by the Chiminello's instrument maker Giovanni Battista Rodella are still preserved in Padua: one at the Museum of Physical Instruments of the University (later illustrated), one at the Botanical Garden and one at the Galilean Academy of Sciences, Letters and Arts.

The wooden frame is 104 cm long plus 11 cm at the basement decoration; the width is 13.5 cm. The glass tube of the thermometer has a scale from −15° to +80 °R (Réaumur) distributed over 73 cm; the tube is 77 cm long and is topped with a closed expansion glass pocket. The external diameter of the tube is 3.3 mm and the internal 2.0 mm. The bulb is a cylinder 77 mm long and 7.7 mm external diameter. The hygrometer tube has the same length and diameter and is topped with an open expansion pocket. The quill bulb is 70 mm long and 7.0 mm external diameter. We suppose that the two bulbs were originally identical and the smaller dimension of the quill today is due to ageing shrinkage over two centuries.

The glass tube of the hygrometer has two scales: from 0 to 310 "apparent degrees" (APP) and from 0 to 32 "absolute degrees" (ABS), both distributed over 73 cm. The 300 APP is coincident with the 32 ABS. On the top, on the side of the 32 ABS level one reads the inscription: "*dryness after 4 h exposure to 25 °R* (i.e. 31.25 °C)". On the bottom, on the side of the 0 level: "*the maximum dampness of natural water*". The scale is reversed, with 0 and 32 ABS respectively corresponding to 100 % and 0 % relative humidity (RH). It should be noted that in dry conditions the mercury column exerts on the bulb 1 atmosphere pressure, and in the long run it may damage the quill, breaking fibres.

3 Calibrating the Chiminello's hygrometer

Chiminello considered that a reliable instrument should have the following characteristics: well determined calibration points, repeatability, no drift and easy temperature correction. However, this was an extremely difficult task because the readings responded to two variables. The relative humidity was the primary cause for changes in volume of the bulb, constituted of the hollow shaft of the feather. The temperature was responsible for the thermal expansion of mercury and, secondarily, of the hollow shaft volume. For this reason Chiminello proposed a complex calibration and a series of corrections. The first correction was to subtract the thermal expansion of the mercury, by comparison with a thermometer. To this aim he built his hygrometer and a Réaumur thermometer with the same dimensional features: two identical capillary tubes and almost equal bulb volumes. Any change in height of the mercury column in the thermometer was representative of the expansion of the mercury for the temperature change. If the hygrometer had the same dimensional features, it had the same thermal effect. Therefore, by subtracting to the hygrometer readings the change of level read in the thermometer (i.e. the thermal disturbance), he removed the temperature dependence referring all humidity readings to the same temperature.

Chiminello thought to solve the problem of a clearly defined scale with a four fixed-point calibration: two in extreme dampness and two in extreme dryness. For dampness, in analogy with thermometer calibration, the quill was immersed in boiling water (first fixed point) and in water with melting ice (second fixed point): the only variable was temperature. For dryness, the quill was kept for 4 h in front of a fireplace with "light fire" (hot dryness calibration) and in winter cold air in the presence of hygroscopic salts (cold dryness calibration). Hot dryness was not well defined, the light fire level being obscure. If we consider that calibration was made in winter to have ice (i.e. at ambient temperature <0 °C, and humidity mixing ratio<4 g/kg) and that if the temperature in front of the fireplace reached 50 °C, RH was <5 %. In order to solve these uncertainties the operation was repeated several times. In addition, repeated temperature and humidity cycles were made to anneal the quill and obtain a stable sensor.

In theory, for the non-linearity of the quill response it would have been advantageous to calibrate at intermediate humidity levels, but this was impossible at that time without the use of deliquescent salts. We built a replica of a Chiminello hygrometer to verify in the laboratory the instrument performances and calibration problems. Calibration of the replica was made in controlled calibration chamber at 20 reference points, i.e. RH=20, 40, 60, 80, 100 % and *T*=3°, 10°, 20°, 30 °C by comparison with well calibrated instruments (Cocheo and Camuffo 2000). The calibration readings are reported in Fig. 2 At the same RH level, the temperature dependence follows a parabolic equation:

$$\mathrm{Y} = -\mathrm{aT}^2 + \mathrm{bT} + \mathrm{c}$$

where a,b,c are positive coefficients variable with the RH level (in this case R^2 >0.99 for all plots). The vertex of each parabola is located at the temperature b/2a. The temperature dependence increases with RH and quill hydration. The quill sensitivity (that is related to the output range) increases with temperature, i.e. from 3° to 30 °C it increases 1.7 times. Keeping constant the temperature, the mercury column decreases when RH increases (i.e. increasing the quill volume). The equation of the quill immersed in water (RH=100 %) is represented by a second order equation with R^2 =0.99 and a bit better (R^2=1) by a third order equation (Fig. 2).

4 The instrumental records and homogenisation of the series

From 1794 to 1826, readings were scheduled at 7:00, 15:00 and 21:00, as reported in the original logs, to represent the daily cycle. At 7:00 readings were close to sunrise and minimum temperature in winter, but not in summer; at 15:00 close to maximum temperature and minimum RH over the whole calendar year; at 21:00 close to the daily average temperature but not necessarily to the RH average. It is possible to make a comparison with nowadays if the same sampling time is followed.

The readings show discontinuities in March 1797, June 1806, March 1811 and October 1818, followed by different ranges and drifts (Fig. 3). Discontinuities correspond to the

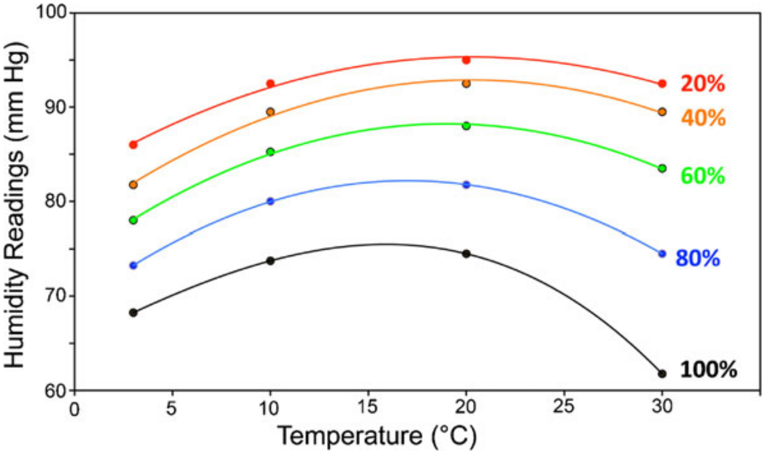

Fig. 2 Calibration of the replica of a Chiminello goose-quill hygrometer, made in controlled calibration chamber at 20 reference points, i.e. RH=20, 40, 60, 80, 100 % and *T*=3°, 10°, 20°, 30 °C

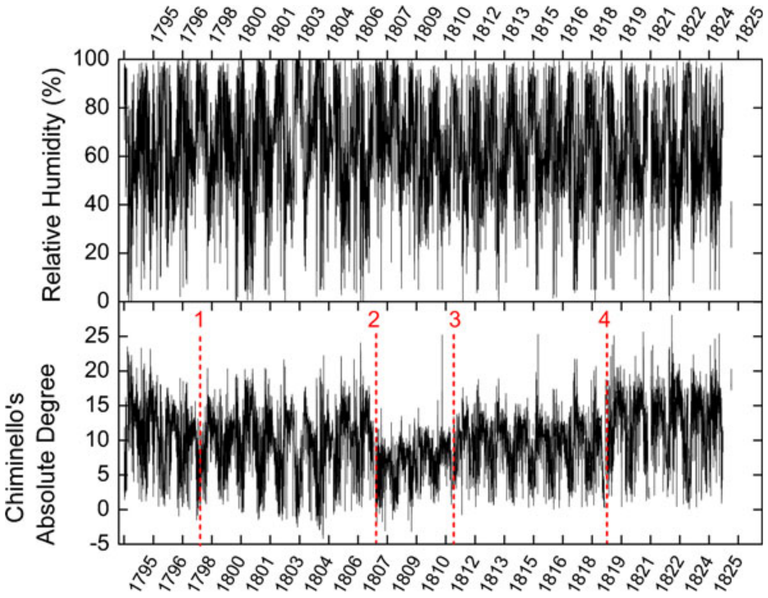

Fig. 3 1794–1826 relative humidity record observed in Padua. Top: the record after correction, homogenization and transformation in modern % unit. Bottom: original readings expressed in Chiminello's Absolute Degree. Discontinuities in March 1797, June 1806, March 1811 and October 1818 are highlighted

substitution of an aged quill with a new one. The uncertainty of calibration explains the different ranges. From these discontinuities we know that the first quill resisted 2.5 years, the second 9 years, the third 5 years, the fourth over 7 years and the last 7 years. The 1794–1797 period cared by Chiminello has good quality. The 1797–1806 period includes negative readings and an increasing trend in high readings frequency with the consequence of underestimating dryness. The 1806–1811 Bertirossi-Busata's period has an increasing trend and a narrow range, for a too high fireplace temperature during calibration. This caused a compression of the scale towards the bottom (i.e. dampness), underestimating elevated readings (dryness). The 1811–1818 period with a sensor installed by Bertirossi-Busata has a narrow range with the same consequences. The 1818–1826 Santini period has good quality.

A correction was made for inaccurate calibration (i.e. change of scale), or quill ageing. Quill ageing may lead to opposite behaviours. If the quill was too scratched, its fibres do not resist to the mercury pressure, and the internal volume will increase lowering the mercury column and generating a trend of decreasing dryness frequency. As opposed, if the quill was not scratched enough, the external fibres become rigid and shrink reducing the pocket volume and raising the mercury level in the tube with an apparent increase in dryness. Drifts generated an apparent shift from dryness to dampness. Long-term drifts were due to ageing of the scratched quills. Another cause of drift was mechanical. The glass tube was gently fastened to the frame with an iron wire; the wood shrinkage loosed the fastening and the heavy glass with mercury slipped down (Camuffo and Bertolin 2012). The scale was drawn on the frame and the tube slippage caused negative readings when the mercury column dropped below the 0 ABS level that corresponded to saturation. Fortunately water vapour saturation is an easily recognizable threshold and, per each period, the ABS readings were linearly corrected to move back the tube, or compensate for the quill ageing, by establishing once again 0 ABS as lowest limit to readings. As opposed, the upper ABS limit is not recognizable with a precise physical threshold, but the upper calibration limit, i.e.

32 ABS, corresponds to about 5-10 % RH modern units. In Padua extremely low RH levels are sometimes reached in winter when arctic or continental polar air blows, or in hot summer afternoons after some weeks without precipitation. It is realistic to suppose that in each recording interval (6 to 10 years) the upper limit (5-10 % RH) should be reached a number of times. Similarly, readings were corrected to reach the upper ABS limit too.

The transformation from Chiminello ABS into modern % RH units was made cross comparing the parallel observations made with the goose quill and the hair hygrometer for the 1812–1826 common period (See fig. 1 in Online Resources 2). By considering the uncertainties of the goose quill and the hair hygrometers, as well the early calibration, we can assume 10 % overall uncertainty.

5 Indoor or outdoor readings?

The original registers are still kept in the library of the Specola. They specify that observations were made in the still visible Meridian Room, 17 m above ground level. At that time the Specola was on the outskirts of the town: now the town has expanded and is in the city centre. The thermometer was kept out of the window, the barometer with another thermometer was indoors, but no mention is made whether the humidity observations were made indoors or outdoors. The hygrometer was not resistant to rainfall. It was certainly kept indoors but the observers might have temporarily exposed it outside at the sampling times. Alternatively, following a common practice, they created outdoor conditions with ventilation, opening windows in opposite sides of the room. In order to ascertain the “indoor” or “outdoor” character of the historic observations, per each of the three sampling times we made a comparison with the corresponding reading over a 8-year record (2000–2007) that we took with a standard weather station at 10 m height on a mast located in a area at the border between town and countryside (i.e. the CNR campus), to simulate the early situation at the Specola. The 0-100 % range was subdivided in 20 intervals, each with 5 % width, and we analyzed the frequency distribution of the RH readings, as follows.

(1) The determination coefficient R^2 was calculated for the frequency distributions of the historic series and the modern series of outdoor RH readings; the same was made but with indoor readings. The R^2 value calculated with outdoor readings was much higher than for indoor readings.

(2) Indoor and outdoor RH frequency distributions have different features. The indoor range is narrow, and the outdoor range is 0 to 100 %. Saturation is frequent outdoors, especially at night-time, but hardly reached indoors (except in damp rooms). Damp rooms are easily recognized because the RH range is narrow and limited to high levels. Outdoor RH is characterized by cycles with maximum during night and minimum in the early afternoon.

(3) Indoor readings have lower variability compared with the external ones, being damped by the building envelope (Camuffo et al. 2013). A test was made on the day-by-day variability, i.e. comparing the standard deviation (SD) of the difference between the RH level of each day and that of the previous one, at the same sampling time. The SD was calculated for the historic record, the outdoor and the indoor modern records.

All the three tests arrived to the same conclusion: the historic record was based on external observations.

6 Past, present and future RH

The distribution of the outdoor RH sampled at 7:00, 15:00, 21:00 in the 1794–1826 period and today (i.e. 2000–2007) are reported in Fig. 4. The main difference was found in the early afternoon, i.e. 15:00 h, when the daily maximum temperature is reached, showing that today

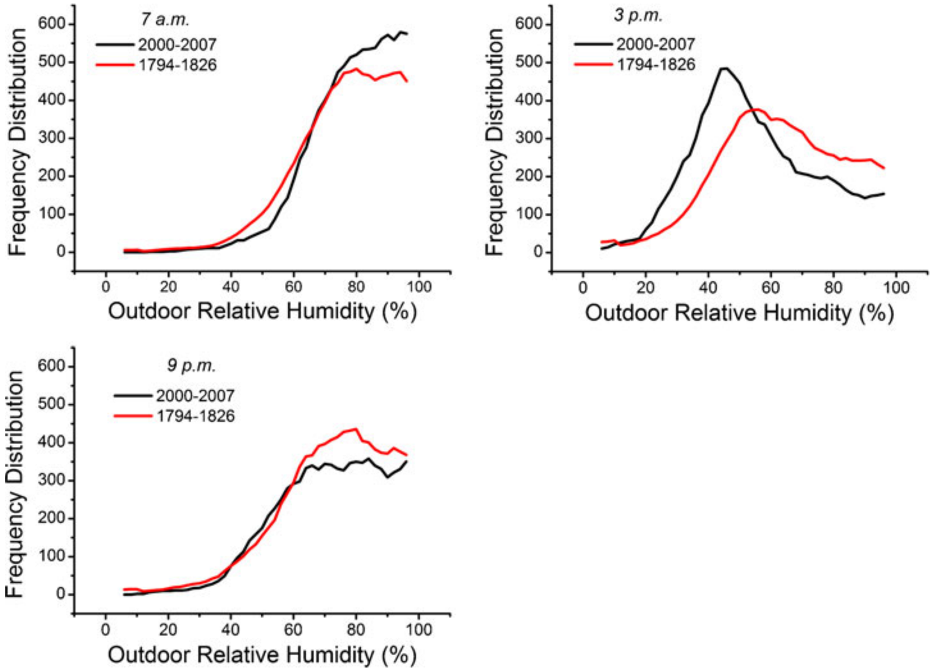

Fig. 4 Outdoor relative humidity (RH) levels sampled at 7:00, 15:00 and 21:00 in the 1794–1826 period and today (i.e. 2000–2007). At 15:00 the RH minima are lowered for two reasons, i.e. the larger urban heating experienced today and the increased roughness of the city that favour vertical air exchanges and mixing

the RH minima are lower. This can be explained because the urban heat island increased in size and roughness. The vegetated area has been reduced, the growth of the town from almost 50,000 to 200,000 inhabitants increased heat trapping and vertical air mixing. The upper air has lower moisture content and vertical mixing removes moisture from the near surface layer (Camuffo and Bernardi 1982).

A comparison of RH distribution over the calendar year in the 1794–1826 historic period and the 1961–1990 reference is reported in Fig. 5

From the two figures we see that the historic and the modern distributions differ for a reduced range in the historic period, especially in the cold season, when dryness was less frequent. This could be explained as an observational bias because the instruments were hung to the North-facing wall that was colder than air, possibly influencing readings. In the mid seasons and in summer the situation changed with a more correct average but a better balance of both extremes. This can be justified by the slow response time of the goose quill sensor. As already mentioned, the observations were taken with the instrument in air current and the ventilation might have been kept for insufficient time to reach equilibrium, missing extremes. It is useful to remind that the suggested time for calibration was 4 h to reach equilibrium. Summer had the best average: this can be explained with a better, continuous ventilation that in pleasant in a hot, humid climate exceeding 30 °C at RH around 70 %.

The 2011–2040 near future and the 2071–2100 far future scenarios have been calculated using the ENSEMBLES model that is a flow-dependent forecast in form of predictive probability distributions. It comprises multiple runs of numerical weather prediction models, which differ in the initial conditions and/or the numerical representation of the atmosphere. In

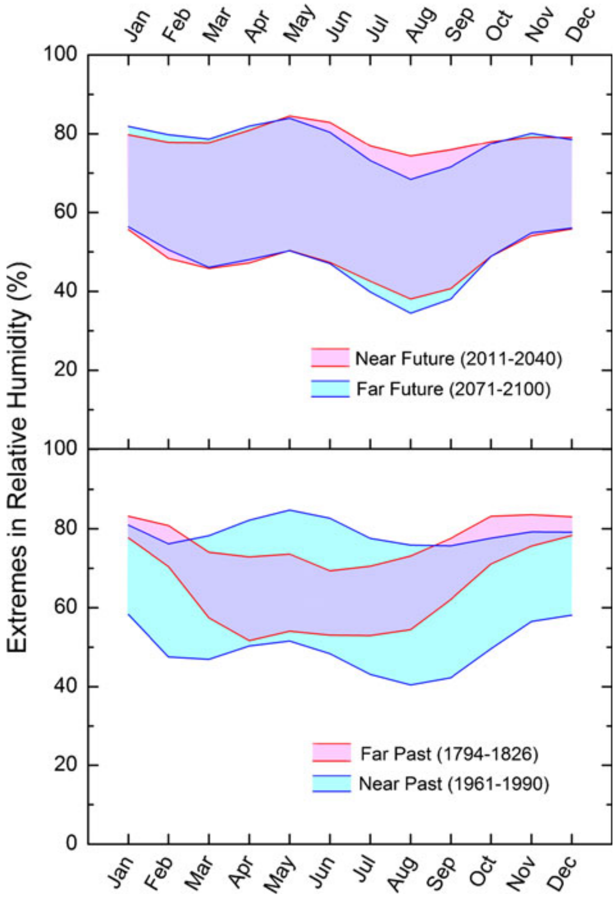

Fig. 5 Relative humidity distribution during the calendar year over a 30-year period. Top: simulation for the near future (2011–2040) and far future (2071–2100) scenarios. Bottom: 1794–1826 historic readings and 1961–1990 reference period

the framework of the EU funded Climate for Culture project, the Max Planck Institute for Meteorology produced the RT2B seasonal cycles per each decade up to 2100 that have been utilized in this paper to perform the regional climate change simulations over the Padua area. Both scenarios show that in winter and spring RH will remain almost unchanged in comparison with the 1960–1991 reference period. In autumn and especially in summer, the RH will maintain the same variability but about 7 % lower. The 2071–2100 scenario shows a small decrease in summer humidity levels.

7 Conclusions

This paper has analyzed some exceptionally rare historic records of relative humidity from 1794 to 1826, simultaneously taken with a Chiminello goose quill hygrometer and a de Saussure hair hygrometer. Although both sensors were constituted of the same protein, i.e. keratin, technical solutions and instrumental performances were different.

Chiminello won the prize of the *Theodoro-Palatina Academy of Sciences*, Mannheim, for the most comparable instrument but, notwithstanding all efforts and many clever solutions, the readings were far from having absolute values that transform peculiar readings into comparable humidity levels. Most of the problem consists in some weakness of the calibration, especially for the dry reference points. However, from a long record it is possible to correct the calibration scale and obtain reasonably accurate data, e.g. in the ±5 to ±10 % interval, making reference to the statistical distribution of data that should be included in the 10 to 100 % range.

It has been possible to cross compare the historic data from the quill and the hair hygrometer, and in addition to the information derived from the historic literature it has been possible to build a replica of the goose quill hygrometer to study in the lab the calibration problems and to know the synergistic effect of temperature and relative humidity. In particular, the temperature dependence of readings follows parabolic equations, with coefficients increasing with the humidity level.

The study has not only clarified a rather unknown instrument, but has shown how to proceed in the recovery and analysis of early historic observations. The climate change since 1794 and the calculation of future scenarios have shown that in Padua the main RH changes happened in the past, but the apparent change is in part explained in terms of urban heat island, instrumental and observational bias. No mayor RH changes are expected for the future, except for some increased dryness in August. This information is relevant for the conservation of cultural heritage sensitive to humidity-induced shrinkage or swelling.

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Online Resource 1

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Short History of Hygrometers

Operating principles of the main types of hygrometers from the 15th to 18th century

1. Weight change.

The earliest hygrometers were invented in the 15th century by **Nicolaus Cusanus** (1565 posthumous), **Leon Battista Alberti** (1485) and **Leonardo da Vinci** (born 1452- died 1519). The principle of the absorption hygrometers was weighing samples of some hygroscopic materials (see Fig.1) , e.g. seeds, cotton, wood or sponges. The methodology based on precise balances was convenient for the earliest period, but later abandoned being substituted by better instruments.

Fig. 1 Absorption hygrometer: a balance was used to detect changes in weight of a hygroscopic sample (D'Alancé 1707)

2. Condensation.

Another methodology was based on the condensation of moisture on a cold surface and at the mid of the 17th century the **Grand Duke of Tuscany, Ferdinand II** with **Evangelista Torricelli** invented a hygrometer based on condensation of moisture on a brass cone filled of ice as in Fig.2 (Magalotti 1667; Targioni Tozzetti 1780). Water resulting from melted ice was drained out. Condensed water dipped and was collected in a graduated glass vessel.

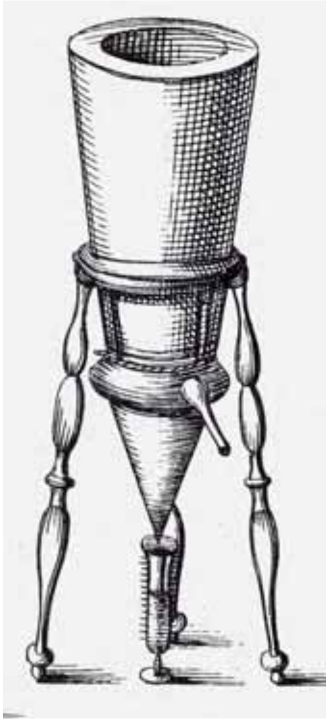

Fig. 2 Condensation hygrometer by the Grand Duke of Tuscany, Ferdinand II and Evangelista Torricelli (Magalotti 1667; Targioni Tozzetti 1780)

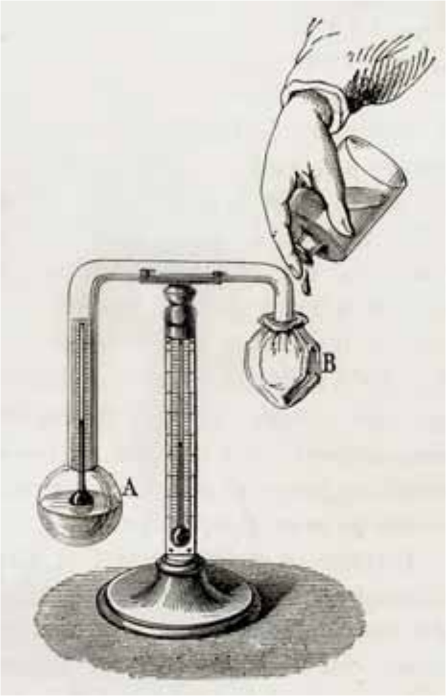

Fig. 3 Daniell's dew-point hygrometer (Ganot, 1860).

John Frederic Daniell (1823) devised a condensation hygrometer to recognize the dew point. He built a closed glass system terminating in two bulbs, one covered with muslin, the other of black glass, and containing ether and a thermometer (Fig.3). Ether being poured on the muslin, the black ball, cooled by the evaporation of the ether within, is soon covered with dew. The inside thermometer gives the dew-point. From the dew point and the air temperature one calculates the relative humidity. This device was the ancestor of the modern chilled-mirror dew point meter, i.e. the most accurate laboratory instrument to measure humidity and to perform calibrations of other instruments.

3.Linear dimensional change or torsion.

In the everyday practice it was observed that paper, leather, wood and other hygroscopic substance shrink when humidity drops and swell when humidity increases; similarly cordage and catgut are shortened and untwisted by moisture. In 1626, for medical purposes, **Sanctorius Sanctorius** (1626) invented hygrometers based on the change in length of a ballasted cord (Fig.4). A cord was stretched horizontally on a wall, and from its centre a ballast ball was suspended. When the relative humidity increased, the cord was tightened and the ball was lifted.

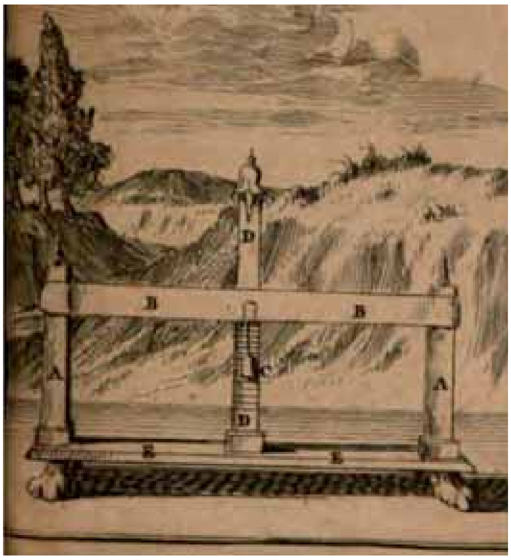

Fig.4 (a) Sanctorius hygrometer based on change in length of a cord ballasted in the middle. This model is very similar to the string hygrometer by Folli and Viviani (D'Alancé, 1707)

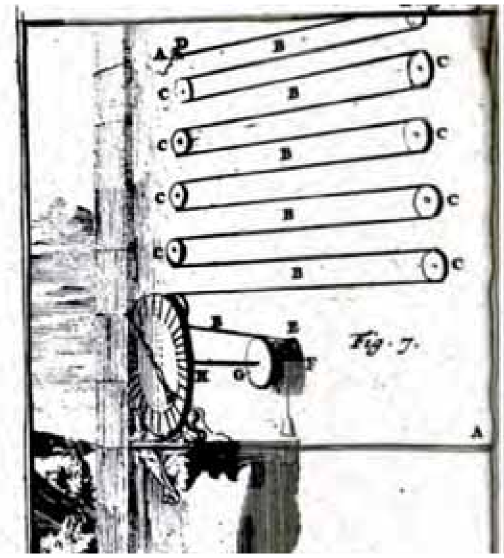

Fig.4 (b) A long cord is fixed at one extreme and is ballasted at the other one. A number of pulleys fixed to the wall reduce the total length from linear to bi-dimensional. The ballasted rope drives a rotating pointer (D'Alancé, 1707)

Fig. 5 Twisted cord hygrometer with rotating pointer built improving the idea by Sanctorius. (D'Alancé, 1707)

Another related methodology devised by Sanctorius was based on the torsion of a twisted cord connected to a pointer (Fig.5). Fixing one extreme to a wall and the other to a pointer, the pointer rotated with the humidity changes.

In 1663 **Robert Hooke** made attempts to employ catgut and "beard of a wild oat, advancing and returning according to the dryness or moisture of the weather" (Birch 1756).

Around 1664 **Giovanni Francesco Folli** and **Vincenzo Viviani** devised two types of string hygrometers based on the elongation of a paper ribbon (Fig.6). However the paper was easily broken and soon substituted with a leather strip. The physical principle was the same as the Sanctorious hygrometer. In the first type the ribbon was weighted in the middle with a small pointer. Dry air causes the paper ribbon to shrink raising the pointer, while humid air causes it to stretch lowering the pointer. In the second type the ribbon was fixed at one end of a wooden tablet and was tight with a small ballast fixed to the other end. Changes in ribbon length displaced the ballast level or drown a pulley with a pointer that rotated over a circular graduated scale.

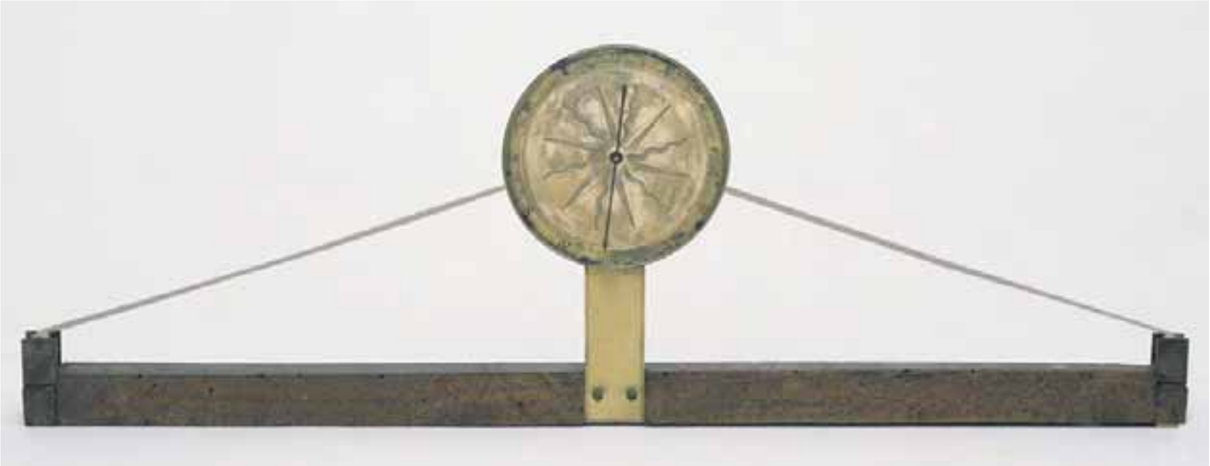

Fig. 6 String hygrometer by Folli and Viviani with rotating pointer.
By courtesy of Museo Galileo- Institute and Museum of History of Science, Florence.

In 1772, **Johann Heinrich Lambert** (1769,1772,1774) built an improved catgut hygrometer.

In 1783 **Horace-Bénédict de Saussure** (1783) invented an instrument made with a hair wound on a cylinder connected to a pointer (Fig.7), the father of the most popular hair hygrometer, see text

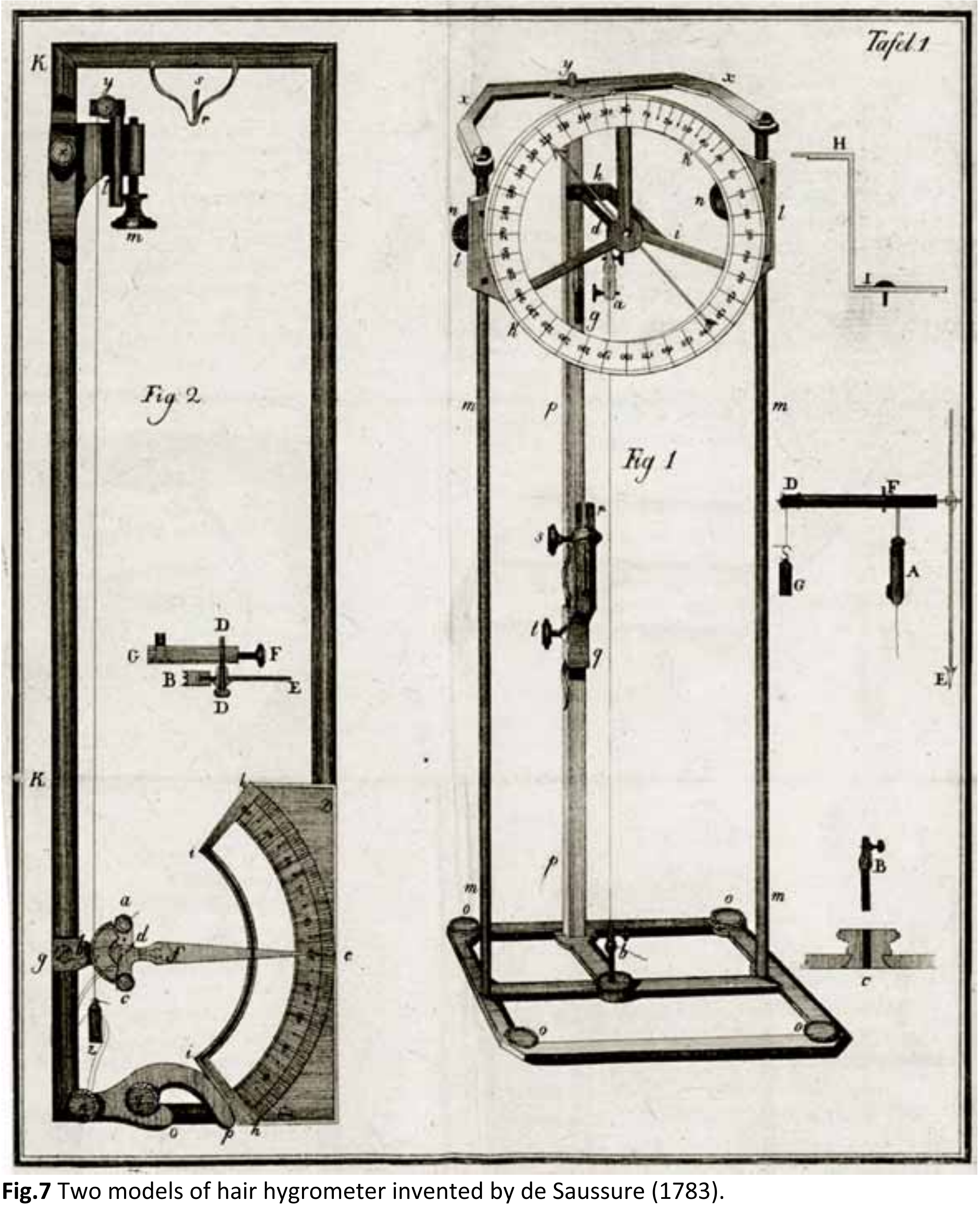

Fig.7 Two models of hair hygrometer invented by de Saussure (1783).

A summary of the above instruments is given in Fig.8 that is a table by Father Louis Cotte (1788)

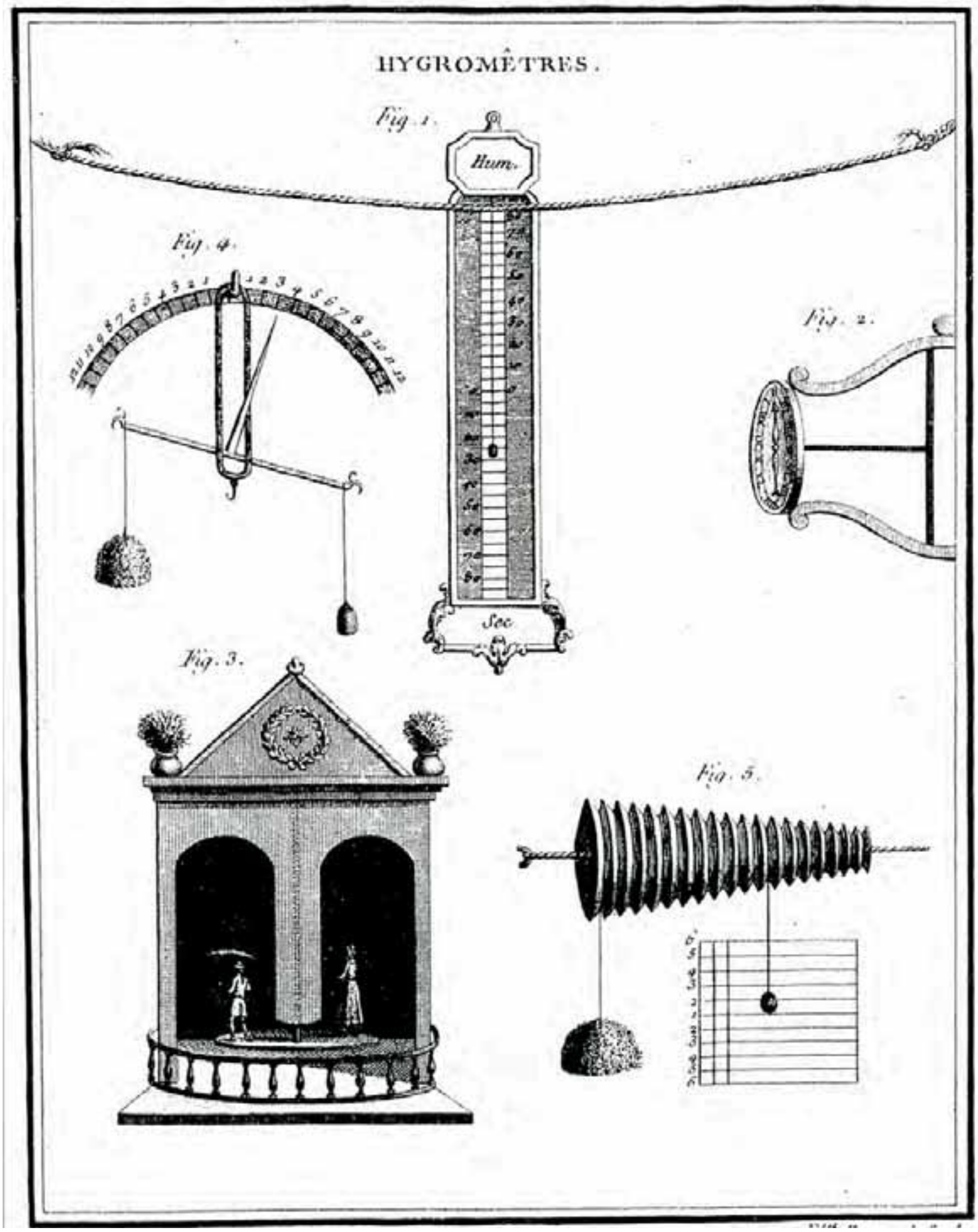

Fig.8 Internal Fig1: Cord expansion hygrometer with ballast suspended in the middle and graduated scale on the back. Internal Fig.2: Twisted cord and rotating pointer. Internal Fig.3: Twisted cord rotating a man with umbrella for humid and a lady for dry weather. Internal Fig.4 A hygroscopic specimen looses or absorbs moisture changing weight and rotating a pointer. Internal Fig.5. A hygroscopic specimen changes weight and changes equilibrium on a conical pulley (equivalent to a balance) moving vertically the ballast at the opposite end. (Cotte, 1788).

4. Volumetric change and the Bulb hygrometers

4.1 Wood

Only a limited number of hygrometers based on volumetric changes were devised. An approach was made noting that wood shrinks at low RH and swells at increasing levels. Following this principle, a hygrometer was developed to monitor such dimensional changes and transform them into a rotation of a pointer on a circular scale (Fig.9).

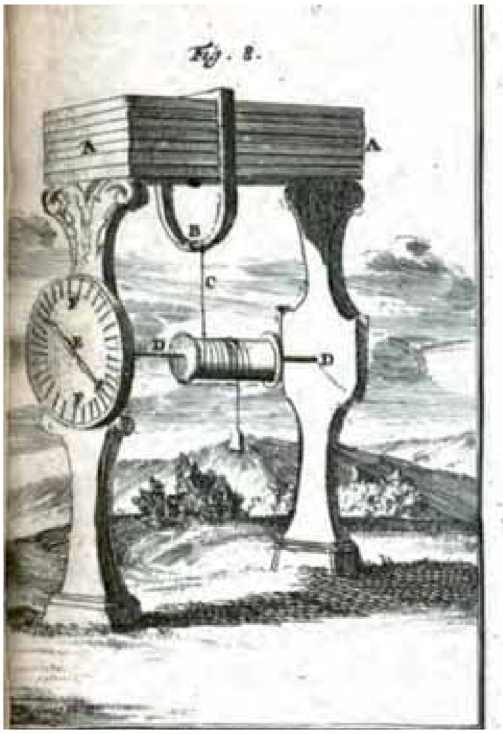

Fig.9 Volumetric hygrometer based on wood shrinkage and swelling. (D'Alancé, 1707).

4.2 Leather, horn, ivory

In 1687, **Guillaume Amontons** presented to the Académie Royale des Sciences, Paris, a hygrometer composed of a vertical glass tube, 3 feet long, and at the bottom he applied a leather bag filled of mercury. When air was moist, the leather bag expanded and mercury descended in the tube (Amontons 1685, 1695; Berryat 1754). The bag with the mercury moved the interface level of two immiscible liquids up and down in the tube.

Later he substituted a horn to the leather bag. The horn sensor was more resistant but increased the time of response (Berryat 1754). However, the general problem was that the mercury in the bulb and the tube responded to temperature as it were a thermometer. The hygrometer needed temperature correction that was realized a century later.

In 1773, **Jean André de Luc** (de Luc 1773-74) improved the horn hygrometer invented by Amontons and built the bulb with an ivory cylinder (Fig.10). This instrument was similar to a thermometer but with an ivory bulb, filled of mercury and with a thin glass tube. The choice of ivory was suggested by the possibility of working accurately the hollow cylinder, with homogeneous material composition and precise final shapes. This was an expensive, slow response, but an almost reliable instrument, and in 1774 it won the prize of the Academy of Amiens, although it had problems in correcting the temperature dependence (Cotte 1788). De Luc later developed another type based on a whalebone sensor.

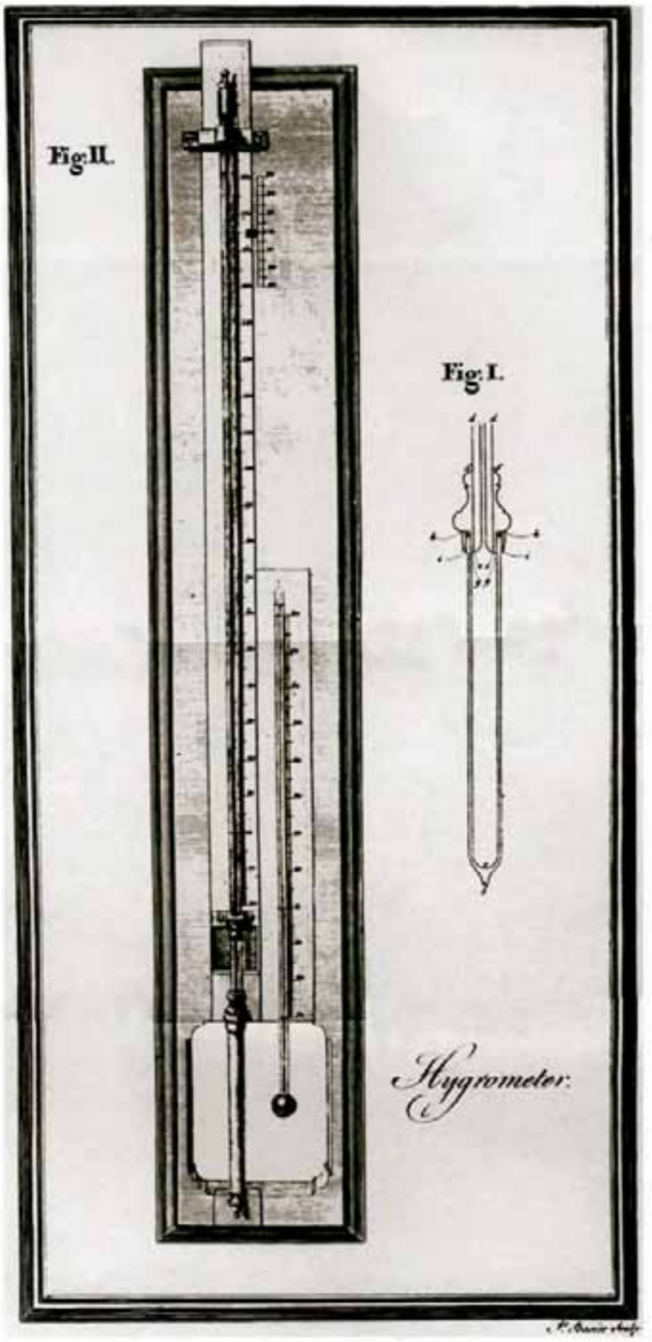

Fig. 10
Internal Fig.II: The de Luc hygrometer (left side) fixed on a wooden frame together with a mercury-in-glass thermometer. The two bulbs had different size and shape.

Internal Fig.I: An expanded detail of the cylindrical ivory bulb.

(De Luc, 1773-74)

4.3 Goose quill

Some time later, Noel Retz (Retz 1779; Retz and Held 1786) thought to substitute the expensive ivory with a cheap feather. In practice, feathers are made out of keratin, the same protein found in hair or horn, and for this reason the horn, hair and feather hygrometers have this protein in common. Retz considered that the quill was resistant to the mercury pressure with negligible drift, with the advantage of low cost and easy preparation (Chiminello 1785). The problem was that Retz made an empirical scale and was unable to provide an accurate calibration to take into account both the temperature and the humidity dependence, and the comparability of the readings with other instruments was also difficult because it was dependent on the peculiar characteristics of each quill and how it was worked, i.e. scratched and annealed. The study of how to solve these negative aspects was the innovative contribution of Chiminello (Fig.11).

Fig.11 Original Chiminello's weather station kept at the Botanical Garden of the Padua University, composed of Réaumur thermometer, Torricelli cistern barometer and goose quill hygrometer. Details of the bulbs and the top of the tubes. Please note that the bulb thermometer and the quill have almost the same volume, and that the capillaries of these two instruments are identical and located side by side to make the temperature correction easier.

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Online Resource 2

Article Title: Early hygrometric observations in Padua, Italy, from 1794 to 1826: the Chiminello goose quill hygrometer versus the de Saussure hair hygrometer

Journal name: Climatic Change

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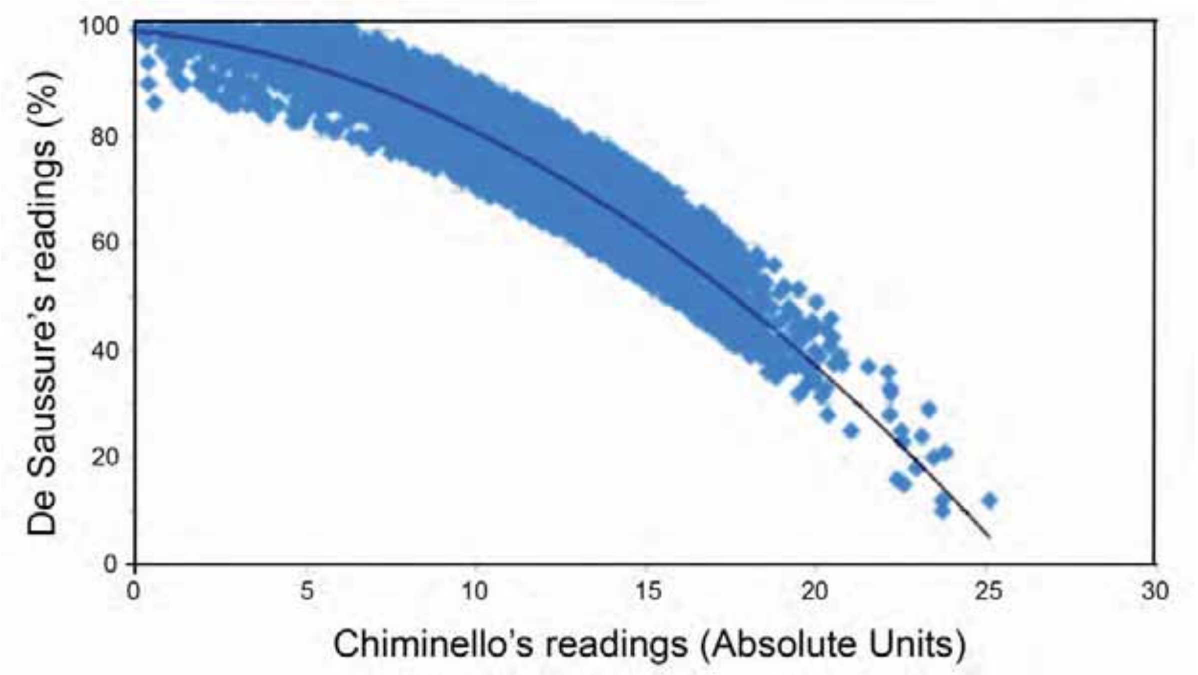

Fig.1 The transformation from the Chiminello's humidity readings (made in Absolute Unit) into modern % unit. The transformation was possible after a cross comparison between the parallel observations made with the Chiminello's goose quill and the de Saussure hair hygrometer for the 1812-1826 common period.