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From time frames to temperature bias in temperature series

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Abstract
The article offers an overview of the time frames used in instrumental series and how to transform them into modern units. In the early instrumental period, time was measured with sundials or mechanical clocks regulated every day with the culmination at noon, making reference to the apparent solar time (AST) and the local meridian. Every day had a slightly different duration, start, and end for the apparent changes of speed of the Sun. When canonical hours were used, hours were computed starting from twilight. In the late eighteenth century, the start was established at midnight. In the mid-nineteenth century, when precise clocks were available, it was possible to adopt an average time, with all days having the same duration, but related to the local meridian. A further step was to unify the time of all cities of a country adopting the time of the capital. Finally, the interregional rails, the telegraph, the telephone, and the international contacts required to unify the different time frames. This lead to the creation of the Coordinated Universal Time (UTC) and the time zones (TZ). The change from AST to UTC introduced two important time differences: one related to the variability of the apparent solar motion and one related to the longitude of the site. Instrumental records, especially the longest ones, are affected by changes in time frames that may cause bias. In this paper, the time changes of 92 selected European cities when they passed from AST to Western European Time, Central Europe Time, or Eastern Europe Time, are considered, and the departures during the calendar year are calculated. Moreover, the bias in temperature derived from the time frame change has also been evaluated in ten case studies over Europe. This paper will assist historians and climatologists to recognize and correct the time departures that affect meteorological series concerning temperature, barometric pressure, and other variables with daily cycles. This correction is crucial to assess climate changes. Specific aims are as follows: to make a friendly explanation of the methodology to pass from old time frames to UTC; to provide transformation equations to remove the bias for the time difference; to pass from time difference to temperature bias to homogenize early records with modern ones.

Keywords Measuring time · Early meteorological records · Observational bias · Correction of temperature series · Air temperature · Climate change · Apparent solar time

1 Introduction

The recovery, correction, and study of early instrumental series, and especially temperature, need a careful homogenization procedure to remove time bias before the historical data are compared with the modern ones to detect climate changes. Early instrumental series are generally based on one, or a few readings taken at selected hours of the *apparent solar time* (AST) read on a local sundial or a clock regulated on the solar culmination. A method to compare early datasets is to reconstruct daily averages, or the average temperature at selected hours of the day, and then compare these values with the corresponding ones from modern datasets. In rare fortunate cases, early observers measured temperature at the particular moment of the day in which the temperature equals the daily mean or is very close to it (Glaisher 1848; Arago 1858). In general, early instrumental records need a long and careful correction work to calculate the daily average or even the average temperature at the particular hours selected by the observer. The amount of the correction varies with the geographical position of the site, the hour of the day and calendar day, and the time frame adopted by the observer. Therefore, it is crucial to know exactly the observing time and the time reference system used in ancient measurements in comparison with modern ones. The transformation to modern reference time consists of two components: a fixed value due to the longitude of the location, and another seasonal one, related to the irregular apparent Sun motion. Finally, the temperature correction requires adding or subtracting the temperature change that occurs during that shift of the reading time, in that specific location, over the calendar year. The same issues also apply to clock-hour barometric pressure means and other quantities with clear diurnal variation such as solar radiation, humidity, and wind speed.

In the literature, the role of radiative processes in meteorology and climatology (Paltridge and Platt 1976) is well known, and the errors generated from biased estimation of the incoming radiation are considered in surface temperature forecasts and analysis (Morcrette 2000; Bilbao and de Miguel 2007; Kjaersgaard and Cuenca 2009; Manners et al. 2009; Alados et al. 2012; Hogan and Bozzo 2015; Zhou et al. 2015). In contrast, when temperature series are recovered, the change of the reference time frame, and the related change of energy balance, is generally disregarded or partially corrected. An interesting example concerns the early records in Switzerland where the time conversion was made considering the geographic longitude (Brugnara et al. 2020a, b), but neglecting the additional contribution for the uneven motion of the Sun. As another example, the meteorological series of Hohenpeissenberg, Germany, located 11° longitude east, with readings taken three times a day was revised and corrected for some bias (Winkler 2009), but without considering that the originally scheduled time was 7, 14, and 21 h AST. If that sampling time was read with a modern clock, it would have been 6:30, 13:30, and 20:30 h, i.e., 30-min difference, causing appreciable temperature bias in summer.

In a series, if the time of observation remains constant over the years, there is an error but this systematic bias will not generate spurious trends in the data analysis. As opposed, changes in the observation time may lead to spurious trends and compromise the study of weather variability as it has been recognized with the US Historical Climatology Network dataset (Menne et al. 2009; Rischard et al. 2018).

When a time frame changes, any correction requires sound knowledge about the history of the series and its metadata, not always available, and about spherical astronomy as well. Only in a few case studies, the astronomical and geographical factors and the related temperature change rate (°C/h) have been considered and the related bias has been calculated and corrected, e.g., Padua 1725–2000 (Camuffo 2002), Verona (Andrighetti et al. 2009), Florence 1654–1670, and 1751–1766 (Camuffo and Bertolin 2012; Camuffo et al. 2020a, 2021), Bologna 1715–1815 (Camuffo et al. 2016, 2017), and Paris 1658–1660 (Camuffo et al. 2020b). The topic is particularly relevant not only when one needs to homogenize records that cover a couple of centuries, but also when studying decadal variability in short records, or for data assimilation in historical reanalysis.

This paper is aimed to calculate the departure between AST and the official times adopted in various European countries; to evaluate the temperature bias that may derive from that departure; finally, to make a friendly explanation of the methodology that may be followed even by people not familiar with astronomical calculations. This will be achieved through the following steps:

i) to make a review of the time frames used in instrumental series and provide the equations to transform them into modern units.
ii) to calculate the difference in time between a local sundial (AST) and the modern reference time used in Western, Central, and Eastern Europe, with 92 European cities taken as examples.
iii) to show how the difference in time may be related to a bias in temperature, with ten case studies.

This work will help historians and climatologists to assess a precise link between old sundial time and modern reference time; to make a correct conversion from old to modern time units; to apply the due temperature correction when early instrumental records are recovered and analyzed; to avoid bias in assessing climate changes.

2 Overview of the time frames used in instrumental records and their conversion

2.1 Sundials, daily hours, and apparent solar time

Since Egyptian and Babylonian antiquity, time was measured using the Sun as a reference. In the first century BC, the Roman writer Vitruvius, in his books *De Architectura* (Book 1, Chapter 6) explained that Roman cities and military camps were built following precise regulations, like solar clocks, with north-south oriented streets called *cardo*, and east-west called *decumanus*. With this precise compass orientation, all buildings on the *cardo* had the eastern side walls illuminated in the morning and vice versa in the afternoon. In the morning, the road surface of the *cardo* was shadowed on the eastern side; at noon, all shadow disappeared; in the afternoon, it was on the opposite side. In the important cities, the main square, i.e., the *forum*, had an obelisk that acted as an enormous gnomon and at noon, the shadow was shortest and pointed to the north, in the *cardo* direction. Practically, the city acted as an enormous urban sundial that regulated activities. The historical center of several European cities still preserve the ancient Roman structure and until the late Middle Age, their inhabitants took advantage of this particular feature.

Sundials were very popular shadow clocks, either horizontal or for walls. The ancestor of all weather stations was the octagonal Tower of Winds in Athens, built by Andronicus of Cyrrhus in 50 BC, composed of eight sundials, one for each wall, and on the top an artistic triton acting as wind wane, that pointed at the names of the eight cardinal winds. Time and weather were considered strictly connected. At the end of the sixteenth century, a treatise (Pini 1598) taught how to build sundials and wind vanes, and establish them on tall columns, to be visible from all sides.

Sundials (Finé 1532; Pitati 1570; Astolfi 1823; Abetti 1876) were based on a shade projected by a protruding rod, called *gnomon*. A particular reference is the solar culmination, i.e., noon, that occurs when the gnomon shade (Fig. 1a), or a spotlight passing through a hole in the gnomon (Fig. 1b), falls on the meridian line, and the a.m. and p.m. hours are in opposite sides.

In ancient Rome, the daytime (from sunrise to sunset) was divided into 12 hours (*horae*), whose start and duration varied with the calendar day, and the nighttime in 4 *vigiliae,* each corresponding to sentry duty. Only at the equinoxes, the diurnal and the nocturnal hours had the same duration. *Horae* were measured with sundials (*solaria*) and *vigiliae* with water clocks (*clepsydrae*). The water clocks (Fig. 1c) were based on a pivot rotating around a horizontal axis, and the driving forces were the weight of a ballast on one side, and a changeable weight on the other side, constituted of a water vessel with a constant-rate discharge through a small hole or a siphon. The loss of water changed the equilibrium, forcing the vessel to rise, and the

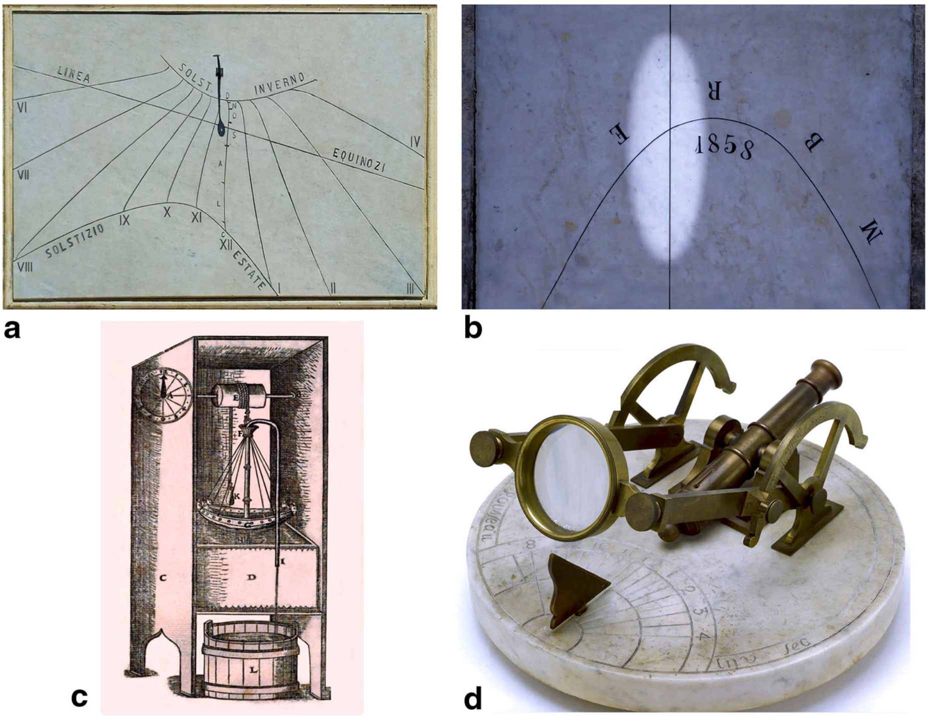

Fig. 1 **a** Wall sundial showing the gnomon shadow at 11:30 a.m. in September. Vertical lines with Roman numerals: hours 6 to 12 a.m. and 1 to 4 p.m. Upper curved line: winter solstice; diagonal line: equinoxes, lower line: summer solstice. **b** Pinhole spotlight crossing the meridian line on the floor of the meridian room at the winter solstice (courtesy of Museo della Specola, INAF, Osservatorio Astronomico, Padua). **c** A siphon water clock with ballast and rotating pointer (from Finé 1532). **d** Horizontal sundial with a miniaturized gun to announce noon, with a lens to fire the gunpowder, and two side goniometers to adjust the declination angle (courtesy of Museo Galileo—Institute of the History of Science, Florence)

time required for a cycle was 1 h. After, it was necessary to manually intervene to reset the system.

In the thirteenth century, with the advent of mechanical clocks, day and night hours were harmonized and the day was divided into 24 equal hours. The most precise mechanical clocks pointed out that there were some small differences between sundials and clocks, i.e., the time the Sun employed to return on the same position, later recognized and explained with the Kepler laws.

The most evident time frame provided by the nature was AST, perceived by direct observation. The specification "*apparent*" is borrowed from the common astronomical use; sometimes "*true*" or even "*actual*" are used, but less frequently. As the day was defined as the time elapsed between the Sun reaching twilight or culmination in two consecutive days, changes of the apparent solar speed for the Earth axial tilt and the orbital eccentricity affect the start and the end of every hour during the calendar year. This problem concerns all early instrumental observations, from the Little Ice Age to the mid-nineteenth century. The duration of the day is also affected, but is negligible to this aim, ranging between −22 s in September and + 31 s in December.

It should be specified that in the eighteenth century and the early nineteenth century, there were a few precise clocks outside astronomical observatories. The clock face was divided into 12 h, starting from midnight or midday. The majority of clocks for common use (including meteorological purposes) had poor performances and were generally adjusted looking at a sundial. In this period, clocks and sundials were different instruments but reported at the same time.

2.2 Canonical hours starting from twilight

In the Middle Ages, all Europe followed the *canonical hours* (CH) also called *Italian or Bohemian time*, based on AST, and the day started at twilight. Some countries, i.e., Italy, Poland, Bohemia, and Silesia, followed this tradition until the end of the eighteenth century. On the other hand, Spain, France, Germany, the UK, and other countries started the day from the upper solar culmination (noon) or the lower culmination (midnight). However, the early use of CH is also documented because some tower clocks survived, with gears making reference to twilight, i.e., Croatia (St Ignatius Church, Dubrovnik), Portugal (National Palace, Mafra), and even the UK (Hampton Court astronomical clock, London). In the specific case of international networks, e.g., Medici Network (1655–1670), Royal Society, London (1724–1735), Royal Society of Medicine, Paris (1777–1786), and *Societas Meteorologica Palatina*, Mannheim (1781–1792), all the observers had to note the hour and the date complying with the protocol established by the organizers, independently of the local clock and calendar (i.e., Julian or Gregorian calendar). Other exceptions may be found when the observers were members of a foreign academy or were willing to publish in some specific journals.

The particularity of CH is that the day died with its light at twilight, accompanied by the bell tolling for the Compline prayer. A day ended and the next began. The value of the hour representing midnight or noon, or any other selected time except twilight, changed over the calendar year. By canon law, clergy had every day seven specified times appointed for prayers and were charged with the task of ringing bells, announcing each hour with a number of tolled strokes equal to the hour. This constituted the official time of every local community.

A technical problem was the identification of the instant of passage from a certain day to another because twilight has not a well-defined transition from light to darkness, especially in the case of mist, clouds, or precipitation. Twilight occurs 30 to 50 min after sunset until the solar disk has completely dropped below the horizon and its light has been extinguished, depending on the actual atmospheric absorption and refraction, the season and geographical position.

Sunset may be found tabulated in astronomical or nautical almanacs reporting solar ephemerides; NOAA and other institutions report online and downloadable calculators for the local apparent time, e.g., https://www.esrl.noaa.gov/gmd/grad/solcalc/calcdetails.html; https://www.timeanddate.com/sun/.

Sunset may be calculated imposing that the height $H_\odot$ of the Sun above the local horizon equals zero, that is:

$$\sin H_\odot = \sin\delta_{\odot,j}\,\sin\phi + \cos\delta_{\odot,j}\,\cos\phi\,\cos\tau = 0 \tag{1}$$

where $\delta_{\odot,j}$ is the declination of the calendar day j, ϕ the latitude, and τ the astronomical hour angle transformed in time hours and tenths of an hour, i.e., $\tau = 180°\ t\ /12$. The t hours are calculated after the upper culmination, i.e., midday assumed as $t = 0$, $t < 0$ in the morning, and $t > 0$ in the afternoon.

The declination of every calendar day can be found in the almanacs reporting the ephemerides or may be computed with astronomical formulae. For meteorological purposes, the following simplified formula (Camuffo 2019) may be used:

$$\delta_{\odot,j} = -23.45\ cos\frac{2\pi(j+10)}{365} \tag{2}$$

The transformation of the time from CH starting from twilight t_{CH} to hours computed from midnight t_M, as in the modern use, is given by the equations:

$$t_M = t_{CH} + t_S + t_D \tag{3a}$$

$$t_M = t_{CH} - (t_S + t_D) \tag{3b}$$

where t_S is the sunset time and t_D the further time needed to reach the twilight darkness, i.e., 30–50 min. Equation (3a) holds for events that occurred in the evening after twilight, but before midnight and Eq. (3b) for events after midnight but before the next twilight. In the latter case, t_S and t_D should be calculated for the previous day.

Equations (3a) and (3b) depend on the latitude of the site and the calendar day. They are used to pass from CH to AST. In Padua (45° 24′ north; 11° 53′ east) the transformation of the reading times from CH to AST required to subtract from 3.5 h in summer to 7 h in winter (Camuffo 2002). It should be noted that the above equations are useful to provide the transformation of CH into a time frame with the day starting at midnight.

From the Middle Ages to the end of the eighteenth century, every city had its local time, starting at twilight and expressed in CH. Hours were announced by bells and were regulated with the apparent Sun or with help of clocks. Sundials responded with precision to the apparent motion of the Sun and could be corrected for the atmospheric refraction (Toaldo 1790). Sundials were considered preferable to clocks, except in case of cloud cover or precipitation when they had to be integrated with mechanical or water clocks, or burning candles with standardized duration.

2.3 The French time starting from midnight and clocks adjusted at noon with the apparent solar time

With the advent of mechanical clocks, it was possible to abandon the CH and start the day at midnight or midday. The choice was dictated by the ruler and the aims. For instance, in the civil use, it was convenient that all events that occurred during the diurnal period had the same date, which means to start the day at midnight; as opposed, astronomers preferred to note their observations within the same day, i.e., starting at midday. For instance, Captain Cook and his astronomer William Wales recorded the same time in different ways and switched when they entered harbor. Therefore, in the same locality, it may be possible to find records with time indicated for astronomical (or sailing style), or civil use. This may generate confusion and requires attention. In addition, a day could be divided in 24 h, or 12 + 12 h (from the lower or upper culmination), or even 6 + 6 + 6 + 6 h (hence the name *siesta* i.e., "the sixth hour", or nap at noon). A problem is that records, logs, and sometimes also official documents, like Hann (1874), omit to specify whether the hour is a.m. or p.m., or the day starts from noon or midnight. This requires caution when recovering data.

At the end of the eighteenth century, the use of clocks became popular in Revolutionary France where clergy and bells were not loved. When in 1789, Napoleon invaded Italy, he dismissed the religious orders, obliged to abandon CH, and pass to another time frame, nicknamed *French time* (Toaldo 1789a). The day was divided into 24 h, i.e., 12 h a.m. starting from midnight and 12 h p.m. starting from noon. This was part of the French metric revolution that abandoned the local units derived from Romans and substituted them with the decimal system, except time that preserved the duodecimal system for hours and months and, in addition, the sexagesimal system for minutes and seconds. Similarly, angles preserved the sexagesimal system. The transition from days starting at twilight to days starting at midnight (given by Eqs. (3a) and (3b)) was a cultural revolution, initially difficult to understand, because in the novel system the midday and midnight had always the same values, but twilight changed every day instead of being fixed.

The technology was poor, and most clocks were very imprecise and needed to be adjusted every day or within a few days in the case of persistent cloud cover. At the end of the eighteenth century, Toaldo (1789b) wrote that the main clock on the tower used as a reference for the clocks in the town should never be over an hour off, not even half an hour off within the space of a few days.

Ideally, clocks were adjusted every day at the culmination, i.e., when the Sun transited across the local meridian. In the most important astronomical observatories, there was a so-called *meridian room*, i.e., a dark room with a small pinhole or a slit on the south-facing wall, and a horizontal north-south line on the floor, representing the local meridian (Fig. 1b). When the solar beam passing through the small opening fell on the local meridian line, this was noon. In the cities where an astronomical or meteorological observatory existed, this was announced with a gun shot, flags, and other systems. Horizontal sundials with miniaturized cannons were produced to announce automatically noon in clear days when a lens concentrated the solar radiation on the vent hole and ignited the gunpowder. The lens needed continuous adjustment over the calendar year to follow the declination angle (Fig. 1d).

Canonical hours, *French time*, sundials, and clocks adjusted at culmination were all related to the apparent solar motion, as perceived by an observer. All of them responded to the real Sun, and only differed for the choice of the starting point of the day and the instrument used to read AST.

2.4 Unevenness of the apparent solar time: the equation-of-time and its departure from the mean time

Suppose to have a precise, modern clock: in this clock, 1 h corresponds to 1/24 of the average duration of all days over the calendar year, and all hours, as well as all days, have the same start and duration. This clock refers to a fictitious Sun representative of the average behavior of the apparent Sun and measures the mean solar time. If this clock is tuned to show 12 h at the average culmination of this fictitious Sun on the local meridian, it measures the *mean local solar time* (MLST), which generally departs from AST except for 4 days a year. The AST-MLST departure is represented by the so-called *equation-of-time* (EoT).

EoT may be defined in slightly different ways: the discrepancy between two kinds of solar time, i.e., AST and MLST; the departures due to the apparently uneven velocity of the Sun as perceived by an observer on the Earth in comparison with a clock; the time extent that the right ascension (celestial coordinate equivalent to longitude) of the apparent Sun departs from the fictitious mean Sun; the time extent that a sundial, or a clock adjusted every day at culmination, departs from MLST, represented by a precise clock. Finally, it can be defined in terms of the difference between AST and the modern UTC system.

The etymology of the name EoT needs clarification. The name "*equation*" does not represent the traditional mathematical statement consisting of an algebraic expression with a sign equal to relate two variables between them, but is a translation from the medieval Latin of the original definition that means the amount of time that every day should be added or removed to "*equate*", i.e., to become equal to, the fictitious mean day. Originally, it represented a table where astronomers noted, day by day, how much the sundial time given by the culmination was ahead or behind the mean time given by a precise clock, i.e., the difference between the apparent culmination of every calendar day, and the fictitious mean value.

EoT is explained in spherical astronomy textbooks and the daily values may be found in tabular form in astronomical or nautical almanacs reporting the solar ephemerides. It may be precisely calculated with the astronomical formulae reproducing the apparent solar motion and planetary perturbations (Zagar 1948; Woolard 1966; Hughes et al. 1989; Müller 1995). For meteorological purposes, where seconds are irrelevant, EoT (in minutes of time and decimals) may be calculated as a sum of the two sinusoidal components (Linch 2012) (Fig. 2), due to the orbital eccentricity and the obliquity of the rotation axis, that is:

$$\mathrm{EoT} = -7.65 \sin\frac{2\pi(j-P)}{n} - 9.86 \sin\frac{4\pi(j+D)}{n} \tag{4}$$

where j is the calendar day, $n = 365.25$ days the Julian astronomical year, and $2 \le P \le 5$ the perihelion calendar day (from January 2 to 5); in the second component, the winter solstice has been kept on 21 December which requires to add $D = 10$ calendar days.

The first factor (red line in Fig. 2) is a sinusoid due to the ellipticity of the Earth's orbit and ranges between ±7.66 min of time each year. The Earth moves on an elliptic orbit with uneven speed, being fastest in early January when Earth is at perihelion and slowest in early July when it is at aphelion. While the Earth makes a complete rotation around its axis, it moves along its orbit, and the additional rotation required by the Sun to face again the local meridian (i.e., local south) is slightly greater than 360° and employs a certain time. This time will be shorter or longer depending on the variation of the speed along the orbit. This effect gives a sinusoidal variation during the calendar year in which the true Sun appears behind or ahead of the fictitious average. The zero point is at perihelion and moves with it.

The second factor (blue line in Fig. 2) is also a sinusoid but with double frequency, due to obliquity because the Earth's rotation axis is tilted in comparison with the orbit (i.e., the ecliptic plane) and, consequently, the apparent Sun moves along the ecliptic whereas the fictitious mean Sun moves along the celestial equator. Over the year, the angle that the ecliptic

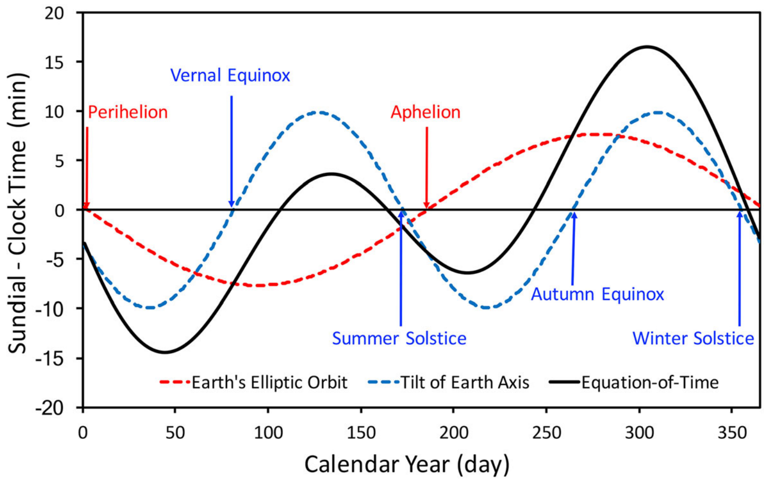

Fig. 2 The equation-of-time and its two eccentricity and obliquity components, i.e., the ellipticity of the Earth's orbit and the tilt of the Earth's rotation axis. Positive values when a sundial appears faster compared to a clock showing local mean time; negative when slower

forms with the plane across the Equator ranges within ±23° 27′. This effect is represented by a sinusoid with a 6-month period and amplitude ±9.87 min of time, in which the apparent Sun appears two times in a year faster (EoT > 0) or slower (EoT < 0), i.e., ahead or behind of the clock representing the fictitious mean. The zero points occur at equinoxes and solstices.

Combining the two effects, one obtains a swinging plot over the calendar year (black line in Fig. 2). The maximum negative departure occurs around calendar day 42, i.e., February 11, and the EoT value is −14 min 6 s; the maximum positive around calendar day 307, i.e., November 3 with EoT value +16 min 30 s. Leap years, as well as leap +1 year, leap +2 years, and leap +3 years, change of the perihelion date, change of the winter solstice, Moon perturbation, and atmospheric refraction will affect a little the mentioned dates (±2 days) and EoT values for ±20 s. The secular change accounts for some 20 s per century. Since the second half of the eighteenth century, the main astronomical observatories published the local ephemerides, making thus possible to perform the meteorological corrections on the base of contemporary evaluations of EoT.

2.5 Precise clocks and mean local solar time

In the industrial revolution, when precise clocks had been available, it was recognized that noon, i.e., the culmination related to AST, changed with the calendar day. Therefore, it was preferable to make reference to a fictitious Sun, with uniform motion, i.e., MLST. Zero hour, i.e., midday, did not coincide with culmination, except four times a year, i.e., around the calendar days 106 (April 16), 165 (June 14), 245 (September 2), and 360 (December 26). Of course, the day started when the fictitious mean Sun passed across the local meridian, and this time frame was representative of a narrow area around the selected meridian, e.g., a specific city.

In a country, every city had its own MLST, different from one city to another, depending on their geographic longitude λ. This was not a problem, at least until the interregional rails, the telegraph in 1848, and the telephone in 1861 appeared. On the other hand, there was an advantage: in all the cities of this country, the Sun culminated when the local hour was

12:00 h, the sunrise was seen to occur exactly at the same hour in all cities and the same for sunset. This means that the cities of this country had times not synchronized, the difference depending on λ. This difference could be relevant or even very relevant to the aims of this paper.

In Italy, from the 1850s and 1860s, a number of cities passed from AST of sundials to MLST of reliable clocks. Local mean times started unevenly in Europe and had a short life, i.e., one or a few decades.

2.6 From local to national time

When the international railway connections were started, and the telegraph lines were installed, and the telephone was adopted, it was necessary to pass from the local to the national scale, unify, and synchronize times. Every country established a common national time, measured with a precise clock, and in general the MLST of the capital was adopted for the whole country.

For instance, the telegraph lines in Italy were installed from 1847 to 1857, and all telegraph connections needed the same time frame. In 1866, after Italy was united into a single state, one of the first acts was the unification of the time frame over the country. The first choice was the MLST of Rome, with 12° 28′ 50″ longitude east (meridian of Monte Mario Astronomical Observatory). However, in 1893 the reference was changed to Mount Etna (15°, 0′ 14″ longitude east) that nearly coincided with the first meridian, 15° longitude east of Greenwich to comply with the UTC regulations discussed in the next section. The time difference was 10 min. Clocks were regulated every day at midday with telegraphic transmission from a central bureau in the capital to all the cities. In Rome, midday was also announced to citizens with a cannon shot and visual signals.

France used AST until 1891 and in 1891 passed to national time assuming the MLST of Paris. From 1911 to 1940, France adopted GMT + 0 h as official time. During World War II, the non-occupied southern part and the occupied northern part used different time frames, i.e., GMT+1 and GMT+2; this frame had repeated changes after the liberation in 1944. Finally, in November 1945, France passed to GMT+1.

In 1848, Switzerland adopted the MLST of Bern, i.e., GMT+0.5 (Wild 1862; Brugnara et al. 2020a). The additional value of 0.5 h is explained because Bern is 7° 26′ 50″ longitude east that corresponds to a time of 29.8 min with reference to the prime meridian, i.e., Greenwich.

Common national times had a relatively short life, in general from the mid-nineteenth century to 1884. The need to pass from a national time frame to an internationally coordinated time frame became evident after the West European Telegraph Union was founded in 1855, and the national meteorological services in the 1850s and 1860s.

2.7 The departure for longitude

When in the same country two sites are compared between them, if their longitudes are different, sunrise, culmination, and sunset will occur at different instants. Therefore, the geographic longitude λ introduces another departure (GL) that should be considered when a number of cities decided to synchronize their time.

When a site is located close to the reference meridian, GL is negligible. When a site is located at a certain longitudinal distance or even far from the reference meridian, this may cause marked GL departures, e.g., several minutes or even 1 or 2 h. The correction for λ is obtained considering that the time employed by the Earth to perform a rotation of 360 degrees of arc is 24 h, which accounts for 1 h difference every 15 degrees of arc of geographic longitude, that is a difference of 4 min of time every 1 degree of arc of longitude. Therefore, the equation to obtain the time deviation for GL (in minutes of time and decimals) is

$$GL = 4\lambda \tag{5}$$

where the longitude λ is measured in degrees of arc and decimals, avoiding the canonical sixtieth transformation, i.e., 1 degree of arc = 60 min of arc. Longitude east of the reference meridian is calculated with the minus sign; west with plus.

2.8 The globalization of time: coordinated universal time and time zones

The advent of the telegraph and the international contacts required that national times were homogenized over a wider spatial scale, involving a global geodetic revision. The need for a global coordination became clear at the Congress of Vienna in 1873, when the International Meteorological Committee was instituted, i.e., the ancestor of the World Meteorological Organization established in 1950. At the International Meridian Conference held in 1884 in Washington (IMC 1884; Pidwirny 1999), it was decided to take the Greenwich Mean Time (GMT) as an official reference. However, in 1967 the International Communication Union, the specialized agency for information and communication technologies of the United Nations, preferred to substitute it with the Coordinated Universal Time (UTC). The Earth was divided into 24 time zones (TZ), from UTC-12 to UTC+12. The zero meridian is Greenwich, and the reference time measured with atomic clocks instead of astronomic motions (Essen 1968; Bartky 2007). Numerically, there was not a sensible change, because UTC is almost coincident with GMT; politically, UTC avoids any preferential mention to specific locations. It should be mentioned that later, some other minor time zones were added to solve some specific problems, but such details are outside the aims of this paper. For weather measurements to be comparable between different locations, the observing hours should be common as far as possible and follow the time standards (Burt 2012).

The basic worldwide system that is currently used as a reference time frame is UTC that constitutes the primary time standard. UTC remains unchanged over the year and is not adjusted for daylight saving time. Europe is divided into time zones as follows (Fig. 3a). The 0th TZ includes the UK, Ireland, Iceland, and Portugal and uses the Western European Time (WET), which coincides with UTC, i.e., WET = UTC + 0. In the past, WET was named Greenwich Mean Time (GMT) because the reference is the Greenwich meridian assumed as a starting point. The 1st TZ, i.e., the Central European Time (CET), makes reference to the meridian 15° longitude east and is shifted by 1 h, i.e., CET = UTC + 1. It includes Spain, Andorra, France, Switzerland, Italy, Austria, Lichtenstein, Germany, Belgium, the Netherlands, Norway, Poland, Czech Republic, Slovakia, Hungary, Slovenia, Croatia, Bosnia-Herzegovina, Serbia, Albania, and Macedonia. The 2nd TZ, i.e., the Eastern European Time (EET), makes reference to the meridian 30° longitude east, and is shifted by 2 h, i.e., EET = UTC + 2. It includes Finland, Estonia, Latvia, Lithuania, Ukraine, Moldova, Romania, Bulgaria, Greece, and Turkey.

A further complication was generated when, in 1916, the daylight saving time (DST), commonly referred to as summer time (ST), was adopted. It was devised for energy saving, but its story is complex and may create confusion (Prerau 2005; Bartky 2007). During both World Wars, DST was implemented by all countries; in particular, the UK adopted 2 h ahead. In the period between the two Wars, DST was generally dismissed except the UK, Ireland, and Paris. After World War II, DST was dismissed again but, after the oil embargo decided by OPEC in 1973, various countries returned individually to DST. In 1996, the European Union (EU) decided to standardize its use over Europe. Finally, EU planned to dismiss DST next October 2021. A problem is that meteorological data relevant at the international level (e.g., synoptic weather forecast, weather maps, aeronautical, or maritime use) are recorded in UTC, while stations aimed at local use (e.g., local weather forecast, civil protection, tourism, agriculture) apply the local official time. Once again, caution is due when recovering data.

The change from AST to the modern UTC and time zone system had introduced two important biases when early instrumental measurements are compared with modern ones: the first is seasonal and is related to the unevenness of the apparent solar motion; the second is a constant shift and depends on the geographic longitude of the site.

If an early instrumental record was taken with readings at sunrise (T_{min}) and in the maximum plateau 2 or 3 h after noon (T_{max}), the average $(T_{max} + T_{min})/2$ is (almost) irrespective of how the daytime was measured and the change of time system from AST to WET, CET, or

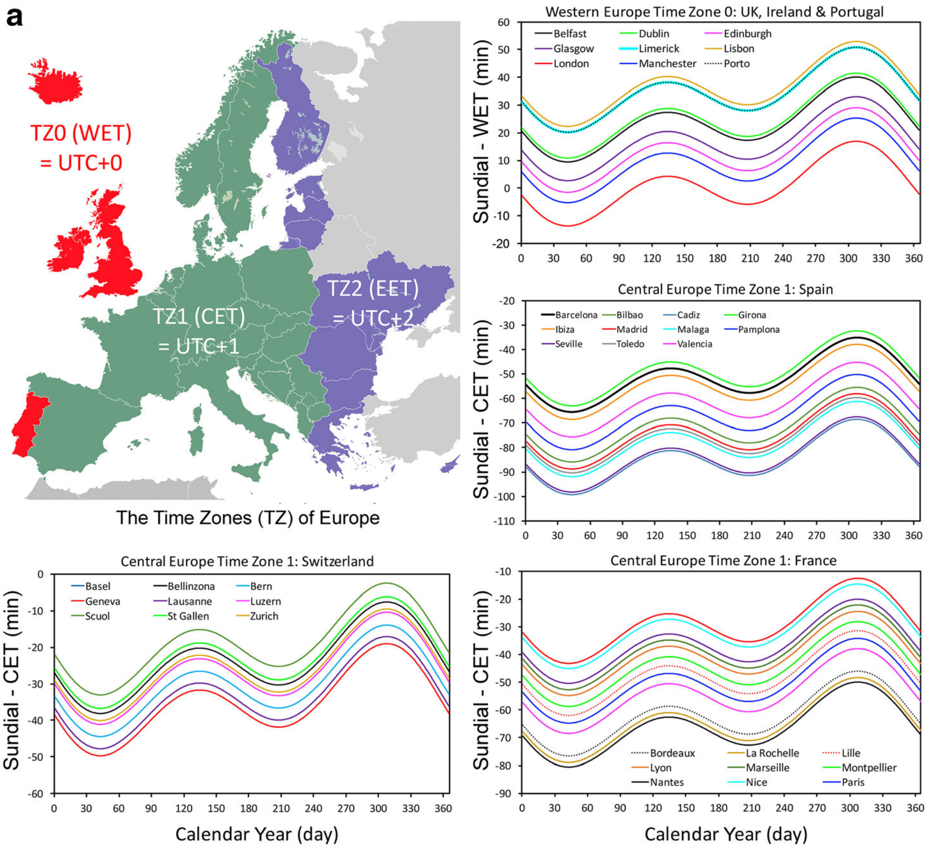

Fig. 3 **a**, **b** The three time zones (TZ) of Europe and difference between the apparent solar time (AST) indicated by a sundial and the Western European Time (WET), the Central European Time (CET), and the Eastern European Time (EET) for selected cities

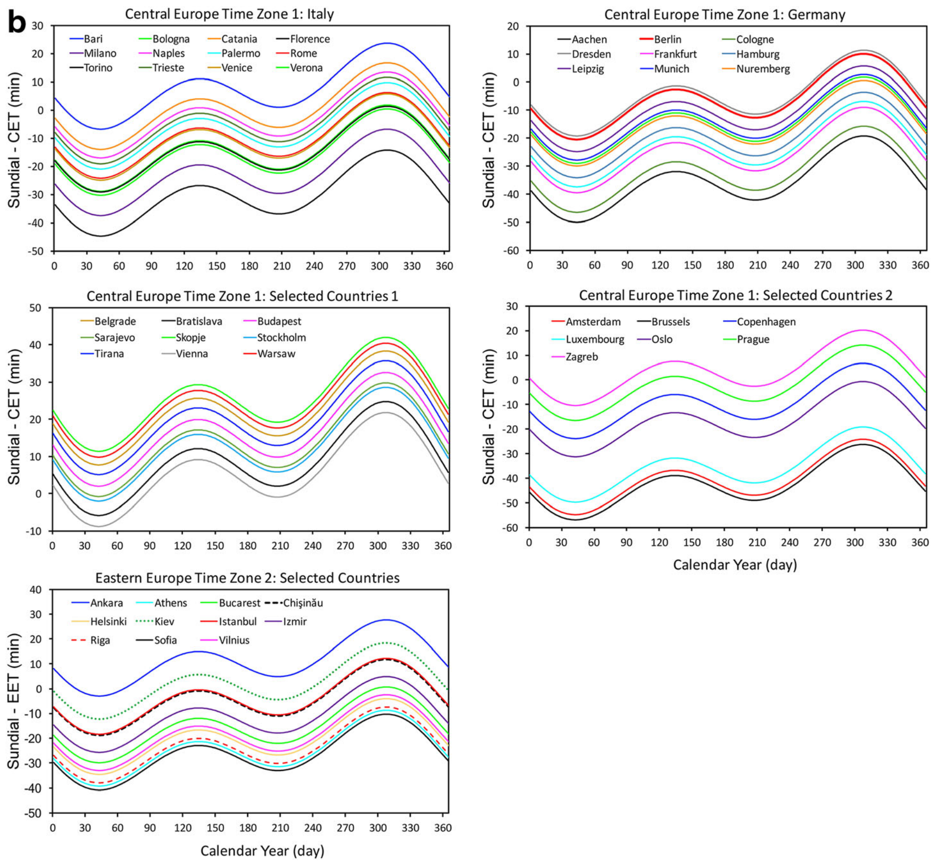

Fig. 3 (continued)

EET is irrelevant. However, if the early record was composed of a single reading, or some readings taken at selected times, the conversion from AST to the modern reference should be calculated for every day of the calendar year.

Similar problems may arise when combining records taken with instruments using different time frames. For instance, weather variables are measured with electronic sensors and are recorded on data loggers in UTC, but sunshine recorders focus on the solar radiation and leave an image line on a strip chart usually in AST.

3 Changing time frame: differences between apparent solar time and modern time

This section is devoted to the practical application of the concepts and formulae given in the previous sections, and applies to all the temperature records taken before the mid-nineteenth century. Table 1 reports 92 examples of European cities selected over the three Time Zones, with different longitude.

Table 1 European cities (and their longitude in degrees of arc and decimals) selected in this work to represent the Western, Central, and Eastern European Time Zones and range of the departure (in minutes of time) from AST and related time zone time

TZ	Country	City	Longitude arc deg	Range* min time
Time zone 0—Western European Time (WET)	UK	Belfast	5.925 W	+9/+40
		Edinburgh	3.188 W	−2/+29
		Glasgow	4.209 W	+3/+33
		London	0.118 W	−14/+17
		Manchester	2.245 W	−5/+25
	Ireland	Dublin	6.266 W	+11/+41
		Limerick	8.630 W	+20/+51
	Portugal	Lisbon	9.142 W	+22/+52
		Porto	8.610 W	+20/+51
Time zone 1—Central European Time (CET)	Spain	Barcelona	2.159 E	−66/−35
		Bilbao	2.925 W	−86/−55
		Cadiz	6.294 W	−99/−69
		Girona	2.821 E	−63/−32
		Ibiza	1.433 E	−68/−38
		Madrid	3.618 W	−89/−58
		Malaga	4.420 W	−92/−61
		Pamplona	1.643 W	−81/−50
		Toledo	4.022 W	−90/−60
		Seville	5.973 W	−98/−68
		Valencia	0.377 W	−76/−45
	France	Bordeaux	0.580 W	−77/−46
		La Rochelle	1.150 W	−78/−48
		Lille	3.057 E	−62/−31
		Lyon	4.834 E	−55/−24
		Marseille	5.381 E	−53/−22
		Montpellier	3.877 E	−59/−28
		Nantes	1.553 W	−80/−50
		Nice	7.266 E	−45/−15
		Paris	2.349 E	−65/−34
		Strasbourg	7.745 E	−43/−13
		Toulon	5.933 E	−50/−20
		Toulouse	1.444 E	−68/−38
	Italy	Bari	16.852 E	−7/+24
		Bologna	11.351 E	−29/+2
		Catania	15.074 E	−14/+17
		Florence	11.250 E	−29/+1
		Milano	9.190 E	−38/−7
		Naples	14.277 E	−17/+13
		Palermo	13.337 E	−21/+10
		Rome	12.482 E	−24/+6
		Torino	7.363 E	−45/−14
		Trieste	13.804 E	−19/+12
		Venice	12.332 E	−25/+6
		Verona	10.999 E	−30/0
Time zone 1—Central European Time (CET)	Switzerland	Basel	7.573 E	−44/−13
		Bellinzona	9.017 E	−38/−8
		Bern	7.450 E	−44/−14
		Geneva	6.140 E	−50/−19
		Lausanne	6.630 E	−48/−17
		Luzern	8.306 E	−41/−10
		Scuol	10.306 E	−33/−2
		St Gallen	9.370 E	−37/−6

Table 1 (continued)

TZ	Country	City	Longitude arc deg	Range* min time
		Zurich	8.550 E	−40/−10
	Germany	Aachen	6.083 E	−50/−19
		Berlin	13.410 E	−20/+10
		Cologne	6.950 E	−46/+16
		Dresden	13.378 E	−19/+11
		Frankfurt	8.684 E	−40/−9
		Hamburg	10.015 E	−34/−4
		Leipzig	12.370 E	−25/+6
		Munich	11.575 E	−28/+3
		Nuremberg	11.077 E	−30/+1
		Stuttgart	9.177 E	−38/−7
		Weimar	11.329 E	−29/+2
	Netherlands	Amsterdam	4.889 E	−55/−24
	Serbia	Belgrade	20.465 E	+8/+38
	Slovakia	Bratislava	17.107 E	−6/+25
	Belgium	Brussels	4.349 E	−57/−26
	Hungary	Budapest	19.040 E	+2/+32
	Denmark	Copenhagen	12.566 E	−24/+7
	Slovenia	Ljubljana	14.505 E	−16/+14
	Luxembourg	Luxembourg	6.130 E	−50/−19
	Norway	Oslo	10.746 E	−31/−1
	Czechia	Prague	14.421 E	−17/+14
	Bosnia	Sarajevo	18.356 E	−1/+30
	Macedonia	Skopje	21.431 E	+11/+42
	Sweden	Stockholm	18.063 E	−2/+29
	Albania	Tirana	19.819 E	+5/+36
	Austria	Vienna	16.372 E	−9/+22
	Poland	Warsaw	21.018 E	+10/+40
	Croatia	Zagreb	15.978 E	−10/+20
Time zone 2—Eastern European Time (EET)	Turkey	Ankara	32.854 E	−3/+28
		Istanbul	28.950 E	−18/+12
		Izmir	27.138 E	−26/+5
	Greece	Athens	23.716 E	−40/−9
	Romania	Bucharest	26.106 E	−30/+1
	Moldova	Chişinău	28.857 E	−19/+12
	Finland	Helsinki	24.946 E	−34/−4
	Ukraine	Kiev	30.524 E	−12/+18
	Latvia	Riga	24.100 E	−38/−7
	Bulgaria	Sofia	23.324 E	−41/−10
	Lithuania	Vilnius	25.280 E	−33/−3

*Note: the range is determined by the two extreme departures that occur on the 43rd and 308th calendar day, respectively, and these two departures are reported separated by "/"

For every calendar day, the EoT values to pass from AST (i.e., a sundial or a clock adjusted daily with culmination) to the modern time frame (i.e., WET, CET, EET) have been considered with 0.1-min resolution and have been calculated with the above equations. In order to avoid confusion, as in astronomy and geography, the same names may be used for quantities referred to different frames (e.g., hours, minutes, and seconds may be referred either to time or geometric arc rotations), the specification "time", or "arc" will be added to avoid misunderstanding.

For the 92 selected locations, and for every day of the calendar year, it has been considered how much the apparent solar time is ahead or behind the mean modern time. The total time

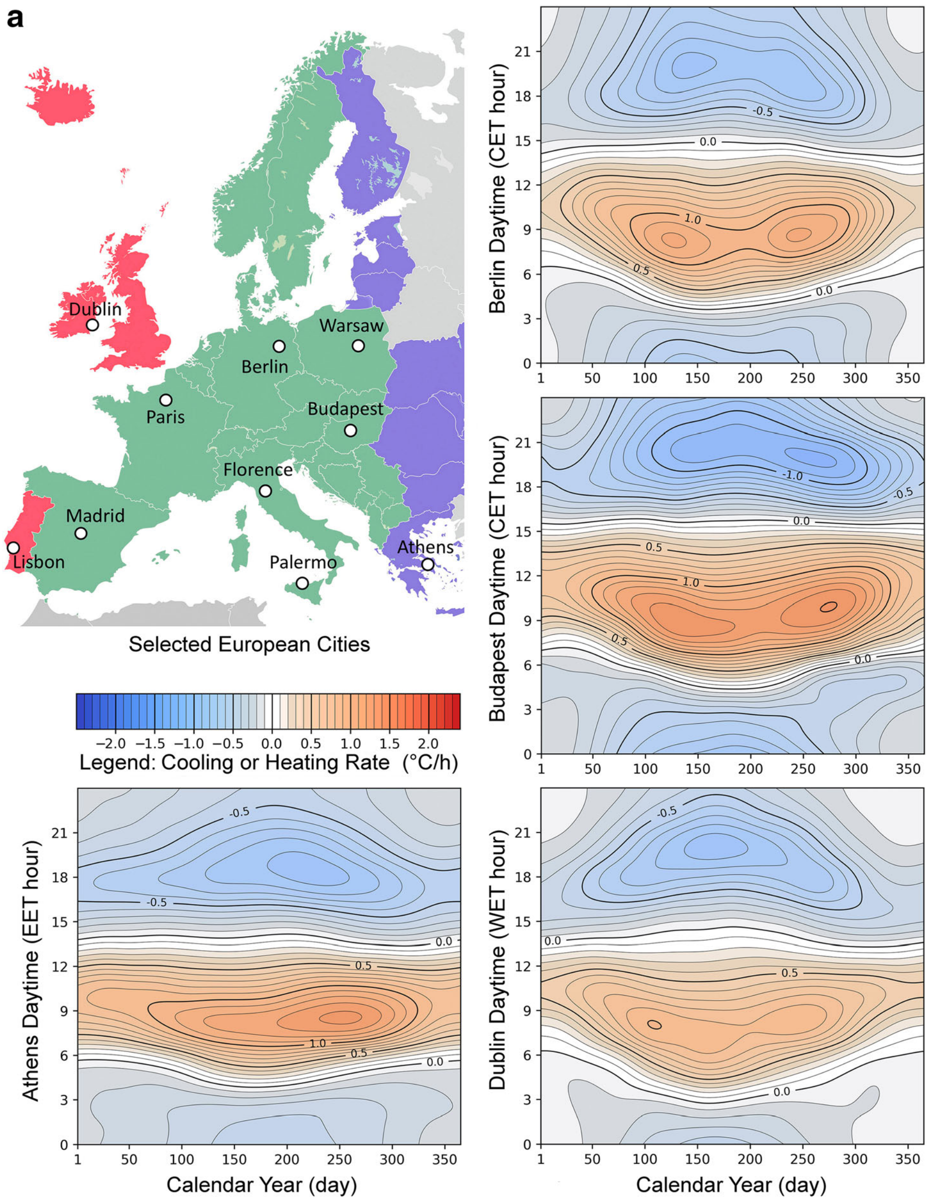

Fig. 4 **a**, **b** Temperature change from a selected hour to the next one (i.e. the temperature change rate), expressed in degrees Celsius per hour, over the calendar year, in some selected European cities. Red: heating rate; blue: cooling rate

departure (TTD) is obtained by algebraically summing the swinging variable EoT due to the Sun, to the fixed value GL due to the geographical position:

$$\mathrm{TTD} = \mathrm{EoT} + \mathrm{GL} \tag{6}$$

The total time departure has been calculated for the time zones 0, 1, and 2, i.e., WET, CET, and EET, and TTD represents AST- WET, or AST-CET, or AST-EET, depending on the time zone of the selected site, as follows.

3.1 Time zone TZ0, WET

In the selected locations of the European time zone TZ0, and specifically the UK, Ireland, and Portugal (Fig. 3a), the time departure of AST from WET ranges from about +50 to −15 min, with 65 min maximum difference between the eastern and western borders of this time zone.

3.2 Time zone TZ1, CET

This is the widest TZ, lying from 9.3° longitude west to 22.5° longitude east, and exceeds 2-h difference (i.e., 2 h 7 min) from the eastern and western borders. In particular, for business connections, Spain and France have preferred to adopt the most common European time UTC+1 instead of UTC+0 which was geographically more appropriate. As most early instrumental series were produced in this wide geographic area, the selected locations of TZ1 have been separately considered for Spain, Switzerland, France (Fig. 3a), Italy, Germany, and other European selected countries (Fig. 3b). These figures show that:

- In Spain, the time departure of AST from CET ranges from about −30 to −100 min, with 70 min east to west maximum difference;
- In Switzerland, from 0 to −50 min, with 50 min east to west maximum difference;
- In France, the AST-CET difference ranges from −10 to −80 min, with 70 min east to west maximum difference;
- In Italy, from +20 to −45 min, with 65 min east to west maximum difference;
- In Germany, from +10 to −50 min, with 60 min east to west maximum difference;
- In the first plot (selected countries 1) of other European countries belonging to TZ1, from +40 to −10 min (in total 50 min) and in the second (selected countries 2) from +20 to −60 min (in total 80 min).

3.3 Time zone TZ2, EET

In the selected locations of the European time zone TZ2 (Fig. 3b), the time departure of AST from EET ranges from about +30 to −40 min, in total 70 min.

4 From time departure to temperature bias

The temperature change rate from a selected hour to another one depends on the solar intensity (which is related to the latitude and the calendar day) as well as the climatic region (which depends on the geographical position and height above the sea level). Therefore, in the case of records, it should be calculated for every site over an adequate reference period.

To this aim, ten examples scattered over different climatic regions of Europe have been considered during the 1961–1990 reference period, taking advantage of the NOAA/NCEI Integrated Surface Database (Smith et al. 2011). The plots of heating or cooling rate ΔT(°C)/

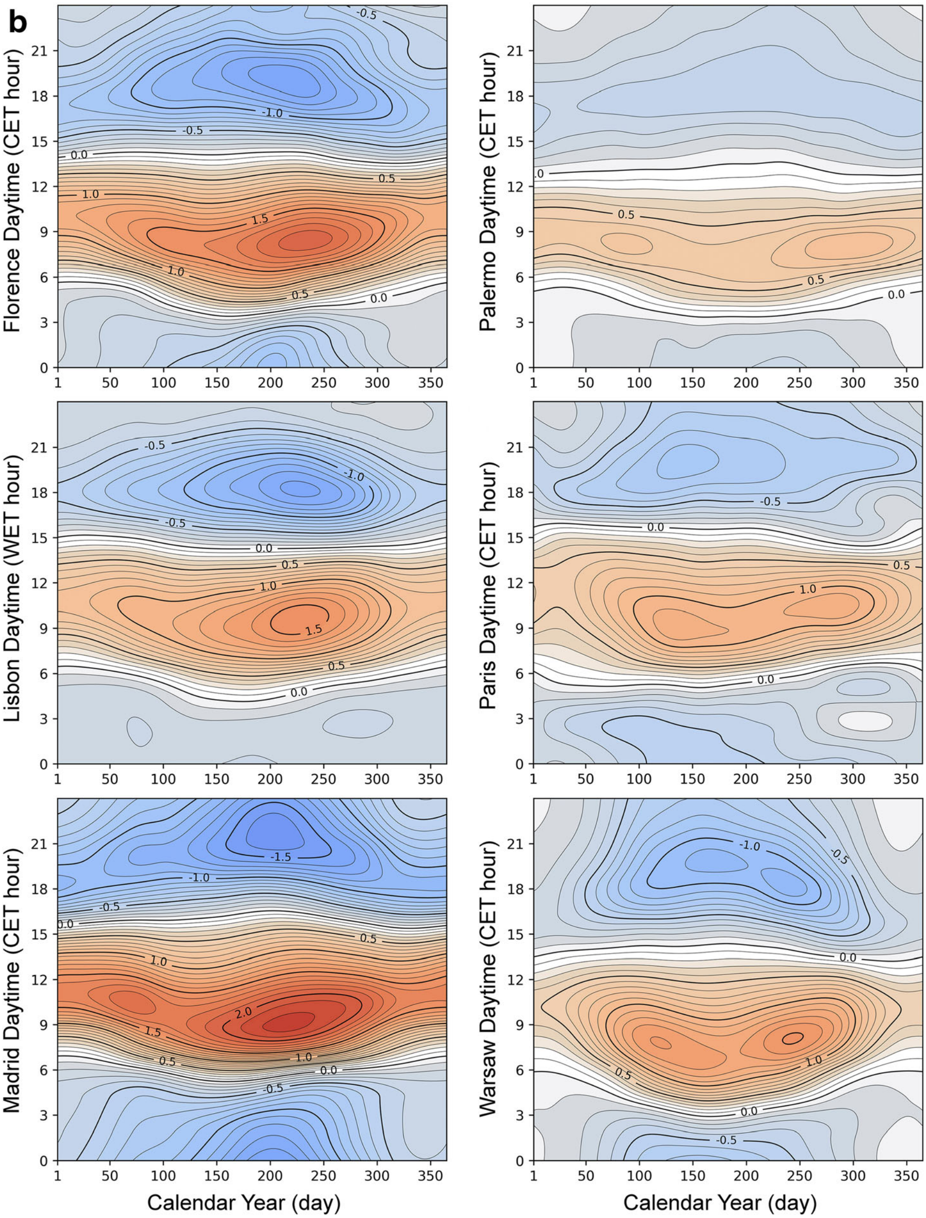

Fig. 4 (continued)

1 h, i.e., the temperature change ΔT(°C) in the selected site over 1-h interval, have been interpolated with a smooth bivariate spline approximation and have been reported over the daily scale and the calendar year (Fig. 4a, b). The highest heating rate occurs in the mid-morning, in summer. Two narrow stationarity bands at zero rate have been found that

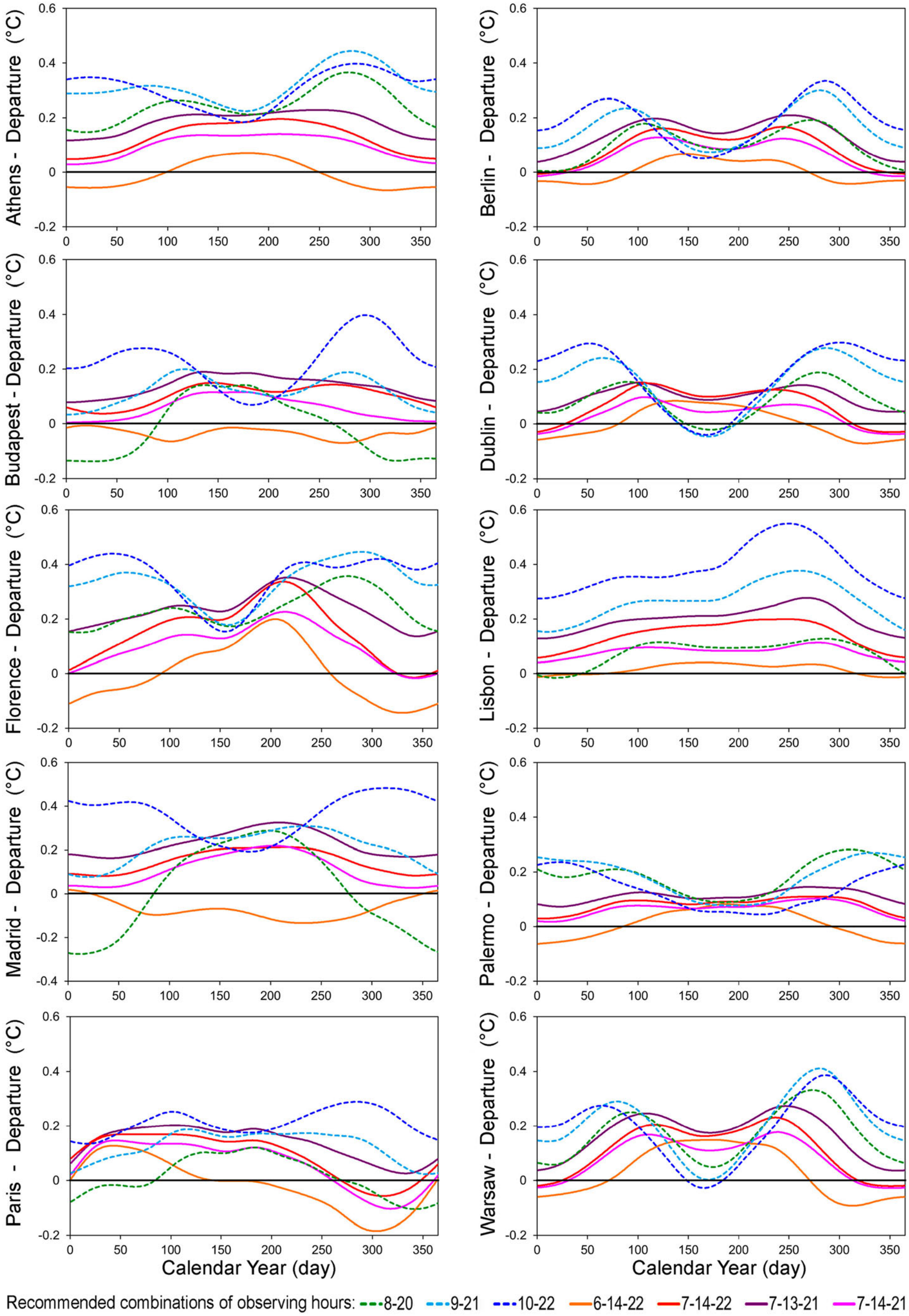

Fig. 5 Departure from the true daily mean when the method based on two or three observations at some recommended hours is applied

correspond to the inversion of temperature when the daily minimum, or the daily maximum, are reached. The minimum is in the early morning, near sunrise. The maximum does not always occur at the same time because, depending on the site, it may happen a few hours afternoon, or even more later (Allen et al. 1998; Vallis 2011). In the selected examples the maximum occurs more or less around 15 h for all stations and all seasons.

Qualitatively, all stations have similar behavior but, quantitatively, marked differences are found, depending on the climatic region. The highest peak of heating rate, i.e., 1.9 °C/h, has been found in Madrid that has a continental climate, followed by Florence with 1.5 °C/h. The lowest peak of heating rates, i.e., 0.6 °C/h, occurs in Palermo where the Mediterranean maritime climate and the ventilation dominate over the high insolation at this relatively low latitude, i.e., 38° 7′ north. Palermo is followed by Dublin with 0.8 °C/h that also has maritime climate, but lower insolation for the higher latitude, i.e., 53° 20′ north.

In the International Meteorological Congress held in Vienna in 1873, the sub-committee suggested some hours of observation to be chosen to give a daily mean of temperature, which should be as near as possible to the true one, i.e., based on 24 h. Specifically, it recommended a list of combinations of two equidistant hours (i.e., 8–20; 9–21; 10–22), or three hours (i.e., 6–14-22; 7–14-22; 7–13-21; 7–14-21), as well as some combinations of four readings including the daily minimum (Hann 1874). The 2- and 3-h methods suggested have been applied (Fig. 5) to the ten European cities considered in Fig. 4. The departures from the true mean are characterized by seasonal swings, but without a regular law: sometimes the largest departures are found in the mid-seasons, sometimes in summer; other times, the minimum departure is in summer. This variability is governed by the solar radiation, precipitation, and the wind regime, and changes with the geographical position and local climate. In general, the combination of the three observing hours gives better results. The most accurate is 6–14–22, followed by 7–14–21, 7–14–22, and 7–13–21.

It should be noted that the AST/UTC correction is relevant in the geographical regions where the solar radiation governs the daily temperature cycle. In the regions where the radiation is weaker, e.g., northern Europe in winter, the air temperature is more dependent upon air masses and wind direction, and the AST/UTC correction can only be regarded as accurate in the statistical sense over a lengthy period.

5 Conclusions

In instrumental records, time was computed making reference to different frames, starting from twilight, noon, or midnight. The two fundamental frames were the ancient AST given by local sundials and the modern UTC system with the adoption of time zones. The transition from AST to UTC happened from the 1850s to 1884. All the instrumental series including the final period of the Little Ice Age need a careful revision of reading times to account for the changed reference time frame, especially when early instrumental data are compared with modern ones in order to assess climate changes. This paper has clarified the various time frames and provides the equations to transform early time frames into UTC, WET, CET, and EET.

Moreover, this paper points out relevant departures between AST and the UTC system with modern clocks regulated on the official time zones. The temperature bias may be particularly important when daily averages were made after one, two, or three readings taken at selected times, because they were consistently different from nowadays.

Only in some particular cases, the time correction is not crucial. One is when the daily averages were computed as the half-sum of a reading at sunrise (i.e., daily minimum) and another at the time of the temperature maximum (Camuffo 2002). Another is when the average is composed of readings taken twice a day at equidistant hours, or similar combinations (Hann 1874). Finally, with regular hourly sampling, the daily averages are correct, but with all hours shifted of a short interval. This might introduce a small departure every day, but their combination is almost negligible for monthly averages. Unfortunately, in the early instrumental period, hourly series are exceptional and very short.

The minimum departure between AST and the modern time frame is around ±15 min for sites located close to the TZ reference meridian. The effect of longitude accounts for the most relevant departures that may reach 1 or even 2 h. Some wide countries, like Spain, France, Italy, and Germany exceed 1-h difference between the eastern and western borders. However, Switzerland that is apparently smaller accounts for 50-min difference between the eastern and western borders.

This paper provides 92 selected examples, which for their high density give a representative image of the European context. The calculated time changes cannot be neglected because in 1 h, or even in a fraction of hour, the air temperature may change by relevant amounts, especially in summer.

Considering ten selected examples scattered over Europe, strong quantitative departures have been found as a consequence of the specific climatic areas. Such departures should be specifically calculated for every site.

This paper intends to assist historians and climatologists in evaluating time departures or correcting records for temperature bias. The key relevance is to provide support for highly accurate revision/recovery/homogenization of early instrumental series, especially when calculating anomalies, or assessing climate changes.

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Availability of data and materials Climatic data in Fig. 4 and Fig. 5 are derived from the Integrated Surface Database of NOAA/NCEI (Smith et al. 2011) https://www.ncdc.noaa.gov/isd

Author contribution All authors have equally contributed.

Declarations

Competing interests The authors declare no competing interests.

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