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Small scale surface heterogeneity and potential inhomogeneities in temperature time series: a case study

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Abstract

Measurements in 7 sites in the Campus of the University of the Balearic Islands (UIB; Mallorca, Spain) during an experimental campaign to study the contribution of local surface heterogeneities on the surface energy budget at one point have been used to characterize the differences in extreme daily temperatures between the sites during a summer month. Absolute temperature differences in this month have reached up to 1.92 (with a median of 0.73) and 2.02 (median of 1.21) °C for daily maximum and minimum respectively. Higher differences in the minimum temperature can be attributed to the stably stratified and weak turbulent conditions at night that enhance local differences in the surface energy fluxes, especially in an area with strong variability of the surface characteristics like the UIB Campus. Instead, during daytime maximum temperature differences are smoothed due to the convection and the horizontal advection due to the sea-breeze. Two sites with longer records allowed to study the seasonal variations of these differences, which were substantially lower in the colder months. These results suggest that relocation of observatories, even at distances as short as 200 m, may introduce important inhomogeneities in the temperature series. Therefore, raw values of series from nearby stations should not be used to infill missing data other series without adequate statistical adjustments.
Key words: temperature series, inhomogeneities, station relocation, surface features

1. Introduction

One of the main problems found when using instrumental time series to study the variability of climate is due to the impact that changes in the observational practices introduce in the measurements. Typical examples are relocation of the observatories, instrument changes, land use changes in the surroundings, etc. As these alterations are of the same order or magnitude than the climate variations that researchers are trying to evaluate, a previous homogenization procedure must be applied to the series to unveil the real climate variability (Conrad and Pollack, 1950).

Many methods have been developed over the years to remove inhomogeneities from the series based on pairwise comparisons between them or with a synthetic series made generally with the better correlated with each problem series (Peterson et al., 1998; Aguilar et al., 2003; WMO, 2020). However, long and fairly complete series are not very common in climatological data-bases and many missing values preclude the use of shorter series whose data could be very valuable otherwise. This has led to the practice of increasing the number of available long series by merging observations of nearby stations (e.g., Squintu et al., 2020; Vincent et al., 2020), following criteria of maximum differences in horizontal distance and elevation.

Nevertheless, it cannot be granted that the applied restrictions allow negligible differences in the observations. When the merged series have a common period of observations it is possible to calculate adjustments to avoid inhomogeneities, but this is not often the case.

This article aims to evaluate the temperature differences that could be introduced in the series of observations by short distance station relocations using an experimental campaign of measurements at several sites closely located. Section 2 explains the instrumental settings and data acquisition, section 3 displays the results, which are discussed in section 4, followed by the conclusions.

2. Data and Methods

2.1. Experimental settings

Nine measuring sites were deployed in summer 2016 (Simó et al., 2016) across the Campus of the University of the Balearic Islands (UIB) during the Subpixel'16 experimental field campaign. The aim was to study the role of surface heterogeneities in the lack of closure of the surface energy balance (Cuxart et al., 2016; Simó, 2018; Simó et al., 2019). Five of these observing stations were selected by maximizing their data availability during a common period of 42 days (from June 15 to July 26, 2016). Data from two other stations which regularly record observations in the Campus were also added, summing up seven measuring sites used in this study.

The University is located in the western part of the Mallorca island, in the Western Mediterranean, at a latitude of 39.64°N (Figure 1). The UIB Campus has an approximate extension of 1 km^2 and is heterogeneous in terms of soil cover, with buildings and roads spread over the natural landscape of the region composed by short vegetation (dry in summer) and sparse trees. This heterogeneity can be appreciated in Figure 2, which also shows the geographic location of the seven sites used in this study, whose coordinates and surface cover description can be seen in Table 1. Site 1 (marked in yellow in Figure 2) has a UIB fully instrumented station to evaluate the surface energy balance (SEB). Sites 2 to 6 locate simpler measuring poles bearing temperature and humidity sensors inside shelters consisting in a double PVC cylinder covered with aluminum paper and with holes in the bottom. This shelter was successfully tested comparing it with the standard parallel plates in the SEB station. Finally, site 7 (marked in red in Figure 2) holds an Automatic Weather Station managed by the State Meteorological Agency (AEMET). The temperature sensor at this site is placed at 1.5 m above the ground, the standard level for Spanish meteorological observations, while sites 1 to 6 had sensors at 1 and 2 m height.

Distances between nearest sites ranged from 206 to 395 m (average: 253 m) and from 587 to 894 m (average: 770 m) between the more distant pairs. Temperature measurements from those seven sites were selected by maximizing data availability during a common period of 42 days (from June 15 to July 26, 2016). Additional data, not limited to this summer campaign, were collected from sites 1 and 7 from 2015-05-19 to 2021-11-30 (2388 days) to determine the seasonality of the differences between their daily extreme temperatures.

The effect of the aforementioned heterogeneity on the surface temperature is treated in the discussion with the help of two Land Surface Temperature (LST) views of the Campus composed by images taken by a FLIR LEPTON Thermal Infra Red camera assembled to an Unmanned Aerial Vehicle flying at a height of 200 m. These individual images were processed to obtain LST maps of the University Campus with 1m resolution (García-Santos et al., 2018).

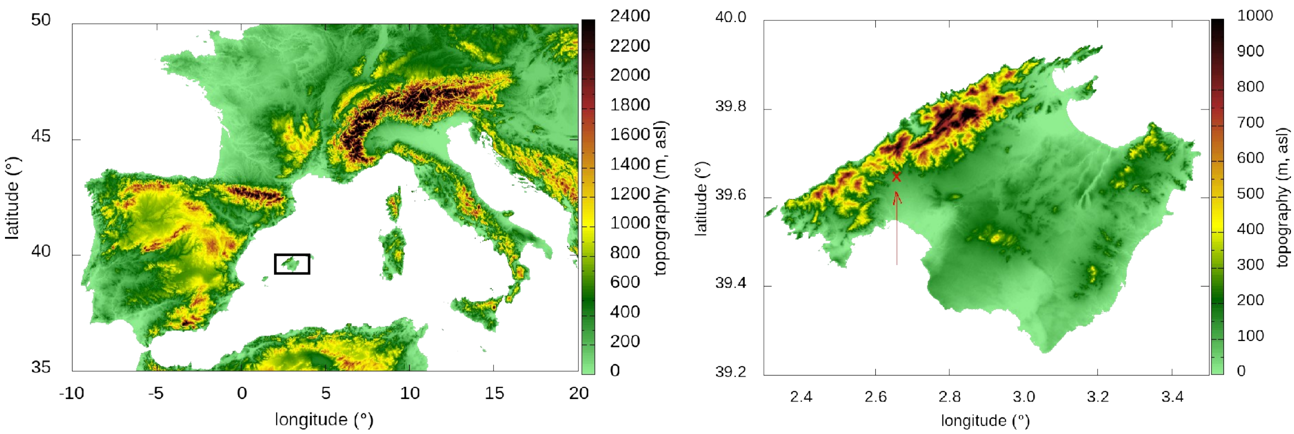

Fig. 1: Geographic location of the University Campus (red X) in the Mallorca island (Western Mediterranean).

Fig. 2: Location of the seven measuring sites marked on a Google Earth satellite view of the UIB Campus.

Table 1: Location, elevation and description of the measuring sites numbered in Figure 2.

Site	Latitude (°)	Longitude (°)	Elevation (m)	Description of the surface cover
1	39.639906N	2.646709E	85	short/dried vegetation
2	39.641242N	2.648144E	88	sparse almond trees
3	39.639262N	2.648889E	86	sparse orange trees
4	39.637614N	2.644067E	86	grass between buildings
5	39.636468N	2.650062E	82	partially paved area
6	39.635722N	2.642906E	90	grass and sparse trees
7	39.642164N	2.643755E	85	sparse almond trees

2.2. Data processing

The fully instrumented UIB station (site 1) provides data every minute, while the measuring poles (sites 2 to 6) recorded data every 5 minutes during the Subpixel'16 experimental field campaign. Finally, the AEMET AWS (site 7) stores data at 10 minutes intervals. Extreme daily temperatures were obtained from these records, and they were calculated also from site 1 with the three different sampling frequencies (1, 5 and 10 minutes) to assess the impact of these differences in the daily values.

Daily maximum and minimum temperature differences were calculated between all possible 21 observing pairs during the 42 summer days of the campaign. The daily temperature extremes of the two stations with longer records (SEB station and AEMET AWS between 2015-05-19 to 2021-11-30) showed inhomogeneities due to sensor changes in 2019-12-23 and 2019-03-08 at sites 1 and 7 respectively. The climatol R package (Guijarro, 2019) was used to correct these inhomogeneities with the help of reference series from the ERA5 reanalysis interpolated to the campus location obtained from https://app.climateengine.com/climateEngine.

The corrections were applied to the data after the sensor changes because of their shorter length, and consisted in decreasing site 1 data by 0.27 °C and increasing site 7 data by 0.09 °C. Differences between these series were calculated only for the 1966 days without any missing subdaily data in both sites.

Average daily wind speed, daily temperature range, water vapor pressure and relative humidity from the AEMET AWS (site 7) were also used to explore their influence on the temperature differences means of a Principal Component Analysis (PCA; Jolliffe, 2002).

The R programming system was used for all statistical calculations and graphics (R Core Team, 2020).

3. Results

3.1. Temperature differences

Maximum and minimum daily temperature differences between all station pairs were analyzed for sensors at 1 and 2 m above ground level (except for site 7, which has the sensor at 1.5 m height).

However, as results from both heights were similar and operative meteorological observations are taken usually at 1.5 or 2 m, for the sake of brevity only results from sensors at 2 m (1.5 m at the AWS) will be shown here.

Figure 3 shows the box-whisker plots of maximum and minimum daily differences between all 21 site pairs. Maximum temperature differences show bigger interquartile ranges, while those of minimum temperature show a wider range of values between station pairs.

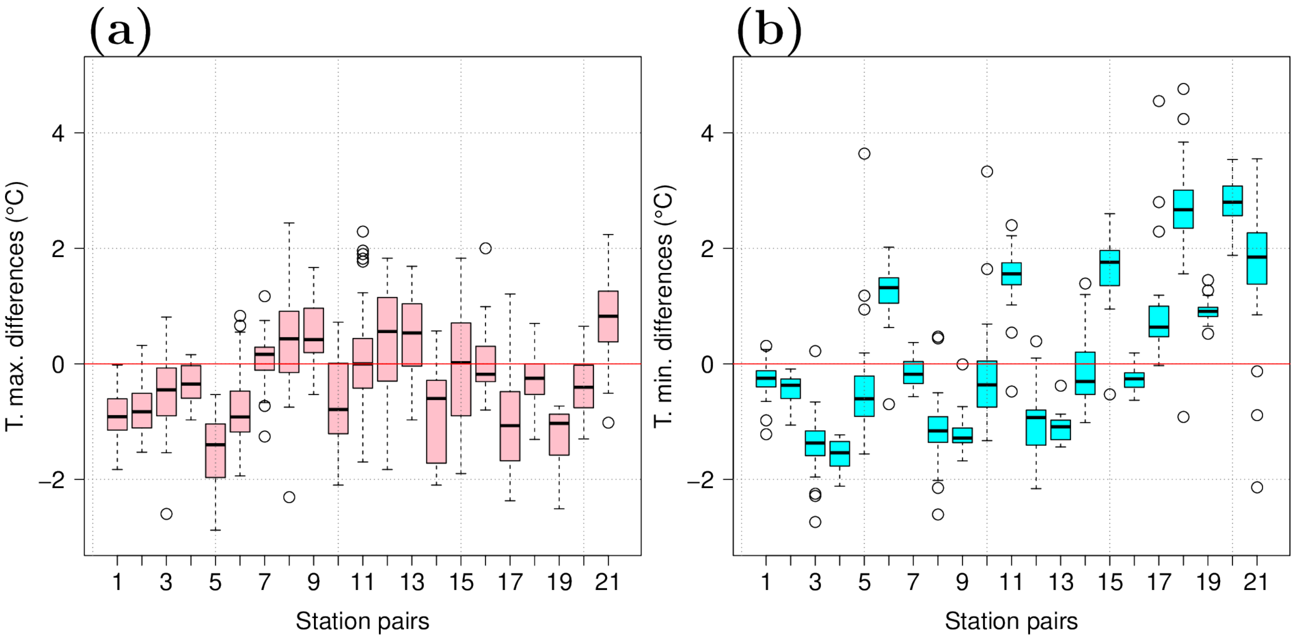

Fig. 3: Differences of daily maximum (a) and minimum (b) temperature between all site pairs.

Considering the averages of the maximum temperature differences, their absolute values reach up to 1.14 °C (Figure 4a), half of them being greater than 0.76 °C. Average minimum differences are higher, as discussed in the previous paragraph, half of them being greater than 1.24 °C, reaching up to 2.12 °C (Figure 4b).

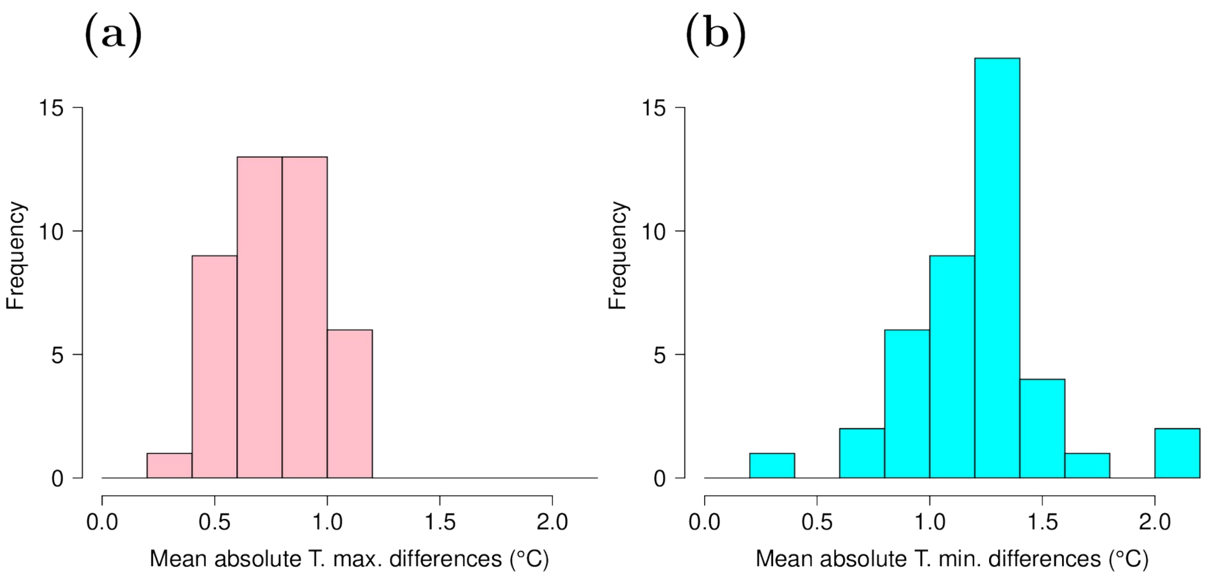

Fig. 4: Histograms of the mean maximum (a) and minimum (b) absolute temperature differences between all site pairs.

These temperature differences are quite independent from the distance between measuring sites, as evidenced by the lack of significant correlation (0.117 and 0.310 for maximum and minimum differences, with p-values 0.613 and 0.171 respectively).

3.2. Seasonality of the temperature differences

The temperature differences shown in the previous section with data from the experimental field campaign are representative of a summer month only. Differences along the seasonal cycle have been studied with the series of the two sites (1 and 7) with several years of common measurements.

Figure 5 displays the monthly summaries of maximum and minimum differences in form of box-whisker plots for the 1966 days with no missing subdaily data between 2015-05-19 and 2021-11-30. Site 7 appears as more “continental” than site 1, with higher maximum and lower minimum temperatures. This can be probably due to its sensor being placed at 1.5 m above the ground, versus the 2 m height of the sensors at the other measuring sites. Anyway, these differences are larger in the summer months, as expected because of the higher intensity of radiation fluxes.

The impact of the different data sampling frequency of the stations (1 minute in site 1, 5 minutes in sites 2 to 6 and 10 minutes in site 7) can be studied with the extreme daily temperatures obtained at these different frequencies from site 1. Table 2 shows that maximum temperatures obtained from 2248 days with complete 1 minute data have been 0.11 and 0.18°C higher than those obtained from data every 5 or 10 minutes respectively. Similarly, daily minimum temperatures have been 0.04 and 0.09°C lower with 1 minute data than with their 5 and 10 minutes versions. Therefore, most part of the differences between the sites must be attributed to their location characteristics, many of the differences being calculated between daily extremes derived from 5 minutes series.

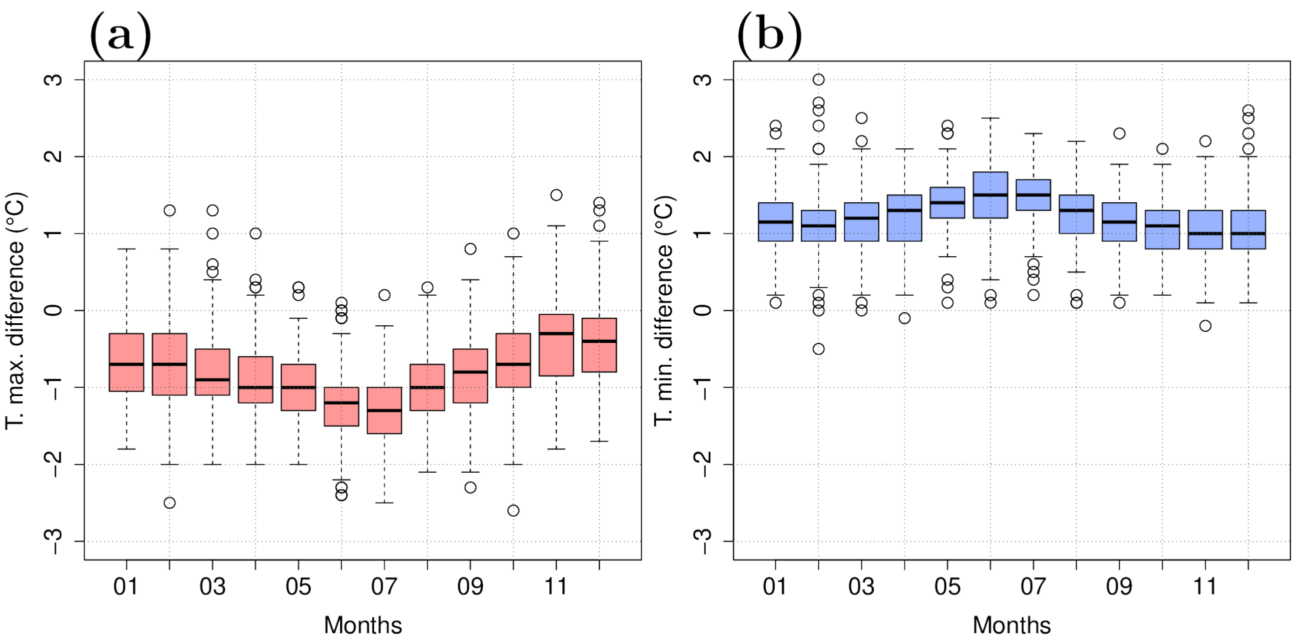

Fig. 5: Maximum (a) and minimum (b) temperature differences site 1 minus site 7 (monthly summaries of the daily differences).

Table 2: Statistical summaries of the differences in extreme daily temperatures obtained from 1, 5 and 10 minute series (in °C).

	Min.	**1st Qu.**	**Median**	**Mean**	**3rd Qu.**	**Max.**
T.max. 1 min – 5 min	0.00	0.00	0.10	0.11	0.20	0.80
T.max. 1 min – 10 min	0.00	0.10	0.10	0.18	0.30	1.20
T.min. 1 min – 5 min	-0.70	-0.10	0.00	-0.04	0.00	0.00
T.min. 1 min – 10 min	-1.40	-0.10	-0.10	-0.09	0.00	0.00

3.3. Potential influencing factors

Daily means of all maximum and minimum temperature differences between the sites are quite independent of the distance between them, as derived from their low Pearson correlation coefficients (0.117 and 0.310 for maximum and minimum respectively), neither of them being significant at the 0.15 level. They have also been examined in relation to daily temperature range and averages of wind speed, relative humidity and water vapor pressure calculated from the 10 minute observations at the AEMET AWS located in the Campus. Table 3 shows the Pearson correlation coefficients between all these variables, with significant values at the 0.05 level enhanced in bold.

Table 3: Pearson correlation coefficients between daily values of maximum temperature differences (dtx), minimum temperature differences (dtn), temperature range (dtr) and average wind speed (ws), relative humidity (rh) and water vapor pressure (vp). (Significant values at $\alpha<0.05$ appear enhanced in bold.)

	dtx	**dtn**	**dtr**	**ws**	**rh**	**vp**
dtx	---	-0.250	-0.128	-0.008	0.137	0.172
dtn	-0.250	---	**0.389**	0.087	**-0.638**	**-0.535**
dtr	-0.128	**0.389**	---	**-0.383**	**-0.534**	**-0.351**
ws	-0.008	0.087	**-0.383**	---	-0.155	-0.045
rh	0.137	**-0.638**	**-0.534**	-0.155	---	**0.522**
vp	0.172	**-0.535**	**-0.351**	-0.045	**0.522**	---

As there is co-linearity between these variables, the most prominent example being relative humidity and water vapor pressure, their inter-relations were examined by means of a Principal Component Analysis on their correlation matrix. This method applies a coordinate transformation from the original dimensions (the 6 variables in Table 3) to new orthogonal axes chosen in decreasing order of explained variance (Jolliffe, 2002). The first two components increase their original unit variance and, jointly with the third component (that keeps most of its original variance) account for nearly 80% of the global variance (Figure 6a). The bi-plots (as described by Gabriel, 1971) displayed in the same figure show projections of variables and cases from the 6-dimensional space onto planes defined by these three more important components. The projection onto components 1 and 2 (Figure 6b) indicates that component 1 is positively correlated with vapor pressure (vp) and relative humidity (rh, strongly linked to the former), and negatively correlated with minimum temperature differences. Component 2 is negatively correlated with wind speed average, and the daily temperature range (dtr) contributes, to a lesser extent, negatively to component 1 and positively to component 2. The other two bi-plots (Figures 6c and 6d) show that component 3 is mainly driven by the maximum temperature differences (dtx), the other variables making negligible contributions.

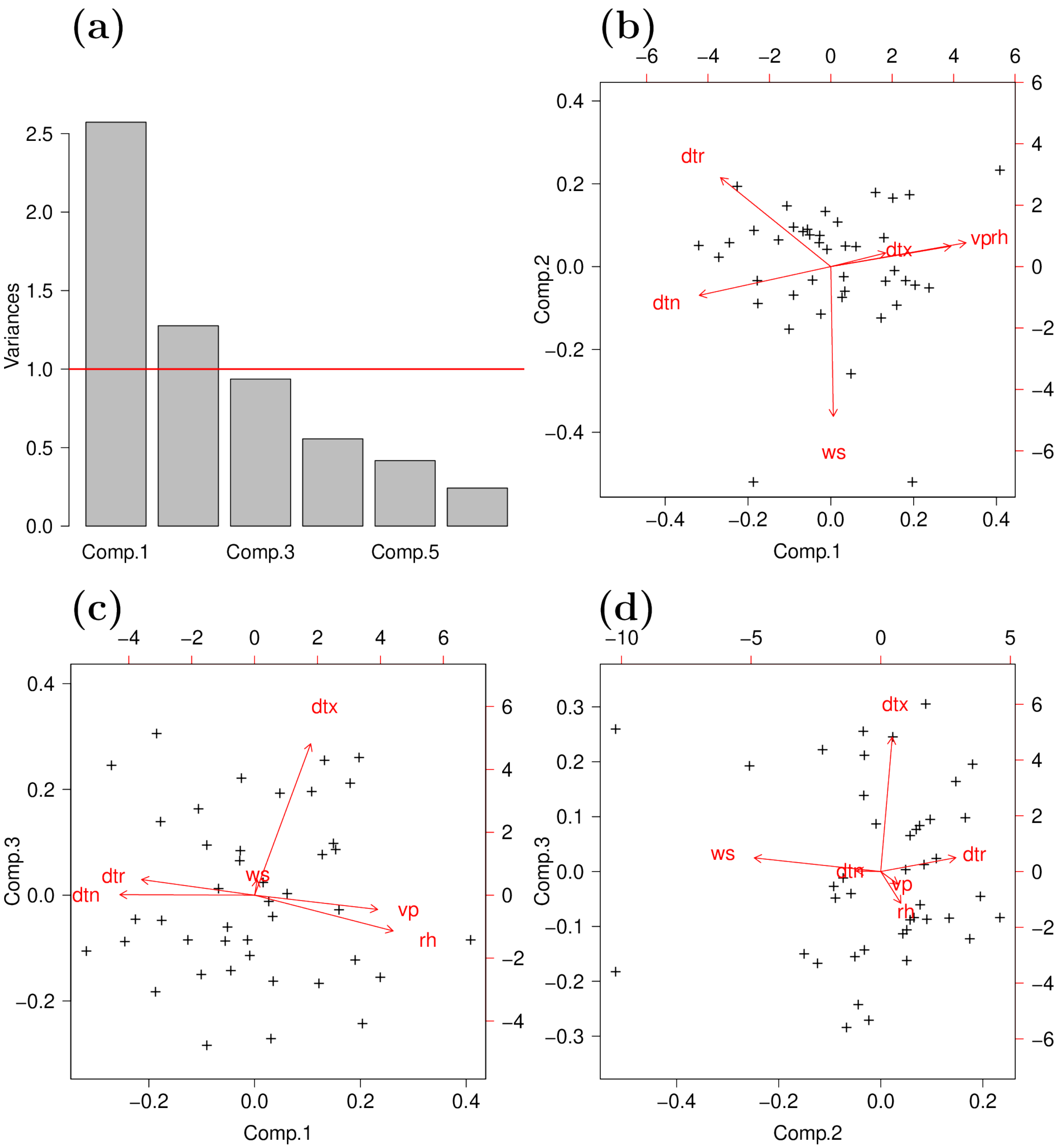

Fig. 6: Results of the Principal Component Analysis of the variables included in Table 3. Explained variance of the components (a) and bi-plots showing the projections of the 42 days (crosses) and variables (arrows) in the 6-dimensional space on planes defined by principal components 1-2 (b), 1-3 (c) and 2-3 (d).

4. Discussion

The lack of correlation of the maximum and minimum temperature differences in the Campus with the distance between the measuring sites shows that the main driver of these differences is the varied importance of the terms of the surface energy balance, depending on the kind of vegetation (or its absence), albedo, soil humidity and thermal conductivity, etc. Figure 7 shows the surface (skin) temperature distribution before dawn and past midday on a clear sky day (19 June 2016). The surface temperature ranges between 9.6 and 15.0 °C during nighttime (Figure 7a), whereas the range during daytime is increased to 31.5 to 51.0 °C (Figure 7b). Air turbulence, especially with moderate to strong wind, would make these differences much less noticeable at 2 m above the ground, but meteorological conditions during the experimental campaign were predominantly sunny, dry (only two days with precipitation: 0.2 and 10.2 mm on June 18 and 29 respectively) and with weak wind (ranging from 1 to 3.4 m·s^{-1}).

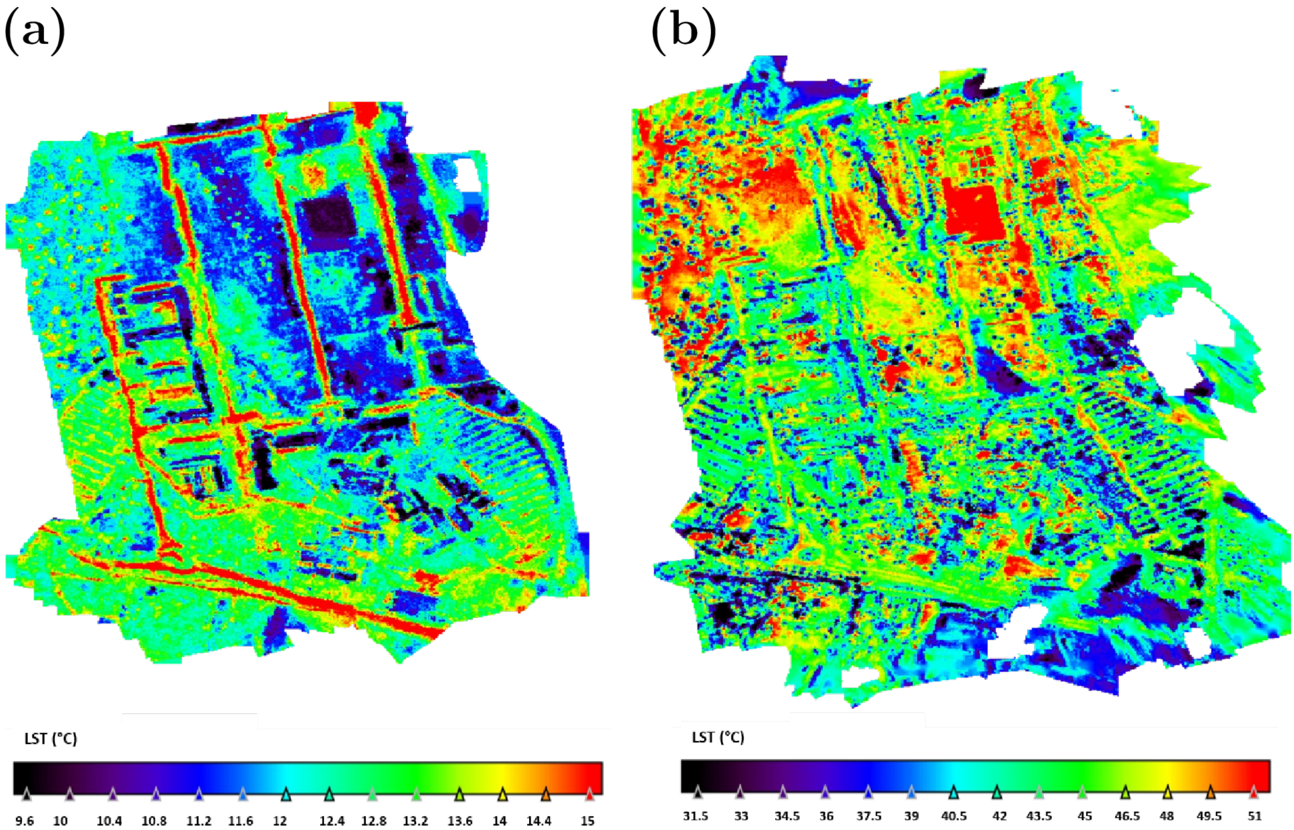

Fig. 7: Land-surface temperature (LST) images taken on 19 June 2016 at 06:00 (a) and 14:00 (b) local time showing the great role of the soil-vegetation system in regulating the temperature of the interface air-ground.

Both Table 2 and the PCA results show that daily temperature differences are higher for the minimum than for the maximum, and also that the former appear influenced by the air water content. Here the daily cycle of the wind speed must play an important role. At night the ground surface cools by infrared irradiation, lowering the air temperature aloft and increasing the air stability of the lower layers. This fact diminishes the wind and associated turbulence close to the surface, hence allowing larger micro-climatic temperature differences that depend on the soil-vegetation characteristics and terrain undulations of the site, since local depressions favor the accumulation of cold air (Martínez et al., 2010). On the contrary, during the sunny hours solar radiation reverses the direction of the energy fluxes, unstabilizing the lower air layers, and the development of the sea breeze (Grau et al., 2021) increases the wind speed and their associated mixing effects, therefore limiting the differences of maximum temperature between sites.

The analysis of the data measured in this experimental campaign has shown how different can be the average maximum and minimum temperatures at distances as short as 200 m. Although there were substantial gaps of missing data along the 42 days in which observations were recorded, the averages are representative of a summer month in a Mediterranean area, and the seasonal variation of these differences calculated with the pair of stations with longer concurrent records have shown that, although with a lower magnitude, they are also important in the colder months of the year.

Although there are clear heterogeneities in the surface characteristics of the Campus area, similar variability can be expected in the surroundings of most operational observatories, frequently situated in suburban or even rural areas with presence of varied vegetation and buildings typical of human occupation. Therefore, these micro-climatic variations can be presumably found in the surroundings of the majority of observatories providing the data that build the series for climate studies. Moreover, the differences observed in this work (medians of 0.73 and 1.21 for maximum and minimum temperatures respectively) are much greater than the observed temperature increments per 10 years obtained in studies for the assessment of climate change, which have been 0.1 to 0.3 °C/decade in the four longest Balearic series of average temperature during 1961-2020 (Guijarro and Jansà, 2022).

It has been a common practice to combine series of neighbor stations in order to obtain long data series for the analysis of local climate variability (as in Squintu et al, 2020 and Vincent et al., 2020) and to increase the number of series in climate data-bases. E.g., neighbor observations up to 12.5 km away have been used to build blended series for the European Climate Assessment and Dataset (ECA&D Project Team 2012), although excluding those with a difference in elevation higher than 25 m. Therefore, the substantial average temperature differences found here even at very much shorter distances suggest that these practices should be avoided or applied with caution, annotating the dates of the joints as probable inhomogeneities, especially in climates where radiative fluxes are the dominant factor in the surface energy balance.

Conclusions

The Subpixel'16 experimental field campaign produced a dataset of meteorological measurements from several sites located in an area of around 1 km^2 with heterogeneous features similar to the environments of typical operational observatories placed in suburban or even rural areas. The analysis of their extreme daily temperatures has served to assess how surface heterogeneities generate micro-climatic variability that can produce substantial changes in the series of observations in case of station relocations, especially at nighttime and during the warm months of the year.

Absolute daily extreme temperature differences have reached median values of 0.73 and 1.21 °C for maximum and minimum respectively, figures clearly surpassing the observed temperature increments per 10 years obtained in studies for the assessment of climate change.

Therefore, it is highly desirable to avoid changing the location of an observatory even by only tenths of meters, and to keep the surroundings unchanged, specially in a complex terrain region.
As the previous requirements are very difficult to achieve along the history of an observatory, it is of paramount importance to document any of those changes, and to store these metadata in the same climate database, to ensure an easy way to provide them to the climate researchers and users in general.

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References

Aguilar E, Auer I, Brunet M, Peterson TC, Wieringa J (2003): *Guidelines on climate metadata and homogenization*. WCDMP-No. 53, WMO-TD No. 1186. World Meteorological Organization, Geneve.

Conrad, V. and C. Pollak (1950): *Methods in Climatology*. Harvard University Press, Cambridge, MA, 459 pp.

Cuxart J, Wrenger B, Martínez-Villagrasa D, Reuder J, Jonassen MO, Jiménez MA, Lothon M, Lohou F, Hartogensis O, Dünnermann J, Conangla L, Garai A (2016). Estimation of the advection effects induced by surface heterogeneities in the surface energy budget. *Atmospheric Chemistry and Physics*, *16*(14), 9489-9504.

ECA&D Project Team (2012): European Climate Assessment & Dataset Algorithm Theoretical Basis Document (ATBD). De Bilt, NL, version 10.5. <https://www.ecad.eu/documents/atbd.pdf>, retrieved on 2022-05-23.

Gabriel KR (1971). The biplot graphical display of matrices with applications to principal component analysis. *Biometrika*, 58, 453–467. doi: 10.2307/2334381.

Garcia-Santos V, Cuxart J, Jiménez MA, Martinez-Villagrasa D, Simo G, Picos R, Caselles V (2018). Study of temperature heterogeneities at sub-kilometric scales and influence on surface–atmosphere energy interactions. *IEEE Transactions on Geoscience and Remote Sensing*, *57*(2), 640-654.

Grau A, Jiménez MA, Cuxart J (2021). Statistical characterization of the sea-breeze physical mechanisms through in-situ and satellite observations, *International Journal of Climatology*, 41:17-30.

Guijarro JA (2019). Climatol: Climate Tools (Series Homogenization and Derived Products). <https://CRAN.R-project.org/package=climatol>, retrieved on 2022-05-23.

Guijarro JA, Jansà A (2022): Variabilidad de las tendencias de las temperaturas e impacto en su comunicación al público: Ejemplo en las islas Baleares. In Martí A et al. (eds.): *Retos del cambio climático: Impactos, mitigación y adaptación*. Asociación Española de Climatología, A-12:341-349.

Jolliffe IT (2002): *Principal Component Analysis*. Springer Series in Statistics. New York: Springer-Verlag. doi:10.1007/b98835. ISBN 978-0-387-95442-4.

Peterson TC, Easterling DR, Karl TR, Groisman P, Nicholls N, Plummer N, Torok S, Auer I, Böhm R, Gullett D, Vincent L, Heino R, Tuomenvirta H, Mestre O, Szentimrey T, Salinger J, Førland E, Hanssen-Bauer I, Alexandersson H, Jones P, Parker D (1998): Homogeneity Adjustments of ’In Situ’ Atmospheric Climate Data: A Review. *Int. J. Climatol.*, 18:1493-1518.

R Core Team (2020): R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. q https://www.R-project.org/.

Simó G, García-Santos V, Jiménez MA, Martínez-Villagrasa D, Picos R, Caselles V and Joan Cuxart (2016) Landsat and Local Land Surface Temperatures in a Heterogeneous Terrain Compared to MODIS Values. Remote sensing, 8(10):849.

Simó G (2018): *Effect of the surface thermal heterogeneities on the atmospheric boundary layer*. Doctoral Thesis, Univ. de les Illes Balears, 233 pp.

Simó G, Cuxart J, Jimenez MA, Martínez-Villagrasa D, Picos R, López-Grifol A, Marti B (2019). Observed atmospheric and surface variability on heterogeneous terrain at the hectometer scale and related advective transports. *J. of Geoph, Research: Atmospheres*, *124*(16), 9407-9422.

Squintu AA, Van Der Schrier G, Van Den Besselaar EJM, Cornes RC, Klein-Tank AMG (2020): Building Long Homogeneous Temperature Series across Europe: A New Approach for the Blending of Neighboring Series. *Jour. Appl. Meteor. Climat.*, 59:175-189, DOI: 10.1175/JAMC-D-19-0033.1

Vincent LA, Hartwell MM, Wang XL (2020): A Third Generation of Homogenized Temperature for Trend Analysis and Monitoring Changes in Canada’s Climate. *Atmosphere-Ocean*, 58:173-191, DOI: 10.1080/07055900.2020.1765728

WMO (2020): *Guidelines on Homogenization*. WMO No. 1245, 54 pp., Geneva.