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The authors would like to thank the Faculty of Geosciences and the Environment (FGSE) of the University of Lausanne (UNIL) for thefinancing, installation and assistance with the maintenance of meteorolog- ical stations in the valley of Nant, and more particularly Bettina SchaeFFi, Nathalie Ceperley, Anthony Michelon, Simon Hiscox Baux, Aur´elien Ballu and Floronea Miesen.

Introduction

1 The extreme heterogeneity of topographies (altitudes, orientations and slopes) in mountain areas signif- icantly influences temperatures at the local scale. In particular, cold air accumulation phenomenon can appear in the bottoms of valleys and topographic depressions, that can strongly influence monthly and annual temperatures in mountainous areas (Fallot, 2021). These influences can distort the temperature interpolations made from in situ measurements and statistical methods, especially at the bottom of certain large alpine valleys (Frei, 2014). Consequently, the estimation of air temperature at very high resolution mountainous areas remains a challenging issue, even in Switzerland, where the density of climatic mea- surement networks in mountains is one of thefinest in the world (Carrega, 2003; Dodson and Marks, 1997; Ceppi et al., 2012; Rebetez and Reinhard, 2023). However, locally accurate climatic products would be of high relevance for broad applications in meteorology, hydrology, ecology, and otherfields, enabling more informed decision-making processes and facilitating eFFective management of mountainous environments, in particular in the

ongoing climate change context. The study site of the natural reserve of the Nant valley in the Vaudois Alps (Switzerland), particularly instrumented within the framework of various projects (Michelon, 2022; Antoniazza et al., 2019; Vittoz et al., 2009) is chosen for this work, in order to take ad- vantage of the relatively long duration of the measurement time series performed at high elevation in this site. The production of locally accurate temperature products is of direct application for ecological works in this valley (Pearman et al., 2008). This work focuses on the application of a high-resolution interpola- tion method of monthly temperatures for the Nant valley site, based on recordings at three meteorological stations available in situ. In order to estimate their performance, these interpolated temperaturefields are compared to two other data sources: the temperatures provided by the high-resolution downscaled product CHCLIM25 and by the ERA5 reanalysis product. An additional in-situ measurement campaign is also performed over a duration of one year to better describe local site eFFects observed in the valley.

Data

Measurements at weather stations in the valley

2 Measurements are available the hourly time step for three meteorological stations installed in the Nant valley (figure 1). Table 1 summarizes the characteristics of the recordings at the three stations used in this study. Given the geographical location of these stations as well as the conditions to which they are subjected (lack of sunshine to power the dedicated solar panels), the series of measurements have significant gaps. The intersection of the recording periods at the three stations being short, the choice is made for this work to use all the chronicles at the three stations averaged at monthly time steps in order to obtain the annual dynamics of the measured temperatures.

Figure 1 - Geographical location of the studied basin: the Nant valley, Bex, Switzerland. View of the Dent de Morcles (2969m) from the Nant mountain pasture (station Chalet).

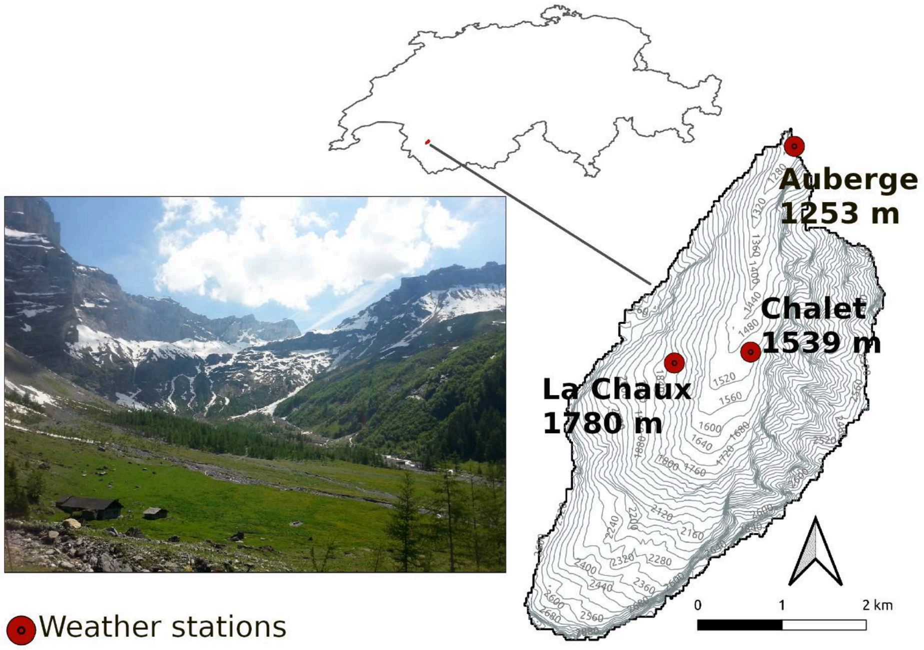


Table 1 - Main characteristics (altitudes, recording periods and fraction of missing data) of the measure- ments at the three weather stations.

Station	Altitude (meters)	Measurement availability period	Missing data
Auberge	1253	2012/01/01 - 2021-08-30	0.3%
Chalet	1539	2015/08/30 - 2021/08/30	21%
La Chaux	1780	2010/02/28 - 2021/08/30	8.6%

Altitudinal lapse rates

3 Several estimates of mean monthly and annual vertical temperature lapse rate have been proposed for mountain areas (Bardou, 2022; Daly et al., 2007; De Saintignon, 1976; Dougu´edroit and De Saintignon, 1984; Val´ery et al., 2010). Bou¨et (1985) defined such lapse rate for the whole of Switzerland by dis- tinguishing two layers of air, one below and one above 1500 m (Table 2). The temperature lapse rate can also be estimated as an annual average. The value of $6.5^{\circ}C.km^{-1}$ corresponds to the case of a standard atmosphere with an atmospheric pressure of 1013.25 hPa and a temperature of $15^{\circ}C$at sea level according to the International Civil Aviation Organization (ICAO) (Hack, 1978). Although this value is not necessarily suitable for representing spatial heterogeneity in mountainous regions, this work proposes to apply this average annual gradient value to define a reference case in order to estimate the impact of the choice of an annual or monthly temperature gradient.

Table 2 - Monthly vertical temperature lapse rates (C/100m) proposed by Bou¨et (1985) for two altitude layers.

Altitude layer (m.a.s.l.)	Jan	Feb	March	Apr	May	June	July	Aug	Sept	Oct	Nov	Dec	Year
500 - 1500	0.24	0.33	0.50	0.61	0.63	0.63	0.63	0.61	0.49	0.39	0.33	0.26	0.46
1500 - 4000	0.54	0.56	0.58	0.61	0.63	0.63	0.63	0.61	0.59	0.57	0.55	0.54	0.59

Other available temperature products

4 Temperatures from two other data sources are compared with temperatures obtained by interpolation of in situ measurements in the Nant valley.

CHCLIM25

5 The Swiss Office of Meteorology and Climatology provides estimates of climate variables at the kilometric resolution on a daily time step, integrating in situ measurements as well as satellite and radar data. The CHCLIM25 product is a high-resolution product developed by Broennimann (2018) based on a downscaling of MeteoSwiss kilometric data. The downscaling of the temperature maps is carried out using a variable lapse rate calibrated by linear regression in a mobile window of $25km^2$ (local regressions) and using the digital terrain model SWISSTOPO at 25 m horizontal resolution. The CHCLIM25 product is available since 1981 and for the future until 2099. Here, the monthly average temperatures over the period 2010- 2020 is used. Indeed, since the temperatures measured in the Nant valley are only available over this period, the choice is made to use the same period for the different products. The monthly average temperature provided by CHCLIM25 is used here.

ERA5

6 The ERA5 climate reanalysis provides climate variables at the hourly time step since 1950 at a horizontal resolution of 30 km over Europe (Mun˜oz-Sabater et al., 2021). The Nant valley is entirely included in an ERA5 grid with an average altitude of 1262 m.a.s.l. Despite the large scale envisaged for the ERA5 product, these data remain useful for several works in mountainous regions, in particular because of the length of its period of availability. A comparison between the ERA5 data and the in-situ measurements thus provides an illustration of the performance at the local scale of this product and could be taken into account for future works. As for the CHCLIM25 product, this work uses the temperature at 2 meters above the ground as a monthly average over 2010-2020, in order to remain consistent with the in situ measurements available over this period.

Methods

Interpolation by inverse weighted distance

7 Monthly temperatures are interpolated on the SWISSTOPO DEM grid at the 25 m resolution using the inverse distance method, weighted by the altitudinal lapse rate

8 Where $T(M)$ is the monthly temperature at grid point M; S_i the ith station of the station network, z_i the altitude of the station S_i, z_M the altitude at the grid point M, and d^{-1} the

inverse of the distance in latitude and longitude. The altitudinal gradientθcan then be defined in annual or monthly time steps, and uniform for the entire domain, or variable by altitude range.

Validation of monthly lapse rates at the weather stations

9 This section presents a validation test of the monthly lapse rates provided by Bou¨et (1985). The monthly average temperatures at each of the three stations are interpolated at the altitude of the other two stations using these lapse rates, depending on the altitudes of the stations. The computed time series can then be compared to the measurements at the station in order to carry out a cross-validation. Figure 2 presents the result of a cross-validation of the use of the monthly lapse rates of Bou¨et (1985) for the interpolation of the temperatures measured in the Nant valley. It can observed that using the lapse rates of Bou¨et (1985) leads to acceptable results for the interpolation of temperatures from the altitude of the Chalet station (1529 m). However, they are not satisfactory for interpolating temperatures at the altitude of the Auberge station (1253 m). This phenomenon could be explained by the accumulation of cold air at the bottom of the valley or another site eFFect at the bottom of the valley.

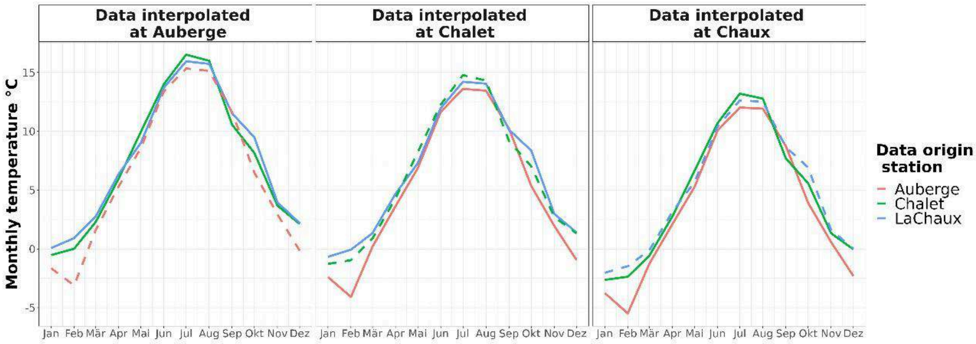
In-situ measurement campaign

10 Afield campaign was set up in July 2021 in order to have in-situ temperature measurements, which represent an additional data source for estimating the performance of the temperature products. In addition, local measurements better describe the local site eFFects in the valley. A series of 30 mini- temperature sensors distributed in the basin is installed, in particular at the bottom of the valley. The hourly recordings of these mini-sensors were collected in August 2022 and make it possible to better characterize the temperature diFFerences at the bottom of the valley compared to the rest of the basin.

Results

11 The monthly temperatures are interpolated on a 25 m resolution grid, from the SWISSTOPO digital terrain model. The CHCLIM25 product using this same terrain model, the temperature maps obtained by interpolation can be compared to the temperatures provided by CHCLIM25 at the monthly time step.

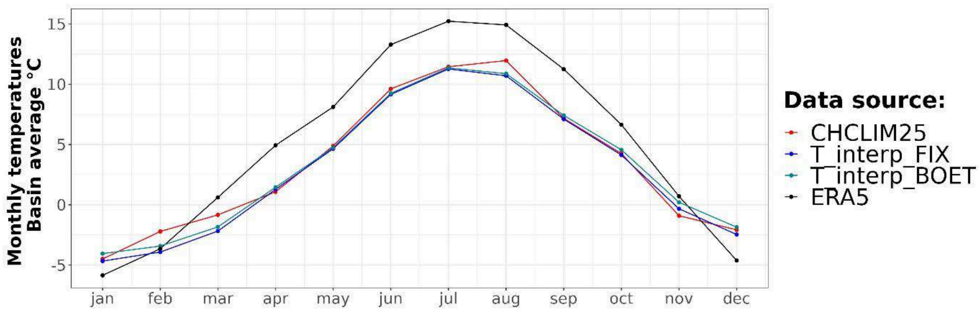
Figure 2 - Cross-validation of the monthly lapse rates of Bou¨et (1985) for the interpolation of the temperatures measured in the Nant valley. Long dashes: Reference observed station temperatures; Solid lines : temperatures interpolated at station from data at another station.



Annual dynamics of interpolated temperatures

12 Figure 3 presents the averages over the basin of monthly temperatures interpolated using either an annual lapse rate or the monthly lapse rates of Bou¨et (1985), as well as monthly temperatures CHCLIM25 and monthly temperatures ERA5. ERA5 temperatures are globally significantly higher than other data sources, especially during the summer. The use of this low resolution product (30 km) therefore seems poorly suited to the estimation of high resolution temperatures in mountain areas. The three data sources CHCLIM25, T interp FIX (interpolations using an annual gradient) and T interp BOET (interpolations using monthly lapse rates of Bou¨et (1985)) show small diﬀerences in summer. In winter (except for the month of February), the CHCLIM25 temperatures are closer to T interp BOET than to T interp FIX. Indeed, the two products CHCLIM25 and T interp BOET using variable monthly lapse rates, the amplitude of the seasonal dynamics can then be greater than when afixed annual gradient is used.

Figure 3 - Mean monthly temperatures over the watershed, interpolated using an annual gradient (T interp FIX) or monthly Bou¨et gradients (T interp BOET), monthly CHCLIM25 temperatures (CHCLIM25) and monthly average of the ERA5 data for the corresponding cell (ERA5).



Spatial distribution of interpolated temperatures

13 Figure 4 presents the maps of the diﬀerence between the monthly CHCLIM25 temperatures and the interpolated temperatures over the basin, using the monthly lapse rates of Bou¨et (1985). On overall, the interpolated temperatures, using an annual gradient or monthly lapse rates, are warmer than CHCLIM25 at the bottom of the valley

and colder than CHCLIM25 at the top of the slopes. The result can be explained by two reasons: i) The measurements at the stations locally influence the interpolation by inverse distance according to their respective biases, while these measurements are not taken into account by CHCLIM25;

14 The altitudinal temperature gradients are weaker in CHCLIM25 than the monthly lapse rates of Bou¨et (1985) (Figure 5). However, the respective influences of these two factors are not distinguished here. An additional source of locally reliable data would then be necessary in order to determine which of these two products is the most locally accurate.

Figure 4 - Difference between the temperatures interpolated over the basin from the monthly vertical lapse rates of Bou¨et (1985) and the monthly temperatures CHCLIM25. The red dots represent the three meteorological stations used.

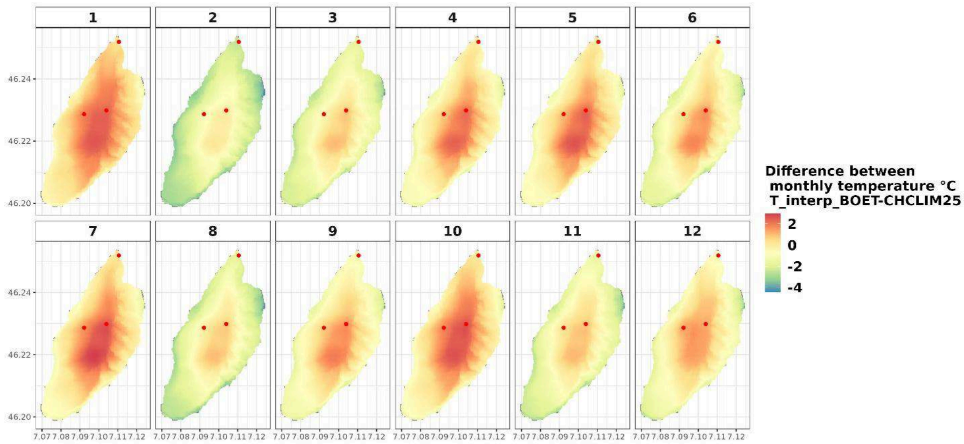
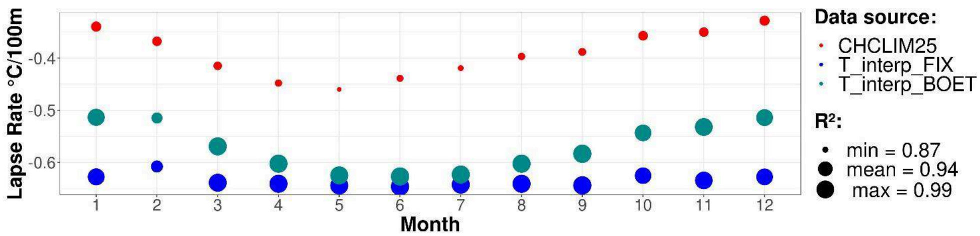


Figure 5 - Monthly temperature lapse rates obtained with the product CHLIM25, or with the interpolation products with monthly lapse rates (T INTERP BOET) or with fixed lapse rate (T interp FIX). The linear correlation coefficient R2 between the altitudes and the monthly temperatures is given by the size of the circles.



Influence of local site effects

15 Figure 6 shows the average hourly temperatures measured at the mini-temperature sensors, between July, 31th 2021 and July, 31th 2022. A marked phenomenon of cold air accumulation at the bottom of the valley is observed, with measurements at the bottom of the valleys up to 2.4°Clower than the measurements at the top of the slope. Additionally, Figure 7 shows the 24-hour average dynamics of temperatures recorded by three loggers: valley bottom, slope side, and slope summit. This result shows 1) that the accumulation of cold air at the bottom of the valley is greater in winter than in summer and that 2) in summer, the shift in sunshine between the bottom of the valley

and the top of the slope induces a strong shift in the diurnal temperature cycle. These measurements illustrate the impact of local site eFFects, due to the geomorphology of the site, via shading and air blocking eFFects. These phenomena are not represented in the interpolation products and their description can be improved in these products.

Figure 6 - Average hourly temperatures measured at the mini-temperature sensors, between July, 31th 2021 and July, 31th 2022. Logger 13, 19 and 24 are marked.

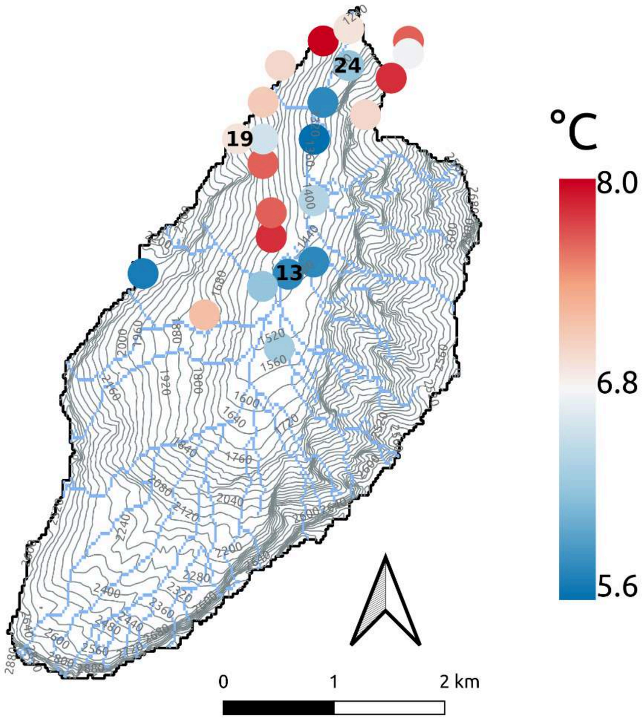
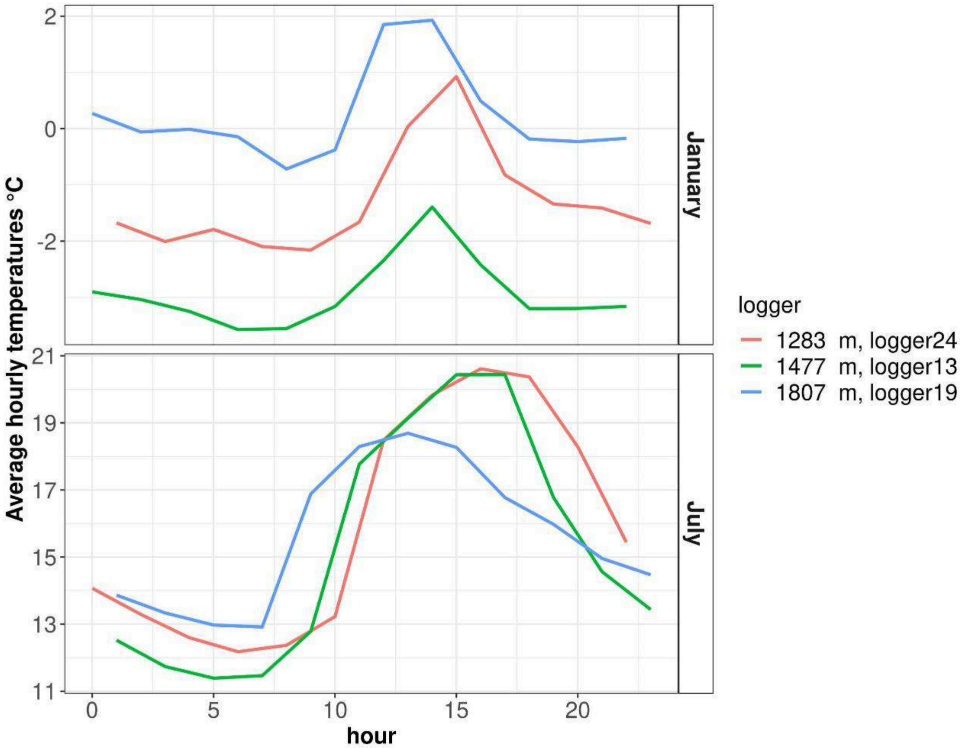


Figure 7 - Hourly dynamics of temperatures recorded by the mini-thermometers for the months of January 2021 and July 2021 at loggers 24 (alt. 1283 m), 13 (1477 m) and 19 (1807 m).



Perspectives: contribution of high-resolution modeling

16 The analysis of the measurements at the three weather stations, in particular in anticyclonic situations, shows that the influence of solar radiation and shading due to the relief on daytime temperatures is not negligible. Taking local orography into account can then improve the modeling of these high-resolution site eﬀects. The AWE-GEN-2d model (Advanced WEather GENerator for a 2-dimensional grid), developed by Peleg et al. (2017), is a stochastic weather generator that simulates meshed climate variables at high spatial and temporal resolution by integrating the impact of orography at the local scale. Hourly temperatures are modeled at a horizontal resolution of 25 m using only input data from the digital terrain model, hourly temperatures measured at the three available stations and the estimates of cloud cover provided by ERA5 for the studied area. The application of this model would then represent an additional data source for this inter-comparison work of the diﬀerent methods for estimating high-resolution temperatures in mountainous areas.

Conclusion

17 This work shows that the temporal dynamics of the temperatures interpolated by weighted inverse distance, coupled with the application of the monthly altitudinal lapse rates proposed by Bou¨et (1985) are well correlated, on average over the studied basin, with the temperatures provided by the high resolution temperature product CHCLIM25. We also observe that the temperatures provided by the ERA5 climatic

reanalysis are higher, on average over the studied basin, than the other studied products, due to the low resolution of the ERA5 product (30 km), which does not take local orography into account. Finally, the choice of the lapse rate (annual or monthly) in the interpolation method does not significantly impact these results. By observing the spatial distributions of the temperaturefields, this work shows that the main diFFerence between the interpolated temperaturefields and the CHCLIM25 temperatures consists of the diFFerence in the values at the bottom of the valley. This result can be explained on the one hand by the inclusion of in situ measurements in the interpolation and on the other hand by the value of the applied altitudinal lapse rates. The results of the in-situ measurement campaign show that the site eFFects (shading and accumulation of cold air) at the bottom of the valley, not modeled in either of the studied interpolation methods, have a significant impact on the temperatures at two meters above the ground. The collection of temperature recordings at many measurement points in the basin then provide an additional source of data, locally accurate, in order to estimate the performance of the various interpolation products studied. Finally, taking into account the impact of orography will make it possible to model site eFFects on a local scale.

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ABSTRACTS

This work compares several methods for estimating high-resolution air temperatures in mountain areas. The case study of a small alpine valley (the Nant valley, canton of Vaud, Switzerland) is used. An interpolation of measurements at three meteorological stations is carried out by applying a weighted inverse distance method, coupled with an altitudinal correction. DiFFerent temperature estimation products are compared in order to assess the performance of interpolation methods: products from CHCLIM25 downscaling, as well as outputs from the ERA5 climate reanalysis. The influence of the use of monthly or annual altitudinal temperature lapse rates is tested. An in-situ measurement network using mini thermometers is also set up to estimate the influence of local site eFFects on temperatures. This work shows that the interpolation of temperatures from in situ measurements, coupled with a monthly temperature lapse rate, makes it possible to model the annual dynamics of temperatures well, however the representation of the eFFects of local sites can be refined.

Ce travail compare plusieurs méthodes d'estimation des températures de l'air à haute résolution en zone de montagne. Le cas d'étude d'un petit vallon alpin (vallon de Nant, canton de Vaud, Suisse) est utilisé. Une interpolation des mesures au niveau de trois stations météorologiques est menée en appliquant une méthode d'inverse distance pondérée, couplée à une correction altitudinale. Différents produits d'estimation des températures sont comparés afin d'évaluer les performances des méthodes d'interpolation : les produits issus de descente d'échelle CHCLIM25, ainsi que les sorties de ré analyses climatiques ERA5. L'influence de l'utilisation de gradients altitudinaux de température mensuels ou annuels est testée. Un réseau de mesure in-situ via des mini thermomètres est également mis en place afin d'estimer l'influence des effets de site locaux sur les températures. Ce travail montre que l'interpolation des températures à partir de mesures in situ, couplée avec un gradient thermique mensuel, permet de bien modéliser la dynamique annuelle des températures, cependant la représentation des effets de sites locaux peut être affinée.

INDEX

Keywords: Swiss alps, air temperature, spatial interpolation, High resolution, Climatology
Mots-clés: Alpes swisses, interpolation spatiale, température de l'air, haute résolution, climatologie

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