High Resolution Temperature Climatology in Complex Terrain – demonstrated in the test area Greater Alpine Region GAR

Final Report

by

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1. Motivation

High resolution climatologies offer a broad spectrum of opportunities for further applications in climate and climate change research. Although this is a well-known fact, up to now a temperature climatology has not existed for the Alpine Region. For precipitation, Frei and Schär, 1998 provided a highly resolved Alpine precipitation climatology based on measurements of some 6000 stations.

The Greater Alpine Region (GAR) has been defined as a region lying between 4-19°E and 43-49°N. At continental scale, it constitutes a sharp “climate divide” in the transitional zone between Atlantic, continental and Mediterranean influences. Its complex terrain ranges between sea level and 4,810 m (Mont Blanc) including mountain peaks, small scale valleys, plains and plateaus, cities with urban heat islands, littorals, glaciated and forested areas, and other landscape features.

The Alpine station network is one of the densest in the world, its area covers about 700000 km² encompassing 13 different national and even sub-national special features, which are often inhomogeneous in their observing practices. Some National Weather Services (NMSs) and research institutes already elaborated national as well as regional climatologies (see list of references). When trying to merge them together however, significant discontinuities appear at the borders, due to the mentioned inhomogeneous observation practices. Also spatial analysis methods and underlying geographical information, and temperature features of neighbouring countries usually are not considered by national analyses projects. At the other tail of the spectrum, Meteo France published the ECSN Climate Atlas of Europe on CD in 2004. Based on only 700 stations for the study region, this coarse Atlas provides a more general overview but cannot reproduce any small scale features. Note for example the not existing Alps in Fig.1

![Figure 1: Annual mean temperature in the period 1971-2000; Map produced within the ECSN Climate Atlas of Europe, Meteo France, 2004](image)

Therefore, the project team of ECSN – HRT/GAR aimed to prepare a High Resolution Climatology for the Greater Alpine Region (4-19°E and 43-49°N) for a 30yrs period with a temporal resolution of 1 month and a spatial resolution of 1 km x 1 km.
2. Project History

In the late 1990s an informal collaboration of a number of countries was established in order to create and maintain the HISTALP data set (Auer et al., 2007). It was more or less this group who agreed to extend that collaboration by calculating common mean monthly temperature fields for the GAR.

In October 2005, at the 26th EUMENET Council, the ECSN HRT/GAR project was approved, the informal collaboration has turned into a formal ECSN partnership including eight ECSN members and non-ECSN members, EU members and countries in transition, Alpine and non-Alpine countries, weather services and research institutes. Project duration was decided for two years starting in January 2006 and ZAMG has been appointed being the responsible project manager.

Table 2: The formal ECSN Partnership

- Austria – Central Institute for Meteorology and Geodynamics
- France – Meteo France
- Germany – Deutscher Wetterdienst
- Hungary – Meteorological Service of Hungary
- Italy – Aeronautica Militare
- Luxembourg – Service météorologique Administration de l’aéroport de Luxembourg
- Norway – Det Norske Meteorologiske Institut
- Switzerland – Meteo Swiss
- United Kingdom – Met Office

Besides the former ECSN community several partners informally supported the project with manpower, data and their national and regional experience. In particular, three Italian treering researchers (Marco Carrer, UNi-Padova, Paola Nola, Uni-Pavia, Renzo Motta, Uni-Torino) stand out by providing a great number of Italian tx-tn-datasets.

Two nationally funded parallel activities supported our project to a great extent, namely:

“The Croatian Climate Atlas”

"HRT NI - High Resolution Temperature Climatology Northern Italy with a special report in Annex 3"
3. Preparation of the data set

Data collection was characterised by an intensive search for existing temperature data for the period 1961-1990 with the leading principle to achieve the highest possible spatial density. High data density is fundamental due to the strong vertical structure of the Alps. The period 1961-1990 was chosen because many weather services had already invested intensive work on data of this official recent WMO – CLINO period.

A more recent period 1971-2000 would have caused major problems, especially in Italy, where a fundamental re-organisation of the existing networks took place during the 1990s. The original number of collected single station datasets was approximately 1800, but not all of them eventually met the requirements in terms of completeness and data-quality. Most of the data were provided in digital form, but data of 187 stations were digitised by ZAMG staff in order to elaborate a station network as dense as possible.

Before the gathered data were ready for analysis, a special quality control was applied. This concerned not only the data themselves, but also the metadata (e.g. coordinates). Fig.2 shows one example of the time consuming but necessary work on exact station location.

![Figure 2: Reconstruction of coordinates of the Meteo Trentino station Passo Tonale (lat:46.2633, long:10.5977, 1880 m s.l.m.), photo source: Meteo Trentino](image)

All activities concerning data collection, correction and adjustments are described in Annex 1 to this report.
4. Construction of the Alpine Temperature Climatology

The climate normals that could actually be used to construct the Alpine Temperature Climatology were 1726, 1448 of them located within GAR. For stage 1 (i.e. regression calculation) another 98 stations had to be postponed due to city centre location (37), direct coast location (35) and extreme inversion location (12) and some due to unknown reasons (14). All in all 1628 stations have been used for the first and overall regression calculation.

After calculating multiple linear regressions and analyses of residuals (details in Annex 2), spatial interpolation of air temperature has been performed within sub-regions. Due to the analyses of residuals six rough-and-ready horizontal sub-regions have been defined, the exact definition of borders was then based on additional regional expert knowledge of project participants. Figure 4 displays the six principal sub-regions with clear borders at the main ridges of the Alps and of the Apennines, but unclear situations in Friuli – Istrìa and the interior Alpine region. For the vertical dimension, an additional group H (stations between 1501 and 3580 m asl) has been defined (Figure 5).

Figure 3: The final ECSN/HRT-GAR station network with climate normals of 1726 climate stations for the period 1961-1990
Figure 4: Map of the six principal horizontal sub-regions within ECSN/HRT-GAR: W–West, N–North, E–East, S–South, C–Eastern Adriatic Coast, P–Po Plain

Figure 5: Vertical sub-region H above 1500 m asl.

Station density was found varying in the different regions. Highest station density was provided in sub-region N, lowest in sub-region W (compare Table 2)
Table 2: Station density in different sub-regions of GAR

<table>
<thead>
<tr>
<th>Sub-region</th>
<th>No. of stations</th>
<th>Station density (1000 km⁻²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>37</td>
<td>0.2</td>
</tr>
<tr>
<td>N</td>
<td>694</td>
<td>2.9</td>
</tr>
<tr>
<td>E</td>
<td>380</td>
<td>2.2</td>
</tr>
<tr>
<td>C</td>
<td>128</td>
<td>0.7</td>
</tr>
<tr>
<td>S</td>
<td>54</td>
<td>1.1</td>
</tr>
<tr>
<td>P</td>
<td>237</td>
<td>2.0</td>
</tr>
<tr>
<td>H</td>
<td>98</td>
<td>1.4</td>
</tr>
</tbody>
</table>

Considering seven sub-regions for every month, seven multiple regressions had to be calculated in the form:

\[ t = a*λ + b*φ + c*z + d*cd + e \]

with

- \( λ \) : longitude
- \( φ \) : latitude
- \( z \) : altitude
- \( cd \) : z-weighted coast distance

However, calculating regressions within two vertical sub-regions only, an artificial break appeared at 1500 m as can be seen in Figure 6. Thus it was decided to work with three vertical layers, 1-700 m, 701-1800 m and 1801-3580 m. For the intermediate layer, an interpolation has been performed at every 1*1km raster pixel.

Figure 6: Comparison of calculated regressions within a two layer and a three layer model.

Now, on the basis of six horizontal and three vertical sub-regions the first raw maps could be drawn. The example map of January is displayed in Figure 7. The same Figure shows the respective residuals within a range of +/- 3.5°C. The regional distribution of residuals offer a number of possibilities for further improvement, such as inversions, coasts, lakeshore, cities and slopes.

A number of such effects were investigated during a special Workshop which has taken place in Vienna in February 2007. A summary of these studies is given in Annex 2.
4.1. Further improvements by working on inversions

13 inversion areas have been identified: Po Plain, Swiss high valleys, Giudicarie, Trentino, Inn Valley, Cadore, Puster Valley, Val Canale, Klagenfurter Basin, Salzach Valley, Mura Valley, Enns Valley, Graz Basin. Examples for the vertical January residual distributions representing inversions are given in Figure 8. A
mean correcting factor in a clear defined altitude (compare Table 3) range has been calculated. This procedure was performed for every single month. Inversions show a prominent annual course which is strongest in December and January with negative temperature deviations up to 3°C. Some of the inversions disappear during summer, but not all of them. Especially Cadore, Swiss high valleys and the Graz Basin are cooler the whole year round (Figure 9). Details in Annex 2

**Figure 8:** Examples for inversions: Height dependence of January temperature residuals for Po Plain and the Salzach Valley. The adjustment factors have been calculated with -0.7°C for Po Plain and -1.9°C for Salzach Valley. The elevation range has been determined with < 250 m in the Po Plain and 500-1000 m in the Salzach Valley. Note the positive residuals in both cases at higher altitudes – they were subject of slope-corrections later (section 4.5)

**Table 3:** Altitude range for adjustment in 13 inversion regions in the GAR

<table>
<thead>
<tr>
<th>area</th>
<th>adjustment range [m asl.]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swiss high valleys</td>
<td>1500–2100</td>
</tr>
<tr>
<td>Inn Valley</td>
<td>&lt;1500</td>
</tr>
<tr>
<td>Giudicarie</td>
<td>&lt;800</td>
</tr>
<tr>
<td>Trentino</td>
<td>&lt;600</td>
</tr>
<tr>
<td>Puster Valley</td>
<td>1000–1600</td>
</tr>
<tr>
<td>Cadore</td>
<td>&lt;1100</td>
</tr>
<tr>
<td>Salzach Valley</td>
<td>&lt;1000</td>
</tr>
<tr>
<td>Klagenfurt Basin</td>
<td>&lt;700</td>
</tr>
<tr>
<td>Val Canale</td>
<td>300–1000</td>
</tr>
<tr>
<td>Mura Valley</td>
<td>&lt;1300</td>
</tr>
<tr>
<td>Enns Valley</td>
<td>&lt;900</td>
</tr>
<tr>
<td>Graz Basin</td>
<td>&lt;400</td>
</tr>
<tr>
<td>Po Plain</td>
<td>&lt;250</td>
</tr>
</tbody>
</table>
4.2. Improvement by working on coast lines

Three areas have been defined (Figure 11) in order to improve the temperature fields near the coastline of Golfe du Lion, Ligurian and Adriatic Sea. Within the 6km-coastline belt, at a distance of 0km maximum adjustments of up +3°C in January and December were taken into account and residuals converged to 0°C at 6km distance. In summer, smaller negative adjustments had to be added. The annual course of maximum adjustments at 0 km distance to coast is displayed in Figure 12.

Note that the coastline correction is not the only consideration of oceanic influence in the analysis. The “altitude weighted coast distance” was already subject of the initial multiple regression models of the coarse resolution principal subregions (Figs. 4 and 5).
Working on coastal areas led to a further improvement of the ECSN/HRT-GAR climatology, as can be seen in Figure 13.

Figure 11: Regionalisation of coast lines for the sub-regions W, P and S.

Figure 12: Annual course of temperature adjustments at 0 km coast distance.

Figure 13: Improvement of the ECSN/HRT-GAR climatology by working on coastlines. left: example of raw January map of Gulf of Lion, right: example of improved January map of Gulf of Lion by adjusting +2.9K (0 km) – 0K (6 km).
4.3. Improvement by working on lake shores

The surroundings of ten lakes or groups of lakes covering more than 10 km$^2$, - except shallow lakes like Lake Balaton or Lake Neusiedl have been used to apply further improvements on the maps (Figure 14).

![Figure 14: Map of GAR displaying 10 lakes regions for ECSN/HRT-GAR climatology improvement.](image)

Temperature of waterside stations at lakes has been compared to altitude adjusted lake surrounding stations. The total difference has been used for the lake area and within a 0-1 km buffer. Half of the difference has been applied within a 1-2 km buffer. The annual course of temperature adjustments is given in Figure 15. Details are in Annex 2.

![Figure 15: Annual course of lake shore adjustments for the improvement of the ECSN/HRT-GAR climatology.](image)
Working on lake surroundings led to a further improvement of the ECSN/HRT-GAR climatology, as can be seen in Figure 16.

Figure 16: Improvement of the ECSN/HRT-GAR climatology by working on lake areas: left: example of raw January map of Northern Italy, right: example of improved January map of Northern Italy by adjusting +1.9 K within 0-1 km and 0.9 K with 1-2 km distance from lakefront. Left: Raw map, improved map.

4.4. Further improvement by working on cities

Cities were identified using the 1-km pan-European land cover database PELCOM (Pan-European Land Use and Land Cover Monitoring, http://www.geoinformatie.nl/projects/pelcom/public/index.htm). Cities have been grouped into mega-cities (>200 km²) and large cities (20-200 km²) separately for the North/East and cities in the South. Temperature of city-centre stations has been compared to altitude adjusted surrounding rural stations. For city centres the total difference, for suburbs within a 0–1 or 0–2 km buffer half the difference has been used for correction. The ECSN HRT-GAR network offered twelve usable urban–rural station ensembles. Details are in Annex 2.

Figure 17: Land-use data of PELCOM. Left: Identifying cities, right: division of cities into mega-cities (>200 km²) and large cities (20–200 km²) and N (dark and light blue) and S (red and orange)
Figure 18: The city of Vienna and surroundings stations.

Figure 19: Annual course of urban heat island temperature difference: left: single stations, right: averaged and filtered course of urban heat island temperature difference for four groups of cities.
Figure 20: Improvement of the ECSN/HRT-GAR climatology by working on cities: left: example of raw January map showing Vienna and surroundings, right: example of improved January map of Northern Vienna and surroundings by adjusting +1.5 K for the city centre and 0.8 K for suburbs.

### 4.5. Further improvement by working on slopes

Using the DEM all slopes > 10° were identified and classified depending on their N, NW/NE, W/E, SW/SE, S aspects.

Figure 21: GAR topography classified for slopes 10° and aspects of N, NW/NE, W/E, SW/SE, S.
For a subset of 100 sites with a sufficient site description a number of different shape-effects showed systematic mean temperature deviations from topographically neutral locations. The strongest (valleys and basins) were considered already under section 4.1, ranking second were slopes for which Figure 22 shows the mean monthly corrections which were applied. Details are in Annex 2.

**Figure 22:** Annual course of adjustments to correct slopes due to the aspects based on a station sample of 85 Austrian sites with extensive topographic descriptions. For Ticino January map e.g. corrections between 0.3 and 0.9K had been applied

**Figure 23:** January temperature field, left: raw map, right improved map with slope adjustment of +0.3 for N, +0.5 for NW/NE, +0.6 for W/E, +0.7 for SW/SE and +0.9K for S orientated slopes.
5. The Final monthly climatologies

Figure 24: Finalised temperature climatologies for January (top) and July (bottom).
After the application of all the described improvements, final monthly climatologies have been calculated. It was a long way to reach the desirable goal of a standard error (SE) below 1K (varying between SE04=0.648, SE12=0.887). We would like to stress that this remaining SE is only partly an error and our ultimate goal was not to reach SE=0K. We have to consider that stations always contain also local peculiarities and do not represent data of a 100% neutral surrounding. Figure 25 displays the way of map improvements from overall simple regression, to overall multiple regression, to regionalisation until final improvements by adjustments for inversions, sea shores, lake shores, cities and slopes.

Figure 25: Remaining standard error of monthly ECSN/HRT-GAR temperature climatologies by applying step by step improvements.
6. Outlook

The created ECSN/HRT-GAR temperature climatology is a high quality data product for a European region with a complex and complicated terrain. Its results are based on the special experience and knowledge of experts of the involved countries, however methods and findings may well be generalised and transferred to other regions. The dataset is now available and ready to support further climate and climate impact research. Here we can present only some of our plans and ideas.

- Making the dataset available (website of ZAMG).
- Producing additional versions at other resolutions: for local practical applications a higher resolution (e.g.: by adding to each 1km² pixel a local vertical lapse rate) would be desirable, or a lower resolution comparative to other existing datasets (e.g. the 1/6° lat-long like the respective precipitation dataset of Efthymiadis et al., 2006 or the ½° lat-long for the continental scale CRU dataset.
- Blending ECSN/HRT-GAR with the long-term HISTALP series to a series of high resolution monthly temperature fields back to 1760 like it was done for precipitation by Efthymiadis et al., 2006: Producing medium resolution three-dimensional monthly anomaly-fields based on the long-term HISTALP series back to 1760 - fit the resolution of the anomaly fields to the achieved 1km resolution - add the anomaly fields to the 1961-90 mean HR-fields - test the results vs. real station data in a data rich period apart from 1961-90
- Using a close fit (tanh) of the liquid-solid precipitation ratio in order to split an already existing long-term precipitation dataset (Efthymiadis et al, 2006) into the solid and liquid components: The basic idea is based on the fact that the solid/liquid precipitation ratio is closely correlated to mean monthly temperature. This allows for splitting the existing Efthymiadis-precipitation dataset (monthly fields since 1800 at 1/6° resolution) into a solid and a liquid part. This method was already successfully applied to some locations in Austria and Switzerland.
7. Project Workshops

- 02-03 February 2006: kick-off meeting in Vienna
- 07 September 2006: ECSN/HRT-GAR Core Group Meeting in Ljubljana during EMS/ECSN 2006
- 20 February 2007: Workshop on study of geographical specifics of air temperature in the GAR
- 2008 04 20: Public Project Presentation and internal Workshop on "post"-project activities

8. Project presentations

- 16-17March 2006: Österreichischer Klimatag, poster
- Final COST-719 Workshop: First steps towards a new Temperature Climatology of the Greater Alpine Region (GAR), oral presentation
- November 2006: oral presentation of ECSN/HRT-GAR activities on the occasion of the 1st MedCLivar Workshop in Carmona-Seville, Spain

8. Project presentations


9. Papers

Based on the ECSN/HRT-GAR grids on request two tailored maps have been produced to be included in the 2nd Report of the state of the Alps (Alpenzustandsbericht). focus: water for the Alpine Convention (Alpenkonvention)

10. References


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Paola Nola – University of Pavia
Giancarlo Rossi – Venice
Renzo Motta – University of Torino
Claude Alesch – Service météorologique de Luxembourg
Ole Einar Tveito – Norwegian Meteorological Institute
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Matthew Perry – UK Met Office
Oliver Bochnicek – Slovak Hydro-meteorological Institute
Zelko Mastorovic, MeteoBiH
Gerhard Müller-Westermeier und Peter Bissoli - Deutscher Wetterdienst
Ksenija Zaninovic, Croatian Weather Service
Tanja Cegnar, Mojca Dolinar - ARSO
Zita Bihari – OMSZ, Budapest:
ANNEX 1

DATA PROCESSING
ANNEX 2

GEOGRAPHICAL SPECIFICS OF AIR TEMPERATURE AND THE GENERAL CONCEPT OF HIGH RESOLUTION SPATIAL ANALYSIS
ANNEX 3

TECHNICAL REPORT OF A NORTHERN ITALIAN RELATED PROJECT
ANNEX 4

PAPER COPIES OF 12 MEAN MONTHLY TEMPERATURE MAPS OF THE ALPINE CORE PART OF GAR
Annex 1 to Final Report

DATA PROCESSING
FOR A HIGH RESOLUTION ALPINE TEMPERATURE CLIMATOLOGY
(ECSN/HRT-GAR)

Vienna, June 2008
DATA PROCESSING FOR A HIGH RESOLUTION ALPINE TEMPERATURE CLIMATOLOGY (ECSN/HRT-GAR)

1. The original data (data sources, providers...)

The initial phase of the Alpine temperature mapping activity was characterised by an intensive search for all existing regular temperature data for the GAR (Greater Alpine Region). The leading principle was to achieve the highest possible spatial density of monthly temperature means for the period 1961-90. High data density is fundamental due to the strong vertical structure of the Alps which causes sub-grid-effects anyway easier to be modelled when network density allows for representative and significant regression analysis also in sub-regions like coasts, cities, inner-alpine basins and others.

The 1961-90-period was chosen because weather services had already invested work into this official WMO-CLINO period. A more recent period (1971-2000 for example) would have caused problems in respect to the inclusion of the 1990s (especially in Italy where a fundamental re-organisation of the existing networks took place in the 1990s). A longer period (e.g. 20th century) would have caused other severe problems in terms of the gaps during the 2 world wars, sparser networks in general and organisational and political breaks. The 1961-90 CLINO-sample is not necessarily the ultimate goal. The 1971-2000 climatology can produced better by working on differences between 1961-1990 and 1971-2000 by including all ECSN/HRT-GAR findings. It is planned to produce any other climatology in a further step (see chapter 6. Outlook). Extensions much further back (late 18th century) can be performed by merging ECSN/HRT-GAR climatology with the HISTALP long-term dataset (Auer et al., 2007) using a similar approach as described for precipitation by Efthymiadis et al., 2005.

To achieve a maximum high spatial density, another precondition was handled less restrictive – full 30-years temporal coverage without gaps was not defined as binding condition. We accepted also datasets with gaps and such which covered earlier or later samples than 1961-90 if highly correlated neighbouring datasets allowed for filling the gaps or adjusting to the reference period - for both purposes a stability of the mean differences between highly correlated series was assumed.

The climatologically interesting but politically and administratively highly scattered “Greater Alpine Region” afforded a time consuming period for data detection, organisation and also digitising. The data collecting finally resulted in about 1800 single station datasets of monthly mean temperatures ($t_m$) or mean daily extremes ($t_x$ and $t_n$) from various providers in the region. Details are shown in Table 1.
Table 1: Overview of data and its sources

<table>
<thead>
<tr>
<th>Country</th>
<th>data source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Austria</td>
<td>ZAMG climate data base</td>
</tr>
<tr>
<td>Austria</td>
<td>Yearbooks of Hydrographical Service of Austria</td>
</tr>
<tr>
<td>Bosnia &amp; Herzegovina</td>
<td>METEOBiH / Zelko Majstorovic</td>
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<td>Yugoslavian Yearbooks</td>
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<td>DHMZ / Ksenija Zaninovic</td>
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<tr>
<td>Czech Republic</td>
<td>CHMI / Vit Kveton</td>
</tr>
<tr>
<td>Germany</td>
<td>DWD / Gerhard Müller - Westermeier</td>
</tr>
<tr>
<td>France</td>
<td>Meteo France / Jean-Marc Moisselin</td>
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<td>Hungary</td>
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<td>Italy</td>
<td>Marco Carrer / University of Padua</td>
</tr>
<tr>
<td>Italy</td>
<td>Maurizio Maugeri / University of Milano</td>
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<td>Italy</td>
<td>Società Meteorologica Italianana</td>
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<td>Italy</td>
<td>Paola Nola; Renzo Motta / University of Pavia, University of Torino</td>
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<td>Switzerland</td>
<td>Meteo Swiss / Michael Begert</td>
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</tbody>
</table>

2. Station locations (coordinate corrections, urban, rural and other specific environments)

The original number of collected single station datasets was approximately 1800 but not all of them finally met the requirements in terms of completeness and data-quality. In a first step duplicates referring to the same site had to be eliminated (which was not clear in each case before a closer look at site-names and coordinates, queries at the data-providers,...). Some of the duplicates were different datasets under the same name and needed a further specification (typically cities with more than one measuring site).

A major problem appeared and had to be solved which is typical for any project which targets at high-resolution spatial climate analysis - the problem of coordinate errors. In former times, the exact geographical position of a measuring site was regarded essential more for the altitude, less for the longitude and latitude parameters. The now existing highly resolved elevation and land-use grids (we planned to use a resolution of at least 1km plus an algorithm to deal with sub-grid elevation variability within) now afford a much more precise anchoring of the measuring sites into the elevation and land-use models to fully exploit their now given wider potential through GIS-based analysis. Examples are the inclusion of land-use effects on temperature (urban-rural, glaciers, lakes, etc), the influence of the local land-forms (basins, slopes, summits,) and a visual residual analysis of the different steps of the modelled \( t_m \) fields versus the point information of the single sites. All those (and a number of other applications) afford precise information on longitude, latitude and altitude of stations.
It was an absolute necessity for further analysis to check each single site location because the majority of coordinates had intolerable location errors for the planned application. The errors were nearly exclusively referring to the longitude and latitude, altitude was much more accurate. The vast majority of errors originated from the fact that many data providers only used geographical degrees and minutes and no subdivision into seconds. This alone shifts some summit stations into nearby valleys, coastal sites into the sea, urban sites into rural surrounding and other intolerable facts.

Of course, it was not possible to visit the real sites and check their location. It was a combined approach of using the station history files and yearbooks, contacting the data providers, and scanning printed maps and digital sources like Encarta, Google-Earth and also internet requests for single sites (e.g. mountain resorts, summits etc...).

3. Adjustment to common 1961-90 reference period (gap-filling and adjustments from other than 1961-90 samples)

Taking into account the existing long-term temperature variability in the region (Fig.1) it is essential to refer all data to a common period.

![Figure1. Annual mean temperatures in the GAR 1760-2003 (anomalies from 1901-2000), green: single years, black: 30-year-CLINO-means, pink: 19th and 20th century means, red: 1971-2000](image)

As already mentioned, one of the reasons to choose the 1961-90 reference was the incomparably greater number of complete datasets compared to others. For France, Switzerland, Germany, Austria, Czech Republic, Slovak Republic, Hungary, Slovenia and Croatia all monthly averages were already either directly calculated from complete datasets or adjusted to the common 1961-90 reference period. For Italy and Bosnia & Herzegovina some of the sampled datasets had either gaps or did not cover the entire 1961-90 period. Some of them were much longer (in single cases reaching back into the 1920s) but ended before 1990. Apart from the respective HISTALP sites (where gap closing had been done already, Auer et al., 2007) the vast majority of incomplete datasets could be gap-filled and/or adjusted using highly correlated comparative station datasets and assuming constancy of the inter-station \( t_m \)-differences.
Finally a network of about 1726 stations (Fig.2) passed the location-correction and the gap-filling and sample adjustment procedures.

![Figure 2: The ECSN HRT-GAR network, black squares indicate mountain stations](image_url)

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4. **Adjustment to common means-calculation (regionalisation according to DTR – estimating mean daily courses for sub-regions or single sites – estimation and elimination of means calculation biases)**

As indicated in Table 2 the observation times and therefore calculation algorithms were not same for provided data. They had to be adjusted before being analysed.
Table 2: Used algorithms for the calculation of monthly mean temperature in the GAR during 1961-1990 (status of provided data)

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Country</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>((7+14+21)/4)</td>
<td>Bosnia &amp; Herzegovina</td>
<td>MLT</td>
</tr>
<tr>
<td></td>
<td>Czech Republic</td>
<td>MLT</td>
</tr>
<tr>
<td></td>
<td>Germany 1961-1986</td>
<td>MLT</td>
</tr>
<tr>
<td></td>
<td>Croatia</td>
<td>MLT</td>
</tr>
<tr>
<td></td>
<td>Hungary</td>
<td>MLT</td>
</tr>
<tr>
<td></td>
<td>Slovenia</td>
<td>MLT</td>
</tr>
<tr>
<td></td>
<td>Slovakia</td>
<td>MLT</td>
</tr>
<tr>
<td>((7.30+14.30+2\times21.30)/4)</td>
<td>Germany 1987-1990</td>
<td>CET</td>
</tr>
<tr>
<td>((tx+tn)/2)</td>
<td>France</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Italy</td>
<td></td>
</tr>
<tr>
<td>pre-adjusted to TRMs</td>
<td>Austria</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Switzerland</td>
<td></td>
</tr>
</tbody>
</table>

About half of the provided data were based on the Kämtz-Formula (Kämtz, 1860)
\[ t_m = \frac{(t_7 + t_{14} + 2*t_{21})}{4}, \]
observing times in MLT a quarter as “true means” (TRMs), either based on hourly values or pre-adjusted to TRMs.

A quarter based on the mean daily extremes \[ t_m = \frac{(t_x+t_n)}{2} \]

Studies for the territory of Austria (e.g. Auer et al., 2001) based on a 10-years 50-stations-dataset (1986-1995) of hourly temperature measurements (henceforth called AT-T24-50) shows that the differences between the 2 estimates and the TRMs are not negligible. Fig. 3 gives respective examples for the biases of the Kämtz-formula and the \((t_x+t_n)/2\)-estimate in some sub-regions of Austria.

Figure 3: Biases of the two estimates for temperature means calculation in respect to the true mean (TRM) derived from the AT-T24-50 dataset

It is evident that the Kämtz-formula is the better estimate for the true means and its maximum 0.2K deviations from TRM can be tolerated for climate mapping compared to other uncertainties which can be expected to produce a remaining mean residual of point measurements vs. HR-fields of approximately 0.5K (Böhm and Potzmann, 1999). The estimate based on \((t_x+t_n)/2\) however exceeds the
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0.5K-threshold in some months and must be regarded as too strongly biased to merge it with the other two groups of data present in the dataset. Table 2 indicates another potential bias in means estimation, the use of CET or MLT for climate observations and measurements. We hope to have thoroughly reconstructed the official respective regulations in the different networks. One of the regulations followed everywhere is the (physically meaningful) neglecting of any daylight saving regulations. But there might be also certain discrepancies between the official regulation and the everyday routine at single stations. Anyway the example of Fig. 4 of a (fictitious) one hour shift of observing times in summer (which would be the “worst case” for any biases in respect to incorrect use of time regulations) demonstrates that such biases are also very small in respect to an application for climate mapping.

![Graph showing bias in K with months and altitude bands]

Figure 4: Potential bias of a Kämtz- \( t_m \)-estimate if daylight saving time (DST) regulation was not neglected

The final decision on the optimal means-estimate for our application was to use the Kämtz-formula. This allowed about half of the data to be included without change, to apply minor adjustments to those with TRMs and to concentrate on finding feasible solutions for the stronger adjustments necessary for French and Italian stations using \((t_x + t_n)/2\).

In detail:

**Austria:** A simple and direct inclusion of means from ZAMG’ and HZB’s climate databases was not possible due to the discrepancies and breaks of observing times in the CLINO period. All datasets had been gap-filled, adjusted to the 1961-1990-period and to TRM already (Auer et al., 2001b). In addition to that, the described AT-T24-50 dataset of mean daily temperature courses (DTC) in 6 Austrian sub-regions plus a DTR-analysis (mean daily temperature range) is used as the basis to derive respective corrections for the other subsets with biased means. Fig. 5 shows typical examples of such mean daily courses for four of the detected six homogeneous sub-regions (2 extra-alpine ones and an inner-alpine one subdivided into 4 altitude bands). Together with an analysis of DTRs (resulting in a best estimate of a factor of 0.9 between the DTR as the difference of really measured daily extremes and the DTR as the difference of the highest and lowest hourly temperature) these data were used to re-adjust the Austrian temperature means to the Kämtz-formula.
Annex 1: DATA PROCESSING within ECSN/HRT-GAR

The Austrian DTCs were also taken as the basis to produce DTC-estimates for Switzerland, Italy and France in order to produce Kämtz- \( t_m \)-estimates also there (details on the following).

![Graphs of daily mean temperature anomalies for different regions](image)

**Figure 5:** Mean daily temperature-courses (DTCs) for January, April, July and October in 4 Austrian sub-regions (sample: AT-T24-50 dataset)

**Switzerland:** MeteoSwiss provided a 91-station dataset of 1961-1990 monthly \( t_n \)-, \( t_x \)- and \( t_m \)-means, \( t_m \) either directly measured (ANETZ-sites) or pre-adjusted (conventional sites) to TRMs. Therefore a relatively simple procedure could be applied to produce first the respective DTRs and DTCs and in a second step derive from them the adjustments from TRMs to Kämtz-means. For most of the sites (especially low elevation sites) Swiss DTRs (and consequently DTCs) are similar to those in Austria, only at high elevations and in the Ticino daily temperature amplitudes are higher than in the Austrian mountains. Fig. 6a shows the respective sub-regional mean DTRs for Switzerland and Austria.

The basic principle for step 2 was the assumed similarity of the relative shape of the DTCs in both countries (later also for the Italian and the French adjustments), the only differences to be caused by DTC-amplitudes (which were estimated by the described multiplication of the real DTRs by 0.9). This vertical shrinking (if DTR is smaller) or stretching (if DTR is wider) of the DTCs is a simple but sufficiently accurate method to produce the necessary DTRs for regions in which only DTRs are measured (like
Annex 1: DATA PROCESSING within ECSN/HRT-GAR

Italy and France). For Switzerland it was applied too to re-adjust the true means (TRMs) to Kämtz-means and verified versus the existing TRMs from Swiss ANETZ stations. The results were positive (Michael Begert, personal communication) and let the method seem appropriate for application in Italy and France as well. Fig. 6b shows the derived adjustments for Swiss sub-regions. They are only slightly higher than those for respective Austrian sub-regions (compare Fig. 3. left) but have the same bimodal shape.

Figure 6a: Mean monthly DTRs for some Swiss (left) and some Austrian (right) sub-regions: Shown are sub-regions 3 (CH-exalp), 2 altitude bands of sub-region 4 and sub-region 5 for Switzerland, sub-region 2 (extra-alpine) and 3 altitude bands of sub-region 1 for Austria, (spatial distribution of DTR-sub-regions is shown in Fig.7)

Figure 6b: Biases of the Swiss means calculated after the Kämtz formula compared to true means (TRMs)
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Figure 7: Regionalisation of Swiss, Austrian, French and Italian sites into homogeneous sub-regions in terms of DTR and DTC

**Italy:** In Italy, a subset of 191 monthly mean $t_x$- and $t_n$-stations (all for-, or adjusted to 1961-90) could be used to apply a procedure similar to the one for the Swiss subset. The difference was that not each site had also the $t_x$- and $t_n$-values available and that the adjustments had to be applied from $(t_x+t_n)/2$-means to the Kämptz-algorithm. The former limitation afforded a regionalisation to produce sub-regional mean DTRs and DTCs for those sites with $t_m$-values alone. The part of Italy present in the GAR had to be subdivided into 4 main DTR-regions, two of them (in the Alps and in the Appennino-Toscana region further subdivided into different altitude bands.

Most of the Italian sub-regions show higher DTRs than the Swiss and Austrian ones from north of the Alps, specifically higher in the Toscana-Appennino region. Only the coastal sites have reduced DTRs due to reduced nightly cooling in the moist maritime air together with the land-sea-wind system which also tends to reduce DTR. Apart from the DTR-
Annex 1: DATA PROCESSING within ECSN/HRT-GAR

Reduction with increasing altitude (steeper in the Apennines), also the Po-plain (subregion 8) has reduced DTR compared to the low-elevation parts of the Alps and the Apennines, obviously a result of dust and fog in this flat region.

Figure 8: Mean monthly DTRs for the Italian sub-regions: shown are sub-regions 8 and 9 (Fig. 6a), sub-regions 6 (Fig. 6b) and 7 (Figure 6c), (spatial distribution of DTR-sub-regions shown in Fig. 7)

Taking into account the higher DTR-values in Italy and the general deficiencies of the \((t_x + t_n)/2\)-approach, it is not surprising that also most of the necessary adjustments to be applied on the Italian \((t_x + t_n)/2\)-means to produce the Kämtz-means are larger than those in Austria and Switzerland. Fig. 9 tells that the adjustments span a range from +0.3K to -0.7K in the lowlands and at the coasts, an even wider one in the Italian Alps and the Toscana-Appennino region from +0.2 to -1.4K. The strongest deviations of the \((t_x + t_n)/2\)-means from the Krämtz-means are given for the cold season, specifically for October. The vertical structure of the adjustments is steeper in the Apennines than in the Alps, possibly due to the lower altitudes of the Apennines (which cause a higher share on summit sites with reduced DTC at lower altitudes already compared to the Alps – a similar effect to the respective Austrian-Swiss-differences).
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Figure 9: Adjustments to be applied on the Italian \((t_x + t_n)/2\)-means to estimate Kämtz-means. 9a shows sub-regions 8 (pad) and 9 (c), 9b shows sub-region 6 in four 500m-altitude bands from a (<500m) to d (>1500m), 9c shows sub-region 7 in five 500m-altitude bands from a (<500m) to e (>2000m). (Spatial distribution of sub-regions shown in Fig.7)

Compared to the adjustments for the Swiss and Austrian data north of the Alps, the Mediterranean climate south of the Alps – together with the less accurate \((t_x + t_n)/2\)-means estimate – made it much more necessary here to adjust the provided means to achieve comparable data to the majority of the other GAR-subsets.

France: MétéoFrance provided 113 \(t_x\) and \(t_n\)-station-datasets which had been quality improved and adjusted to the 1961-90 reference period during the “Le Climat de la France”-project (MétéoFrance, 1999). 45 of them (those east of 3 deg E) were included into the GAR-dataset. A regionalisation of Eastern France in terms of DTR resulted in a subdivision into 3 parts (visible also in Fig.7):

- a large sub-region (11) covering NE-France (approximately north of 45 deg N and east of 3 deg E)
- a Mediterranean sub-region (10) south of 45 deg N but excluding the coasts
- Mediterranean coasts of France east of 3 deg E (9)
The high similarity of the French sub-regions 11/10 to the Swiss/Italian sub-regions 3/6 advised to use the respective adjustments derived from the Swiss and Italian regional mean DTRs and DTCs (based on much denser networks) as a basis to calculate the respective single station adjustments necessary for the two French non-coastal sub-regions. The French coastal sites had been included in the respective analysis of sub-region 9 already and the respective DTRs and DTCs could be used without change anyway.

**Figure 10:** Adjustments to be applied on the French \((t_x + t_n)/2\)-means to estimate Kämtz-means: regional means (bold) plus the 1-standard deviation range (thin lines). 10a shows sub-region 11 (French-NE), 10b shows sub-region 9 (French-Mediterranean coasts), 10c shows sub-region 10 (French Mediterranean inland). (Spatial distribution of sub-regions shown in Fig. 7)

Fig. 10 shows the resulting adjustments for the three French sub-regions in a slightly different style than those for Austria, Switzerland and Italy (where only the means were included). It shall underline that the adjustments were calculated for each single site. The relatively small 1-standard deviation range (the thin lines) confirms the alternative to use regional mean adjustments as well without severe quality reductions. The general features of the adjustments are similar to those: largest for the Mediterranean inland sites with values of more than 1K in some months,
slightly reduced for coastal sites and reduced to less than 1K for each month for the non Mediterranean NE of France.

5. Description of the final version of the alp-map-1961-90 dataset (station map, station list, provider statistics, two first raw regionalising alternatives: (tm(long), tm (lat) and tm(alt) vs. coarse sub-regions)

After having corrected, completed and adjusted the original data to a common reference period and to a common means estimate, a final dataset of 1726 single sites monthly temperature means has been made available for the high-resolution gridding. Experience from national or regional gridding activities suggested an initial elimination of urban influenced sites and such with temporarily not yet clearly understood stronger deviations from preliminary \( t_m \)-altitude models. 37 urban suspected too warm stations were detected and 25 with cold or warm biases. The former have been used later to produce an additive urban heat-islands-field based on urban-rural temperature differences and on a HR-land-use model. The latter have been dedicated to closer examination: some may be completely eliminated due to remaining error suspicions, some may indicate regional special regions like for example the high Engadin or some other high elevated flat basins or wide valleys with remarkable negative temperature deviations mainly in winter. The last Figures shown below shall provide a first outline of the given spatial temperature variability in the GAR which will have to be reduced to produce the aspired modelled monthly temperature fields. It will be vertical, latitudinal and longitudinal gradients as well as special features like land-sea effects and others which will have to be handled.

Figure 11: Scatter diagram of January and July mean temperatures for the entire GAR versus altitude (sample with elimination of urban and bias-suspected stations)
Annex1: DATA PROCESSING within ECSN/HRT-GAR

Figure 12. Coarse resolution sub-regions of the GAR: 1: C (coastal), 2: MM (Mediterranean mountains), 3: MMC (N-Italian Inland), 4: NE (northeast-continental.), 5: NW (northwest-Atlantic)

Fig.13: Scatter diagram of January and July mean temperatures for the coarse resolution sub-regions of the GAR versus altitude, left: 4 leading sub-regions, right: sub-region WNE further subdivided into NW and NE. (sample after elimination of urban and bias-suspected stations, spatial distribution of the sub-regions shown in Figure 12)
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Figure 14: Scatter diagram of July mean temperatures for the entire GAR versus longitude (left) and latitude (right), (sample after elimination of urban and bias-suspected stations).

Figure 15: Scatter diagram of January mean temperatures for the entire GAR versus longitude (left) and latitude (right), (sample after elimination of urban and bias-suspected stations).
Glossary of abbreviations and acronyms

CET: Central European Time
DST: Daylight Saving Time
GAR: Greater Alpine Region
MLT: Mean Local Time
tm: monthly mean temperature
tx: monthly mean maximum temperature	n: monthly mean minimum temperature
TRM: true mean (24 hours)
AT-T24-50: Austrian hourly temperature data set of 50 stations
ZAMG: Central Institute for Meteorology and Geodynamics
HZB: Central Hydrographical Service of Austria
DTC: Daily temperature course
DTR: Daily temperature range
CLINO: 30 years Climate normal period, WMO recommended
HISTALP: Historical instrumental climatological time series of the Greater Alpine Region
ECSN – HRT/GAR

High Resolution Temperature Climatology in Complex Terrain – demonstrated in the test area Greater Alpine Region GAR

Annex 2 to Final Report

GEOGRAPHICAL SPECIFICS OF AIR TEMPERATURE AND THE CONCEPT OF ECSN/HRT-GAR

Vienna, June 2008
1. Concept to reach the goal of ECSN-HRT/GAR

To reach the goal of ECSN-HRT/GAR a number of considerations have to be taken into account. On from the beginning it was clear to use the power of GIS tools for spatial modelling. In connection with our concept was defined as the following:

- Allow for a final standard error because climate station data always have final measurement uncertainties and describe local climate effects
- Apply only statistical modelling with a physical meaning (consequently this means that we did not apply residual interpolation by e.g. Kriging)
- Model only temperature effects inherent in the HRT-GAR climate station network
- Validate the spatial temperature model only on station data and not on gridded data because of large differences in DEM elevations to station elevations (errors and difference point to grid cell)

2. Geographical effects to be considered

Concerning the geographical effects to be considered we decide between larger and smaller scale effects.

Larger scale effects
- Dependency of air temperature on elevation including inversions during winter
- Large scale continentality effect (dependency on longitude)
- Global radiation effect from inclination of sunbeam (dependency on latitude)
- Regional scale dependency of air temperature on distance to the sea (considering advection of air masses)

Smaller scale effects
- Local scale dependency of air temperature on distance to the sea (land-sea brise circulation effect)
- Lake effect
- Urban effect
- Cold air pools effect
- Slope effect

First of all we have to study how well our DEM GTOPO30 represents the existing station network (Figure 1). A straight line would be a perfect reproduction of the true orography, but as one can see sometimes relatively big differences are occurring and above 2500 m all high alpine stations are represented in pixels to low. GTOPO30 is a global digital elevation model (DEM) with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer). It has been made freely available by the United States Geological Survey, shortly USGS. On http://edc.usgs.gov/products/elevation/gtopo30/gtopo30.html more information has been made available.
Figure 1: Comparison of station elevation and station elevation represented by DHM pixels of GTOPO30.

3. Distance-from-the-sea effect

Beside the most relevant effect played by geographical location (mostly latitude and, to a lower extent, longitude) and elevation, also the distance from the sea can affect environmental temperature. The sea is characterized by higher heat capacity than the air, in fact the land warms up and cools down more quickly than the sea. So, places located near the sea experience cooler temperatures than nearby inland places in summer and warmer temperatures in winter. This effect has been studied and quantified on the basis of the temperature climate normals of three coastal regions of the GAR: Po Plain Adriatic coast, Dalmatian Adriatic coast, and Tyrrhenian coast.

The sea effect on coastal stations has been studied by analysing the multiple regression residuals obtained by using elevation and latitude as predictors. Figure 2 shows the scatter plot of the January temperature residuals versus the distance from the sea (expressed in degrees) for the Po Plain Adriatic coast. The positive relative anomaly of the stations close to the sea compared to those farther from the coast is evident. On the contrary, in summer the behaviour is opposite, with the coastal stations proving cooler than the inland ones. In both cases the sea effect is (obviously) maximum close to the sea and it fades approximately linearly to zero at a threshold distance from the sea that is dependent on the season, such distance being maximum in summer and minimum in winter (in spring and autumn the sea effect is more or less negligible).

The linear fits shown in Figure 2 represent the signal to be subtracted from the residuals in order to take the sea effect into account or, better, the additive predictor to be added to the model in order to obtain white-noise residuals.
Annex 2: GEOGRAPHICAL SPECIFICS within ECSN/HRT-GAR

Figure 2: Scatter plot of the January (left) and July (right) temperature residuals versus the distance from the sea (expressed in degrees) for the Po Plain Adriatic coast; y-axis display the mean temperature in °C, x-axis the distance to sea in deg.

The sea effect turned out to be not the same when estimated for the other coastal regions, showing a remarkable dependence on the geography and morphology of the coast and its inland.

4. Lakeside effects

For seven larger lakes in the GAR a few lakeside and some more comparative sites in the surroundings could be identified and used for the comparison. As for all temperature means have been altitude adjusted before using. The three larger water bodies of the GAR are included in the analysis (Lago di Garda, Lac Léman, Bodensee / Lake Konstanz), the steppe-like shallow Balaton (more frequently freezing in winter than all the other analysed lakes) is included as well as the group of three medium size northern Italian Fjord-like lakes of Como, Lugano and Maggiore. The results from northern Italy are physically understandable and show cooler lakesides in the warm and warmer ones in the cold season. This meets the expectations based on the physics of the effect and the evidence already existing within ZAMG from some smaller Austrian lakes (gained some years ago during the work at the digital climatology of Austria). Not really expected, but clear to see in the data, are the systematically warmer lakesides of the two large western-and northern pre-alpine lakes (Bodensee and Lac Léman). They have to be used anyway, although the physical reason for the summer-heat excess of the lakeside sites is not clear. But the comparisons seem to be all right, altitude effects can be excluded, and for Bodensee we could use 9 lakeside and 13 remote sites, for Lac Léman 5 lakeside and 7 remote sites. The only really questionable case is the one of Balaton. Here the comparison produced colder lakesides in February and slightly warmer ones the rest of the year. This may be due to the possibility of freezing in later winter here, but the comparison could be based on from lakeside sites only and 7 rather remote comparative sites. Due to a special climatic situation of one of the two lakeside sites we have not applied any additional lakeside modifications on the temperature fields round lake Balaton. This makes sense also if the very shallow depth of this lake is taken into account. The same conclusion has been drawn for the similarly formed shallow lake Neusiedl at the Austro-Hungarian border.
Table 1: Deviations of mean monthly temperature at lakeside sites from remote sites in the surroundings, shown are the mean differences lakeside minus remote for 1961-1990, altitudes adjusted to lake-level

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Figure 3: deviations of mean monthly temperature at lakeside sites from remote sites in the surroundings. Shown are the mean differences lakeside minus remote for 1961-1990, altitudes adjusted to lake-level

5. Urban effects

For the urban regions we decided to choose the following proceeding: Firstly exclude urban infected stations from the dataset, then produce typical urban excess temperatures for the mean months 1961-90 and finally overlay those on the “rural” temperature fields. 12 cities could be used, for which a sufficient number of urban and rural sites in the surrounding exists. Those single city-subsets were each adjusted to constant altitude (using the draft regional t(z) models already analysed during the project). To keep any altitude biases small, only comparative rural sites were used which had altitude differences of less than 200m to the urban site(s). Figure 4 shows the result, mean monthly urban excess temperatures for 12 cities in the GAR. Three of the urban regions produced questionable results. The Torino case with more than 2° mean urban temperature excess seems large for a Mediterranean city, where theory expects less pronounced heat islands, particularly in summer (less evapotranspiration in the surroundings, stronger urban cooling through shading). The Milano-Bergamo case
can be considered more typical and reliable for the Mediterranean part of the GAR. Praha and the combination of medium size southern German cities are supposed to be too low and not realistic. For those cities further investigations should be done, but the project dataset does not contain the necessary data. The other analysed cities show reliable results, not in contradiction with the respective literature on urban heat islands.

**Figure 4:** Mean monthly altitude adjusted urban excess temperatures for 12 urban sub-regions in the GAR. Sample: 28 urban and 109 comparative rural sites for 12 cities or urban regions of several cities

**Figure 5:** Same as Fig.1 but for four generalized model cities (respective values in Table 2)

Finally our conclusion was to produce two city models (depending on city size) for two sub-regions, one for the NW-N-E and one for the Mediterranean part of the GAR. Table 2 and Figure 5 show those models which have been applied on the final monthly fields based on rural sites only.
Table 2: Urban temperature excess, but for four generalized model cities in the GAR

<table>
<thead>
<tr>
<th></th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
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<th>AUG</th>
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<tbody>
<tr>
<td>mean large N,E</td>
<td>1.12</td>
<td>1.10</td>
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<td>0.99</td>
<td>0.98</td>
<td>0.99</td>
<td>1.16</td>
<td>1.22</td>
<td>1.21</td>
<td>1.26</td>
<td>1.01</td>
<td>1.00</td>
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<tr>
<td>mean large S</td>
<td>1.28</td>
<td>1.16</td>
<td>0.71</td>
<td>0.30</td>
<td>0.35</td>
<td>0.38</td>
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<td>0.68</td>
<td>0.69</td>
<td>0.83</td>
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<tr>
<td>mean medium N,E</td>
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<td>mean medium S</td>
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<td>0.50</td>
<td>0.53</td>
<td>0.71</td>
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</table>

6. Shape effects

Table 3: deviations of mean monthly temperature at sites in specific shape-surroundings from the mean over all sites (sample: 100 Austrian sites 1961-1990, shape parameters taken from station descriptions)

<table>
<thead>
<tr>
<th>Group means of specific mesoscale surroundings</th>
<th>GROUP</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
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<th>SUM</th>
<th>AUT</th>
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<th>YEAR</th>
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<td>0.243</td>
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<tr>
<td>standard dev</td>
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<td></td>
</tr>
<tr>
<td>m+sd</td>
<td>m-sd</td>
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<td>-0.29</td>
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<td>-0.19</td>
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<td>Basin</td>
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<td>0.325</td>
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<td>0.5</td>
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<td>0.305</td>
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<td>0.262</td>
<td>0.202</td>
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<tr>
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<td>0.544</td>
<td>0.601</td>
<td>0.641</td>
<td>0.861</td>
<td>0.961</td>
<td>1.553</td>
</tr>
</tbody>
</table>
| To modify the temperature fields according to special effects caused by the shape of the altitude model, for the time being only a study on the basis of a set of 100 Austrian sites with good metadata about the shape of station sur-
roundings could be used and points at the size of the expected effects. Similar studies for non Austrian sites are not available.

Figure 6: Mean monthly deviations of sites located in special landscape-shape from a neutral (flat) meso-scale surrounding from the mean over all stations. Bold: mean deviations, thin: ±1stdev.range (sample: 100 sites 1961-1990 of the Austrian climate network)

7. Cold air pools effect

Cold air pools are a ground-based layer of air confined by topography colder than the air above. They usually form in winter when solar radiation input is too weak to remove the cold air layer. Regionally analysed temperature fields confirmed that alpine air pools are frequent and prominent to be seen even in mean monthly temperature fields.
Figure 7: mean monthly temperature in Carinthia (south of Austria) displaying the cold air pool of Klagenfurter Becken with negative temperature deviations up to -5°C.

Cold air pools have been defined from too cold residuals and topography.

Figure 8: scatter plot of air temperature residuals and altitude in the Klagenfurter Becken.
8. Effects not to be included in the analyses

A number of additional effects modifying the alpine temperature fields are well known existing however could not be treated within the project. On the hand the network did not allow for such special analyses (like those for sea-shores) and also from literature we could not find specifications which would allow for being included in an overall analysis.

8.1 Effects of forests on the temperature field

Forests are covering large parts of the alpine landscape and are expected to modify the temperature field in the forests themselves, but also in their nearer surroundings. We could not find enough references which would have been allowed to include this effect in our analyses.

8.2. Effects from glaciers and snow fields

Air above glaciers is expected to be considerably cooler in the warm season, when snow cover has vanished from the high Alpine non glaciated surroundings. This is due to two reasons. The one is based on the different heat balance of ice compared to solid surface with or without vegetation; the second is caused by advective heat transport from higher parts of a glacier via the "Gletscherwind". Measurements published by Greull, 2006 showed that using a constant lapse-rate could introduce some more problems.

8.3 others

there are effects which could not be included into the ECSN/HRT-GAR considerations, like sink holes (e.g. dolines in karst regions), or rice-fields covering large areas of the Po plain.
Figure 10: Doline temperature profile at Grünloch, Herzkogelplateau, Austria.
1. Introduction

This technical report presents the activities performed by the University of Milan and ISAC-CNR Research Group in the frame of the ECSN/HRT GAR project. Such activities addressed the construction of 1961-90 High-Resolution monthly Temperature (HRT) climatologies for Northern Italy. These climatologies were obtained by means of a geographical model aiming at capturing the dependence of temperatures on a number of geographical and morphological features.

The general goal was to estimate monthly temperature climatic normals (clinos) on a regular grid (1 km$^2$ resolution) covering all Northern Italy and part of Central Italy. This estimation was checked by means of a 664 station network in order to keep the mean absolute error (MAE) and the root mean squared error (RMSE) below the optimal threshold of 1 °C.

2. Data

The data used for the construction of the monthly HRT climatologies are monthly climatic normals (1961-90) of 664 stations within a 576,000 km$^2$ area encompassed by 6-14 °E and 42.5-47.5 °N longitude and latitude limits. The spatial distribution of such stations (fig.1) is sufficiently homogeneous, even though two regions (French Alps, the Marche) are poorly covered. The average station density is 1 station each 870 km$^2$ (1 station each approximately 600 km$^2$ without considering the seas). The stations are evenly located in plain, hill and mountain areas (fig. 2).
Beyond the station data, the 1 km$^2$ GTOPO30 digital elevation model (DEM) was used. The Italian data were provided by: University of Turin, University of Padova, University of Pavia, SIMN (the former Italian Hydrographic Service), Autonomous Province of Bozen, SMI (Italian Meteorological Society), AMI (Italian Military Aviation), UCEA (Central Office of Economical Agriculture).

Fig. 1 : Spatial distribution of the stations used for the construction of the HRT climatology.

Fig. 2 : Elevation distribution of the stations in our data-set: light blue crosses indicate plain stations, yellow triangles represent hill stations, scarlet squares are referred to mountain stations.
3. The geographical model (Part I: leading variables)

3.1 Temperature versus Elevation

The first variable considered in the geographical model was elevation. The obvious physical reason for this is the progressive vertical cooling of the air due to the fact that the atmosphere is primarily warmed by the heat emitted from the Earth’s surface. Such an effect is well known from literature, even though in large part of the area under examination important thermal inversions do occur, especially in winter. Such thermal inversions significantly reduce the correlation among temperature and elevation, causing the common variance \(R^2\) to drop from about 0.9 in late spring and summer to approximately 0.65 in late autumn and winter months.

The first attempt to capture the elevation dependence of temperature consisted in a two-layer model obtained by applying linear regression to two subsets of stations: the stations from 0 m to 1500 m and the stations from 1500m to 4000m. Actually, such an attempt, though reasonable for an area with complex orography, did not work properly as for several months, a discontinuity of about 2 °C was found. So it was decided to simply perform a linear regression over the whole database, even though in order to reduce the error, coast stations (less than 50 km from the Ligurian, Tyrrhenian or Adriatic Sea), lake stations and urban stations were not considered.

This linear regression was performed on a monthly basis: it allowed to obtain the following relation:

\[
T_{\text{stations}} = aH_{\text{stations}} + b
\]

where \(a\) is the vertical lapse rate and \(b\) the temperature at 0 m.

As expected, the highest (in absolute value) vertical lapse rates were found for summer months (e.g. July: -0.68°C / 100 m, see fig.4), whereas the lowest ones were found for winter (e.g. January -0.43°C / 100 m, see fig.3).
Once the temperature dependence on elevation was obtained on the basis of the station data, it was assumed that the same dependence could be extended to the whole area represented by the 1 km$^2$ grid.

Such a procedure can be summarized in the following two steps:

1.) \textit{We got }$a, b$ \textit{by a linear regression }$T_{\text{stations}} \text{ vs } H_{\text{stations}}$.

2.) \textit{Using the same coefficients }$a, b$ \textit{we calculated }$T_{\text{model}} = aH_{\text{model}} + b$ \textit{for each grid cell of the considered area.}$

where $H_{\text{model}}$ is the elevation of the grid cell from GTOPO30 digital elevation model (it is the average elevation of the cell, not the elevation of the grid cell’s centre).

The result of this procedure is an estimation of the normal temperature value of each grid cell (1 km$^2$ resolution).
The next step was the comparison between the modelled normal temperatures and the observed values. Such a comparison was performed by studying the residuals, that are the differences between the observed temperature and the modelled normal values of the stations.

Such a procedure can be summarized by the following steps:

3.) Using \( a, b, H\text{\_stations} \Rightarrow \text{we calculated back} \ T\text{\_station\_modelled} = aH\text{\_station} + b \) for each station

4.) From \( T\text{\_station}, T\text{\_station\_modelled} \Rightarrow \text{we calculated the residual} \ R\text{\_station} = T\text{\_station} - T\text{\_station\_modelled} \) for each station.

If the residual \( (R) \) is positive the model assigns to the station a temperature value that is colder than the real measured value, vice versa, if the \( R \) value is negative the model assigns to the station a temperature value that is warmer than the real measured value.

The study of the residuals allows both to check the overall accuracy of the model and to represent the geographical pattern of the residuals. The study of such residuals is a key issue in the selection of further variables to be considered in order to improve the model’s ability to capture the geographical complexity of the territory.

The overall accuracy of the model, including only the temperature dependence on elevation, was evaluated for each month of the year by means of the following statistical parameters: mean error (ME), mean absolute error (MAE) and root mean squared error (RMSE), see fig. 6.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
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<td>1.24</td>
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<tr>
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<td>1.11</td>
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<td>1.54</td>
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<td>1.58</td>
<td>1.89</td>
<td>2.37</td>
<td><strong>1.63</strong></td>
</tr>
</tbody>
</table>

Fig. 6: Accuracy of the model including only the dependence of temperature on elevation.

Such results highlight that, by considering only elevation, the geographic model would still be very far from the optimal threshold of 1.0°C for MAE and RMSE. In particular, the high RMSE values suggest that there are several stations with rather high absolute residuals, because RMSE is enhanced by the biggest errors.
The spatial behaviour of the residuals was studied by plotting the distribution of the residuals, see e.g. fig. 7 for January.

![Fig. 7: Spatial distribution of the residuals of the model including only the temperature dependence on elevation for January: blue bubbles represent positive residuals, white bubbles are related to negative residuals. The size of a bubble is proportional to the size of the residual.](image)

Such plots highlight that a model developed only considering temperature versus elevation is not satisfactory (fig.6): in fact the residuals show a non-negligible latitude effect, a Po Plain cold winter pool in the lowlands, a remarkable sea effect, a slight longitude effect, a very small urban heat island effect, an inversion effect in the Alpine and Apennine valleys and a different sea effect between Ligurian and Tyrrhenian Seas and Adriatic Sea.

### 3.2 Temperature versus Latitude

The second variable considered in the geographical model was latitude. The obvious physical reason is the progressive decrease of temperature from the Equator to the Poles (approximately -0.8/-1.4 °C/ degree at mid-latitudes) due to the different radiative budget at the Equator and the Poles (Pinna,1977).
The approach was similar to the one assumed while considering temperature versus elevation, but from this second step on the residuals obtained from the previous step were used in the linear regressions.

Fig. 8-9: Temperature residuals (after taking into account the temperature dependence on elevation) vs. latitude for January and July

Such a procedure can be summarized by the following two steps:

1.) From $R_{\text{stations}}$ at 1st step $\Rightarrow$ we found $c, d$ from regression $R_{\text{stations}}' = c(Lat)_{\text{stations}} + d$

2.) Using the same coefficients $c, d$ $\Rightarrow$ we calculated $R_{\text{model}}' = c(Lat)_{\text{model}} + d$

where $c$ represents the temperature decrease for each latitude degree and $Lat_{\text{model}}$ is the latitude of the grid cell from GTOPO30 digital elevation model (that is latitude of the grid cell’s centre). The latitude dependence of temperature ranges from -0.77 °C / °Lat in March to -1.35 °C / °Lat in January, whereas the average value over the year is -0.92 °C / °Lat. Such a decrease gives a difference of approximately 4 °C between Rome and Milan in winter and, for example, in March a grid cell at 43 °N is, only considering latitude, approximately 5.4 °C warmer than a grid cell at 47 °N.

The common variance coefficient of the linear regression between temperature and latitude ranges from 0.28 (May) to 0.56 (October).

The next step was the comparison between the modelled normal temperatures and the observed values. As discussed for elevation, such comparison was performed by studying the residuals.
In other words, the estimated temperature of each station according to the model, including the effects of elevation and latitude, was first obtained and, secondly, the difference between the observed and modelled values for each station was calculated.

Such a procedure can be summarized by the following steps:

3.) Using \( c, d, (\text{Lat})_{\text{stations}} \Rightarrow \) we calculated back \( R^*_{\text{station modelled}} = c(\text{Lat})_{\text{station}} + d \) for each station.

4.) From \( R^*_{\text{station}}, R^*_{\text{station modelled}} \Rightarrow \) we calculated the new residual \( R^*_{\text{station}} = R^*_{\text{station}} - R^*_{\text{station modelled}} \) for each station.

5.) We used \( T^*_{\text{model}} = T^*_{\text{model}} + R^*_{\text{model}} \) for each grid cell of the considered area.

As for the elevation, also in this case, the overall accuracy of the model was evaluated by means of the following statistical parameters: ME, MAE and RMSE, see fig. 10.

<table>
<thead>
<tr>
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<tr>
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<td>0.21</td>
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<tr>
<td>MAE</td>
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<td>0.75</td>
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<tr>
<td>RMSE</td>
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<td>0.94</td>
<td>0.96</td>
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<td>1.05</td>
<td>0.95</td>
<td>1.07</td>
<td>1.26</td>
<td>1.67</td>
<td>1.17</td>
</tr>
</tbody>
</table>

Fig. 10 : Accuracy of the model including only the dependence of temperature on elevation and on latitude.

Such results highlight that, by considering elevation and latitude, the geographical model would still be above the optimal threshold of 1.0°C for RMSE, but the MAE is below this threshold. Both MAE and RMSE are considerably smaller after this second step: MAE is smaller than 1.0°C and RMSE is 1.17°C, but in 4 months out of 12 it is already smaller than 1.0°C.

Also in this case, the spatial behaviour of the residuals was studied by plotting the distribution of the residuals, see e.g. fig. 11 for January.
Such plots highlight that a model developed only considering temperature versus elevation and latitude is not satisfactory: in fact, e.g., from the residuals map of July (fig. 11) the sea effect (a cooling effect) is evident and the same can be said for the lake effect.

### 3.3 Temperature versus Longitude

The third variable considered in the geographical model was longitude. The inclusion of longitude among the variables that can influence temperature normals is due to the fact that the area under examination, especially the Po Plain, tends to show an Eastward increasing continentality.

The data display that the longitude effect is completely negligible in summer months, but it is not negligible in winter months (fig. 12-13).
The approach adopted for longitude was the same used for temperature versus elevation or versus latitude.

Such a procedure can be summarized by the following two steps:

1.) From $R_{\text{stations}}^{\text{step 2}}$ we found $e, f$ from regression $R_{\text{stations}}^{\text{step 2}} = e(Lon)_{\text{stations}} + f$

2.) Using the same coefficients $e, f$ we calculated $R_{\text{mod.el}} = e(Lon)_{\text{mod.el}} + f$

where $e$ represents the temperature variation for each longitude degree, $Lon_{\text{model}}$ is the longitude of the grid cell from GTOPO30 digital elevation model (that is longitude of the grid cell’s centre). For example, it was found a longitude effect of 0.22 °C / °Lon in January (see fig. 12) and of -0.098 °C / °Lon for July (see fig. 13).

The common variance coefficient varies from 0.0002 (August) to 0.0831 (December), that is, the variance explained by this linear regression never exceeds 8.3%.

The next step was the comparison between the modelled normal temperatures and the observed values. As in the previous steps, such a comparison was performed by studying the residuals.

In other words, the estimated temperature of each station according to the model including the elevation, the latitude and the longitude effects was calculated first and, secondly, the difference between the observed and modelled values for each station was calculated.
Such a procedure can be summarized by the following steps:

3.) Using \(e, f, (Lon)_{stations} \Rightarrow \) we calculated back \( R^{\prime\prime}_{station \ mod \ modelled} = e(Lon)_{station} + f \) for each station

4.) From \( R^{\prime\prime}_{station \ mod \ modelled} \Rightarrow \) we calculated the new residual \( R^{\prime\prime}_{station} = R^{\prime\prime}_{station} - R^{\prime\prime}_{station \ mod \ modelled} \) for each station

5.) We used \( T^{\prime\prime}_{mod \ el} = T^{\prime\prime}_{mod \ el} + R^{\prime\prime}_{mod \ el} \) for each grid cell of the considered area.

Once again, the overall accuracy of the model was evaluated by means of the following statistical parameters: ME, MAE and RMSE, see fig. 14.

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<tr>
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<td>0.19</td>
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<td></td>
<td>0.01</td>
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<tr>
<td>MAE</td>
<td>1.33</td>
<td>0.98</td>
<td>0.75</td>
<td>0.74</td>
<td>0.85</td>
<td>0.90</td>
<td>0.83</td>
<td>0.75</td>
<td>0.83</td>
<td>1.00</td>
<td>1.32</td>
<td></td>
<td>0.92</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.62</td>
<td>1.22</td>
<td>0.95</td>
<td>0.94</td>
<td>0.96</td>
<td>1.08</td>
<td>1.15</td>
<td>1.05</td>
<td>0.95</td>
<td>1.07</td>
<td>1.25</td>
<td>1.62</td>
<td>1.15</td>
</tr>
</tbody>
</table>

Fig. 14: Accuracy of the model including the dependence of temperature on elevation, latitude and longitude.

The statistical parameters show a small improvement after this third step (for MAE and RMSE) but the intrinsic bias is still present in all months. The only important enhancements are noticeable in January and December.

By considering only the three main geographical parameters (elevation, longitude, latitude) the model satisfies the MAE threshold of 1.0 °C, but not the RMSE one. Anyway, at this point, the general features of the statistical errors were quite satisfactory, this is the reason why many spatialization climate models in literature consider just three parameters: elevation, latitude and longitude. The main problem was the unsatisfactory spatial pattern obtained: some important geographical effects, such as the sea effect, were not taken into account. So, it was necessary to evaluate secondary geographical and orographical effects.
4. Statistical Analysis (Part II: secondary effects)

4.1 Facet / slope exposure and summit / valley effects

The residuals obtained after taking into account the three leading geographical effects discussed in chapter 3 were further subjected to analyses aiming at identifying more significant relations between temperature and as many geographical and morphological features as possible. Such analyses were performed by plotting the spatial distribution of the residuals and by comparing the average residuals of particular subsets of stations. The first morphological effect that was taken into account was the summit or the valley location. A summit station was expected to measure warmer temperature (thus, positive residuals) than a valley station. The reason is that a mountain top location receives more hours of direct solar radiation than a valley station and it is not subjected to the cooling effect due to negative radiative balance at the surface, which produces thermal inversions during the night.

In order to investigate such an effect, a summit station was defined as a station belonging to a grid cell whose elevation is higher than the eight surrounding cells (among these, only stations located at elevations higher than 400 m were considered, and stations on the mountain or hill slopes were rejected), while on the other side, a valley station was defined as a station belonging to a grid cell whose elevation is lower than the eight surrounding cells (among these, only stations located in mountain areas were considered as valley stations, while stations on the Po Plain, for example, were rejected). Stations located on mountain passes were considered as valley stations for they are climatologically similar to valley stations for temperature. According to these definitions, approximately 75 summit stations and 105 valley stations were identified.

The monthly averages of summit and valley station residuals are shown in fig. 14. The results confirm the different thermometric behaviour of summit and valley locations especially in winter, when the difference between summit and valley residuals can get to about 2.5°C.
The second morphological effect considered was the geographical slope exposure (hereinafter “facet”). The stations’ facets were estimated by associating the grid cells facet values provided by GTOPO30 digital elevation model to any pertaining station. Such grid cell facets were simply calculated as the direction of the gradient of the function

$$Z = z(x, y)$$

where $z$ is the elevation and $x$ and $y$ are the coordinates defined according to, respectively, Eastward and Northward axes. (See fig. 15)
Naturally, positive residuals were expected for South-facing stations and negative residuals for North-facing stations. The analysis of the residuals, that was performed after excluding summit and valley stations and stations belonging to cells whose slope is lower than 0.05, did not produce remarkable results for North-facing stations (i.e. stations whose gradient direction is between 0° and 90° or 270° and 360°); on the contrary, South-facing stations showed positive residuals in all months, with values peaking in summer. So, facet effect was assumed to vary between $\pi/2$ and $3\pi/2$, whereas for the other exposure angles the effect was assumed to be zero.

A more detailed analysis highlighted not only an obvious solar duration effect, but also an influence of the actual exposure, whose effects can be remarkably different when considering a purely Southward exposure rather than a South-West or a South-East exposure.

In order to capture the overall effect of facet exposure, the following model was created:

$$ R_{\text{facet}} = -\alpha \sin\left(\frac{\pi}{2} - \text{facet}\right) $$

where $\text{facet}$ represents the direction of the gradient of $z (x,y)$ and $\alpha$ is a monthly-dependent coefficient that represents the exposure effect concerning purely South-facing grid cells. The monthly values of the $\alpha$ coefficient identified on the basis of a facet-based station residuals analysis and on knowledge-based considerations about the duration of the days in the different month are shown in fig. 16.

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<tr>
<td>$\alpha$</td>
<td>0.4</td>
<td>0.5</td>
<td>0.6</td>
<td>0.7</td>
<td>0.8</td>
<td>0.9</td>
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<td>0.6</td>
<td>0.5</td>
<td>0.4</td>
<td>0.3</td>
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</table>

![Fig. 16 : Values of $\alpha$ coefficient for facet exposure effect](image)

It is interesting to observe that the $\alpha$ values are approximately twice as big in summer than in winter: this result depends on the fact that in summer a South-facing station receives twice the solar radiation than a North-facing one.

Once the morphological (such as summit, valley and facet features) effects were defined, the approach adopted was similar to that described in chapter 3. Once more, it was
assumed to extend the station results to the grid cells; in particular, the procedure followed these steps:

a) for summit and valley grid cells, an effect equivalent to the average of the residuals of the corresponding cells with stations was assumed (obtained after the evaluation of the three leading geographical variables effects were removed);
b) for grid cells with facet between $\pi/2$ and $3\pi/2$, an effect given by

$$R^V_{mod \, el} = R_{facet} = -\alpha \sin\left(\frac{\pi}{2} - (\text{facet})\right)$$

was assumed.

If the summit/valley and the facet effects are defined respectively by $R^{IV}$ and $R^V$, it can be written:

$$T^{LM \, mod \, el} = T^{m \, mod \, el} + R^{IV \, mod \, el} + R^V_{mod \, el}$$

$$R^{LM \, station} = R^{m \, station} - R^{IV \, station \, mod \, el} - R^V_{station \, mod \, el}$$

where $T^{m \, mod \, el}$ represents the estimation of the temperature by the geographical model including only the leading variables, $T^{LM \, mod \, el}$ represents the estimation of the temperature by the geographical model including the leading variables and the morphological effects (summit/valley and facet exposure effects) and $R^{LM \, station}$ are the new residuals for every station after this step. A plot of this effect for January is shown in fig. 17.

Fig. 17: Map of facet exposure and summit/valley effects for January.
Even though the effects of the morphological variables were not as large as the leading effects and even though they only concerned a subset of the grid cells, a significant improvement in the model’s skill resulted after the inclusion of these effects. The overall accuracy of the model, after this step, is shown in fig. 18.

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<th>Nov</th>
<th>Dec</th>
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<tbody>
<tr>
<td>ME</td>
<td>0.08</td>
<td>0.03</td>
<td>-0.07</td>
<td>-0.16</td>
<td>-0.19</td>
<td>-0.22</td>
<td>-0.26</td>
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<td>0.05</td>
<td>0.06</td>
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<td>-0.07</td>
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<tr>
<td>MAE</td>
<td>1.10</td>
<td>0.88</td>
<td>0.72</td>
<td>0.74</td>
<td>0.75</td>
<td>0.85</td>
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<td>0.77</td>
<td>0.88</td>
<td>1.08</td>
<td></td>
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<tr>
<td>RMSE</td>
<td>1.40</td>
<td>1.12</td>
<td>0.92</td>
<td>0.94</td>
<td>0.96</td>
<td>1.08</td>
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<td>1.05</td>
<td>0.93</td>
<td>0.99</td>
<td>1.12</td>
<td>1.38</td>
<td>1.09</td>
</tr>
</tbody>
</table>

Fig. 18: Accuracy of the model including the dependence of temperature on the three leading geographical variables and on the morphological variables.

It is worth noticing that, at this point, the MAE is already below the threshold of 1 °C in every month, with the only exceptions of January and December; also the RMSE is below the threshold of 1 °C in five out of twelve months.

4.2 The sea effect (Part I: Ligurian, Tyrrhenian and North-Adriatic Seas)

The fifth step concerned the evaluation of the sea effect: a cooling sea effect in summer and a warming effect in winter were expected in the first kilometres inland from the coast. Moreover, a different behaviour of the different Italian coasts was expected according to knowledge of local climate patterns.

In order to evaluate the Sea effect in the area under examination, four separate zones were considered: Ligurian Sea (French Riviera, Liguria), Tyrrhenian Sea (Tuscany and northern Latium), North-Eastern Adriatic Sea (Friuli and Istria), South-Western Adriatic Sea (Veneto, Romagna and Marche). Such a separation is well justified by the geographical characteristics of the territory studied. Ligurian and Tyrrhenian Seas are both on the Western side of the Italian Peninsula, while the Adriatic Sea is on the Eastern side. Furthermore, the Adriatic Sea must be split into two sub-regions because the two areas
have a different coast exposure and the southern area is much more exposed to cold Eastward winds, especially in winter. Thus, in this step, Ligurian, Tyrrhenian and North-Eastern Adriatic effects were studied, whereas South-Western Adriatic is discussed in chapter 4.5.

A sub-set of coast stations (only stations not farther than 60 kilometres from the coast) was selected in order to perform monthly linear regressions between the station residuals, obtained after taking into account the temperature dependence on the leading geographical variables and on the morphological variables, and the distance from the coast for every station of this sub-set. According to these definitions, 35 stations for Ligurian Sea area, 45 stations for Tyrrhenian Sea area and 30 stations for North-Eastern Adriatic Sea area were identified.

Fig. 19-20 : Temperature residuals (after taking into account the temperature dependence on leading geographical and on morphological variables) vs. distance from the Mediterranean coast for January and July.

Fig. 21-22 : Temperature residuals (after taking into account the temperature dependence on leading geographical and on morphological variables) vs. distance from the Tyrrhenian coast for January and July.
Such a procedure can be summarized by the following two steps (it was used for each month, for each different Sea Area):

1.) From \( R_{\text{stations}}^{\text{LM}} \) \text{ at } 4^{\text{th}} \text{ step } \Rightarrow \text{ we found } g, h \text{ from regression } \\
\[ R_{\text{stations}}^{\text{LM}} = g(DistCoast)_{\text{stations}} + h \]

2.) Using the same coefficients \( g, h \) \Rightarrow \text{ we calculated } R_{\text{mod el}}^{\text{LMS}} = g(DistCoast)_{\text{mod el}} + h \\

where \( R_{\text{stations}}^{\text{LM}} \) are the residuals after the evaluation of the leading geographical effects and of the morphological effects, \( (DistCoast)_{\text{stations}} \) is the distance from the coast of the stations, \( (DistCoast)_{\text{mod el}} \) is the weighted distance from the coast of the grid cell. This weighted distance from the coast was based on a simple algorithm that sums up the linear distance from the nearest sea coast and the height differences (orographical obstacles) between the grid cell and the nearest sea coast (see fig. 25).

It was found a Sea effect for the Ligurian Sea of 3.1°C in January on the Ligurian coast (see fig. 19) and of -2.0°C for July (see fig. 20); it was found a Sea effect for the Thyrrenian Sea of 2.2°C in January on the Tuscan coast (see fig. 21) and of -1.6°C for July (see fig. 22); it was found a Sea effect for the North Adriatic Sea of 2.3°C in January on the Friulan Coast and Istria (see fig. 23) and of -0.7°C for July (see fig. 24).

Moreover, it was found that the Ligurian Sea and the Tyrrhenian Sea influence climate inland to 40 km from the coast, the North-Eastern Adriatic Sea to 60 km.
Fig. 25: Weighted distance from the coast for the area under examination

Fig. 26: Warming sea effect (except South-Western Adriatic) for January.
The next step was the comparison between the modelled normal temperatures and the observed values. As in the previous steps, such a comparison was performed by studying the residuals.

In other words, the estimated temperature of each station according to the model including the elevation, the latitude, the longitude, the summit/valley, the facet exposure and the sea effects was calculated first and, secondly, the difference between the observed and modelled values for each station was calculated.

Such a procedure can be summarized by the following steps:

3.) Using \( g, h, (\text{DistCoast})_{\text{station}} \) we calculated back \( R^{\text{LMS}}_{\text{station modelled}} = g(\text{DistCoast})_{\text{station}} + h \) for each station.

4.) From \( R^{\text{LMS}}_{\text{station}} \), \( R^{\text{LMS}}_{\text{station modelled}} \) we calculated the new residual \( R^{\text{LMS}}_{\text{station}} = R^{\text{LMS}}_{\text{station modelled}} - R^{\text{LMS}}_{\text{station modelled}} \) for each station.

5.) We used \( T^{\text{LMS mod el}} = T^{\text{LMS mod el}} + R^{\text{LMS mod el}} \) for each grid cell of the considered area.

The overall accuracy of the model shows a remarkable improvement in the statistical parameters (fig. 27).

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<tbody>
<tr>
<td><strong>ME</strong></td>
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<td>-0.09</td>
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<td>-0.07</td>
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<td>-0.11</td>
<td>-0.08</td>
<td>-0.05</td>
<td>-0.08</td>
<td>-0.13</td>
<td>-0.15</td>
<td><strong>-0.10</strong></td>
</tr>
<tr>
<td><strong>MAE</strong></td>
<td>0.93</td>
<td>0.80</td>
<td>0.72</td>
<td>0.72</td>
<td>0.72</td>
<td>0.82</td>
<td>0.81</td>
<td>0.73</td>
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<td>0.77</td>
<td>0.93</td>
<td></td>
<td><strong>0.79</strong></td>
</tr>
<tr>
<td><strong>RMSE</strong></td>
<td>1.20</td>
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<td>0.91</td>
<td>0.96</td>
<td>1.18</td>
<td><strong>1.00</strong></td>
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</tbody>
</table>

Fig. 27 : Accuracy of the model including the dependence of temperature on the three leading geographical variables, on the morphological variables and on the sea effect.

An intrinsic bias is still present, but the Sea effect variables and the MAE is now below the threshold of 1 °C in every month, even in January and in December; the average RMSE is just equal to the threshold of 1 °C and it is below the threshold in seven out of twelve months.
4.3 The Lake effect

The sixth step concerned the evaluation of the Lake effect: a slight cooling Lake effect in summer and a slight warming effect in winter were expected in the first kilometres inland from the lake coasts: the lake effect is very similar to the Sea effect, but it is a smaller effect and it decreases inland to a very small distance from the lake coast (not more than 5-10 km compared to 30-70 km for Sea effect).

In the geographical area under examination, 4 sub-Alpine (Maggiore, Lugano, Como, Garda) and 5 North-Alpine lakes (Zurich, Bodensee, Leman, Neuchatel, Vierwaldstattersee) were studied: each lake was studied separately.

As for the sea effect, a sub-set of “lake” stations (only stations not farther than 10 kilometres from the lake) was selected in order to perform monthly linear regressions between the station residuals, obtained after taking into account the temperature dependence on the leading geographical variables, on the morphological variables and on the sea effect, and the distance from the lake for every station of this sub-set. According to these definitions, only 25 lake stations were identified.

The same approach used for sea effect de-trending was adopted.

Such a procedure can be summarized by the following two steps (it was used for each month, for each lake):

1.) From \( R_{\text{LMS}_{\text{stations}}} \) at 5th step \( \Rightarrow \) we found \( i, j \) from regression \( R_{\text{LMS}_{\text{stations}}} = i(Dist\text{Lake})_{\text{stations}} + j \)

2.) Using the same coefficients \( i, j \) \( \Rightarrow \) we calculated \( R_{\text{LK}_{\text{mod\,el}}} = i(Dist\text{Lake})_{\text{mod\,el}} + j \)

where \( R_{\text{LMS}_{\text{stations}}} \) are the residuals after the evaluation of the leading geographical effects, of the morphological effects and of the Sea effect, \( (Dist\text{Lake})_{\text{stations}} \) is the distance from the lake of the stations, \( (Dist\text{lake})_{\text{mod\,el}} \) is the weighted distance from the lake of the grid cell calculated from the GTOPO30 (it takes into account the linear distance from the nearest lake, the elevation of the grid cell and the orographical obstacles between the grid cell and the nearest lake).
It was found that for Bodensee, Vierwaldstattersee and Neuchatel Lakes the lake effect is negligible and that the 4 lakes South of the Alpine ridge have very similar coefficients: so, the i, j coefficients were re-calculated and averaged for them.

For example, it was found on the Garda Lake coast, in January, a warming effect of approximately 1 °C, that is smaller than the Ligurian warming winter effect on French Riviera (approximately 2.6 °C / 3.2 °C) just on the coast.

The average residuals calculated for the lakes, related to the first kilometre from the lake coast, are shown in fig. 28.

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<tr>
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<td>-1.02</td>
<td>-1.16</td>
<td>-1.12</td>
<td>-1.01</td>
<td>-0.75</td>
<td>-0.25</td>
<td>0.28</td>
<td>0.85</td>
<td></td>
</tr>
</tbody>
</table>

Fig. 28 : Values of residuals at 1 km from the lake coasts.

The sub-Alpine Lakes (Maggiore, Como, Garda, Lugano), show a warming effect in winter that is stronger than the Leman Lake one, on the contrary the Leman Lake show a stronger cooling effect in summer; moreover the average yearly lake effect is a cooling effect for the Leman Lake and it is a warming effect for the 4 sub-Alpine lakes.

Once again, the next step was the comparison between the modelled normal temperatures and the observed values. As in the previous steps, such a comparison was performed by studying the residuals.

Such a procedure can be summarized by the following steps:

3.) Using \( i, j, (\text{DistLake})_{\text{station}} \Rightarrow \) we calculated back \( R_{\text{station modelled}}^{LK} = i(\text{DistCoast})_{\text{station}} + j \) for each station

4.) From \( R_{\text{stations}}^{LMS}, R_{\text{station modelled}}^{LK} \Rightarrow \) we calculated the new residual \( R_{\text{station}}^{LK} = R_{\text{station model}}^{LMS} - R_{\text{station modelled}}^{LK} \) for each station

5.) We used \( T_{\text{mod el}}^{LK} = T_{\text{mod el}}^{LMS} + R_{\text{mod el}}^{LK} \) for each grid cell of the considered area.
The overall accuracy of the model shows a small improvement in the statistical parameters of the model (fig.29).

<table>
<thead>
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<tbody>
<tr>
<td>ME</td>
<td>-0.19</td>
<td>-0.12</td>
<td>-0.08</td>
<td>-0.07</td>
<td>-0.05</td>
<td>-0.04</td>
<td>-0.08</td>
<td>-0.07</td>
<td>-0.05</td>
<td>-0.07</td>
<td>-0.15</td>
<td>-0.18</td>
<td>-0.10</td>
</tr>
<tr>
<td>MAE</td>
<td>0.91</td>
<td>0.79</td>
<td>0.71</td>
<td>0.72</td>
<td>0.70</td>
<td>0.76</td>
<td>0.81</td>
<td>0.80</td>
<td>0.71</td>
<td>0.71</td>
<td>0.76</td>
<td>0.91</td>
<td>0.78</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.18</td>
<td>1.02</td>
<td>0.91</td>
<td>0.90</td>
<td>0.89</td>
<td>0.97</td>
<td>1.04</td>
<td>1.00</td>
<td>0.91</td>
<td>0.90</td>
<td>0.95</td>
<td>1.17</td>
<td>0.99</td>
</tr>
</tbody>
</table>

Fig. 29: Accuracy of the model including the dependence of temperature on the three leading geographical variables, on the morphological variables, on the Sea effect and on the lake effect.

4.4 The Po Plain cold air pool effect

By observing the winter residual distributions after the evaluation of the elevation, the latitude, the longitude, the Sea and the lake effects, it was noticed that in 5 months (from November to March) the stations located in the Po Plain have negative residuals, especially high from December to February. This is due to the inversion phenomena which frequently occur in the Po Plain lowlands and to the cold air masses stagnating in the Po Plain; furthermore, this effect is coupled with the longitude effect caused by continentality.

This phenomenon was not studied just considering the stations located in the Po Plain, but the area under this influence was enlarged towards South until Lat 42.5°E on the Eastern side of the Apennines, thus encompassing the area between the Adriatic coast and the Apennines because the cold air masses effect is present not only in the Po Plain but even on the Adriatic coast in Romagna and Marche.

It was decided to model this effect considering also the elevation as a parameter, because, from the residuals obtained after the evaluation of the leading geographical variables, the morphological variables, the sea and the lake effects, a relation between such negative residuals and elevation was found: the residuals tended to decrease as the elevation increased.
From the analysis of the residuals, it was inferred that the inversion phenomena are not present in the Western part of Central Italy (that is the Tyrrhenian Sea coast, in fact Tuscany and Latium are generally warmer than Romagna and Marche in winter months). In order to define the area influenced by the ‘Po Plain’ effect, only stations located at an elevation not higher than 600 m were considered: this threshold was chosen to include the hill area in the South-Western of Piedmont where the inversion phenomena are present. Another condition was added to model this effect: grid cells must have a slope value smaller than 0.15: thus hill sides and Pre-Alps were excluded because air masses can only station on locally flat areas. According to these conditions 105 stations were selected for the analysis.

![Fig. 30-31: Temperature residuals (after taking into account the temperature dependence on leading geographical on morphological variables, on Sea and lake effects) vs. elevation in the Po Plain area for January and July.](image)

Such a procedure can be summarized by the following two steps (it was used for every month):

1.) From $R_{LK\text{ stations}}^{6th}$ step $\Rightarrow$ we found $l, m$ from regression $R_{\text{stations}}^{PP} = l(elev)_{\text{stations}} + m$

2.) Using the same coefficients $l, m$ $\Rightarrow$ we calculated $R_{\text{mod el}}^{PP} = l(elev)_{\text{mod el}} + m$

where $R_{\text{stations}}^{PP}$ are the residuals after the evaluation of the leading geographical effects, of the morphological effects and of the Sea end the lake effects, $(elev)_{\text{stations}}$ is the elevation
of the stations, \((elev)_{\text{model}}\) is elevation the of the grid cell from GTOPO30 digital elevation model (it is the average elevation of the cell, not the elevation of the grid cell’s centre).

It was found that this effect is noteworthy in five months: from November to March (e.g. -1.4 °C at 5 m in January), whereas in late spring, in summer and in early autumn months this effect is negligible (see fig. 30-31).

Another interesting result is that in the proximity of the coast, in winter, the warming sea effect prevails against the cold air masses effect up to 5 kilometres from the coast in Veneto and in Romagna.

As the same, it was evaluated the comparison between the modelled normal temperatures and the observed values by studying the residuals.

Such a procedure can be summarized by the following steps:

3.) Using \(I, m, (elev)_{\text{station}}\) we calculated back \(R_{\text{station modelled}}^{PP} = I(elev)_{\text{station}} + m\) for each station

4.) From \(R_{\text{station}}^{LK}\) stations, \(R_{\text{station modelled}}^{PP}\) we calculated the new residual \(R_{\text{station}}^{PP} = R_{\text{station}}^{LK} - R_{\text{station modelled}}^{PP}\) for each station

5.) We used \(T_{\text{mod el}}^{PP} = T_{\text{mod el}}^{LK} + R_{\text{mod el}}^{PP}\) for each grid cell of the area under examination.

After the evaluation of the so-called Po Plain effect, statistical parameters of the model show an improvement (see fig. 32).

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
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<th>Oct</th>
<th>Nov</th>
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</thead>
<tbody>
<tr>
<td>ME</td>
<td>0.00</td>
<td>0.01</td>
<td>-0.02</td>
<td>-0.07</td>
<td>-0.05</td>
<td>-0.04</td>
<td>-0.08</td>
<td>-0.07</td>
<td>-0.05</td>
<td>-0.07</td>
<td>-0.03</td>
<td>-0.01</td>
<td>-0.04</td>
</tr>
<tr>
<td>MAE</td>
<td>0.84</td>
<td>0.75</td>
<td>0.69</td>
<td>0.72</td>
<td>0.70</td>
<td>0.76</td>
<td>0.81</td>
<td>0.80</td>
<td>0.71</td>
<td>0.71</td>
<td>0.72</td>
<td>0.85</td>
<td>0.76</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.08</td>
<td>0.96</td>
<td>0.89</td>
<td>0.90</td>
<td>0.89</td>
<td>0.97</td>
<td>1.04</td>
<td>1.00</td>
<td>0.91</td>
<td>0.90</td>
<td>0.91</td>
<td>1.08</td>
<td>0.96</td>
</tr>
</tbody>
</table>

Fig. 32 : Accuracy of the model including the dependence of temperature on the three leading geographical variables, on the morphological variables, on the Sea effect, on the lake effect and on the Po Plain effect.
The most important refinement is the removal of the intrinsic bias for winter months, in fact ME is null, e.g., for January. The average MAE and RMSE are both below the 1 °C threshold.

Some further considerations: small geographical corrections (the effect was dampened as Latitude decreases, below 44 °N) were introduced to create a model that reproduce in the most accurate way the station data (see fig. 33).

The model was created considering a one-layer atmosphere: in general, this could lead to a wrong evaluation of temperatures in the first 500 meters. In this case, the Po Plain inversion effect corrects this intrinsic problem.

In order to compare the results obtained after the inclusion of the Po Plain effect in the one-layer model with the results that it would be obtained if it had been used a two-layer atmosphere (elevation split threshold at 1500 m), such a two-layer model was applied.
It was found that the model described in this report (i.e. the one-layer atmosphere model plus the Po Plain effect in five months) is more similar to station data than the two-layer model: in fact, the overall accuracy of the statistical parameters show is better for the one-layer atmosphere model, the average MAE is lower (0.75 versus 0.9), and also the RMSE is lower (0.95 versus 1.15).

4.5 The Sea Effect (Part II: South-Western Adriatic Sea)

The seventh and last step concerned the evaluation of the South-Western Adriatic Sea effect: as for the other seas in the area studied, a cooling Sea effect in summer and a warming effect in winter are expected in the first kilometres inland from the coast.

The conditions for the station selection were the same adopted in chapter 4.2, thus we selected 20 stations for this analyses.

The residuals (for the selected stations) obtained after the evaluation of the temperature dependence on the three geographical and the morphological variables, of the Sea, the lake and the so-called Po Plain effect were studied in order to analyze their dependence on the distance from the South-Western Adriatic Coast with a linear regression performed for every month (see fig. 34 for January and fig. 35 for July).

The procedure is formally the same explained in chapter 4.2, and it can be summarized by the following two steps (it was used for every month):

![Figure 34](image1.png)
![Figure 35](image2.png)
1.) From $R^{PP}_{stations}$ at 7th step we found $o, p$ from regression $R^{AS}_{stations} = o(DistCoast)_{stations} + p$

2.) Using the same coefficients $o, p$ we calculated $R^{AS}_{model} = o(DistCoast)_{model} + p$

where $R^{PP}_{stations}$ are the residuals after the evaluation of the leading geographical effects, of the morphological effects and of the other effects already evaluated, $(DistCoast)_{stations}$ is the distance from the coast of the stations, $(DistCoast)_{model}$ is the weighted distance from the coast of the grid cell. This weighted distance is the one used in chapter 4.2 (see fig. 25).

It was found a Sea effect for the South-Western Adriatic Sea of 1.0 °C in January on the Marche coast (see fig. 34) and of -0.6 °C for July (see fig. 35), moreover the South-Western Adriatic Sea influences climate inland up to 40 kilometres (see fig. 36)

Fig.36 South-Western Adriatic Sea warming winter effect for January

Temperatures measured in Marche are hotter than in Veneto, because of a less intense Po Plain cooling effect in winter and because of the Latitude effect. The main difference between North-East Adriatic influence and the South-West one is the smaller cooling
summer effect: this probably depends on the Alps that are an orographical barrier against cold weather fronts for the Northern part of the Adriatic Sea.

Once again, the next step was the comparison between the modelled normal temperatures and the observed values. As in the previous steps, such a comparison was performed by studying the residuals.

Such a procedure can be summarized by the following steps:

3.) Using $o$, $p$, $(DistCoast)_{station}$ we calculated back
$$R^{AS}_{station modelled} = o(DistCoast)_{station} + p$$
for each station

4.) From $R^{PP}_{station}$, $R^{AS}_{station modelled}$ we calculated the new residual
$$R^{SS}_{station} = R^{PP}_{station} - R^{AS}_{station modelled}$$
for each station

5.) We used
$$T^{SS}_{model} = T^{PP}_{model} + R^{AS}_{model}$$
for each grid cell of the considered area.

$R^{SS}_{station}$ and $T^{SS}_{model}$ are, respectively, the final residuals for every station and the final temperature values for every grid cell.

Such quantities were used to calculate the final statistical parameters of the climatological model, thus the overall final accuracy of the model is shown in (fig. 37).

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
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<th>Jul</th>
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<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Average</th>
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</thead>
<tbody>
<tr>
<td>ME</td>
<td>-0.04</td>
<td>-0.02</td>
<td>-0.03</td>
<td>-0.06</td>
<td>-0.05</td>
<td>-0.04</td>
<td>-0.08</td>
<td>-0.07</td>
<td>-0.06</td>
<td>-0.09</td>
<td>-0.05</td>
<td>-0.04</td>
<td>-0.05</td>
</tr>
<tr>
<td>MAE</td>
<td>0.83</td>
<td>0.74</td>
<td>0.69</td>
<td>0.71</td>
<td>0.70</td>
<td>0.76</td>
<td>0.81</td>
<td>0.79</td>
<td>0.71</td>
<td>0.70</td>
<td>0.71</td>
<td>0.83</td>
<td>0.75</td>
</tr>
<tr>
<td>RMSE</td>
<td>1.06</td>
<td>0.96</td>
<td>0.89</td>
<td>0.90</td>
<td>0.89</td>
<td>0.96</td>
<td>1.03</td>
<td>1.00</td>
<td>0.91</td>
<td>0.90</td>
<td>0.90</td>
<td>1.07</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Fig. 37: Final accuracy of the model including the dependence of temperature on every geographical, morphological and physical effect considered.

A small negative bias in winter months is present, but the geographical MLR model satisfies the error thresholds (MAE and RMSE are smaller than 1 °C); these parameters evaluation substitutes a jack-knife cross validation.
5. Future improvements

5.1 The Urban Heat Island Effect

It is well known that big cities (more than 50,000 inhabitants and population density at least 300 inhab/km$^2$) can cause an urban heat island especially in winter, during calm nights with clear sky (Oke, 1973; Oke, 1982).

In this study 25 urban stations in the Italian area were considered and linear regressions between temperature residuals versus population (number of inhabitants), versus the logarithm of population (as some papers suggest), versus density of population, versus the logarithm of density were performed. The results did not show a clear urban heat island (UHI) effect.

Maybe this is due to an incorrect classification of the stations: in the HISTALP database there are stations labelled as “urban” that are located a few kilometres away from the cities or, in some cases, the stations are located in airports which are not in the urban area (Milan Malpensa station is an example of that misleading label).

Another reason that may cause this difficulty in clearly detecting the UHI effect may be due to the fact that this phenomenon has a very local scale which is linked to features like the materials used for buildings, the canyon-free factor, the sky-view factor and so on.

Therefore, the characteristic spatial scale of the UHI is the micro-scale. Such a scale is unfortunately very hard to be captured with the HRT HISTALP database which has, on one hand, a low spatial density of stations and, on the other hand, a not sufficiently precision (less than 50 m) in the latitude and longitude geographical coordinates of the stations, thus causing problems to determine the right position of all stations.

Anyway, in spite of all these problems, it was decided to include in the HRT climatologies a first and very preliminary evaluation of the UHI effect. Such an estimate was based on regressions of the temperature residuals obtained after considering all the effects already described in this report, versus population. The regressions were not only performed for
the Italian area, but for the entire GAR, selecting three groups of stations (stations with a population between 50,000 and 500,000 inhabitants, between 500,000 and 1,000,000, more than 1,000,000). The preliminary results show that the UHI effect varies with density of population: it ranges, for towns between 500,000 and 1,000,000 inhabitants, from 0.4 °C to 0.9 °C in winter and from 1.3 °C to 2.2 °C in summer.

The inclusion of the UHI effect does not improve statistical parameters of the model described in this report. The ME and the RMSE does not change, and the MAE improves only 0.01 °C.

In order to better consider the urban heat island effect in an oncoming future, it would be helpful a better localization and choice of “urban” station will be necessary and it will probably be useful taking into account not only the land cover value associated to the grid cell where a temperature station is located, but also the land cover values of the surroundings grid cells (8 cells at least) and, in the end, analyses based on couples of urban versus rural stations located no more than 25 km from one another can probably give a more detailed study of the UHI effect.

### 5.2 The Land Cover / Land Use Characterization

In recent literature no papers trying to include land cover in construction of high resolution temperature climatologies were found. In order to evaluate a land cover effect, a high resolution and updated land cover data set, a great number of stations and a very efficient code to perform the analyses are requested. There are two different land cover grids useful for the GAR area.
This first one is PELCOM Land Cover pan-European database (fig. 38), it is data updated to 2001 and this is not the best solution for 1961-90 climatologies. The data are projected using Albers Conical Equal Area projections, the resolution is 1 km$^2$ for each grid cell.
The second one is USGS Land Cover Eurasia database (fig. 39), it is updated to 1993. The data are projected using Interrupted Goode Homolosine projections or Lambert Azimuthal Equal Area projections, and its spatial resolution is 1 km\(^2\) for each grid cell.

A great number of stations is needed to evaluate the land cover effect, because a significant number of station data should be associated to each kind of land cover. Each station is located in a grid cell with its land cover value (which corresponds to a different land type, for example deciduous forest, grassland, shrub land and so on), then data stations will be joined into small groups (one group for every land cover type).

The classification scheme of PELCOM land cover database has 14 land cover categories: at least, for each category, 20 stations are needed (but 50 would be preferable). The model described in this report is based on 664 stations, thus the HISTALP database has enough stations to perform a land cover study for the Northern part of Italy. On the other side, the USGS land cover scheme has more than 20 land cover different categories: in this case it will be necessary to perform the data analysis using a greater area (the whole GAR with their 1750 stations) because a greater number of temperature stations is needed.

It can be supposed that a land cover effect evaluation will significantly improve the model, even though the benefits of the use of land cover data can be estimated only in future works.
6. Results: HRT monthly maps for 1961-90

6.1 The Fortran code

A Fortran program with a simple structure was encoded (with a subroutine for each effect) and it was used to pass from residual data and temperature modelled values for each station to gridded temperature climatologies. Twelve short (from 450 to 650 code lines, it depends on the number of effects considered, for example in winter months there is no Po Plain effect) programs were written (one for each month) and one for the average temperature climatology. The thirteen programs final run did not take more than 30 minutes: fast Fortran codes were created to produce our final model with gridded data (the so called climatologies). Thus station data were converted into continuous gridded data. Then it was used GMT (Generic Mapping Tools, a free software available online thanks to Honolulu University, department of Geophysics) to create the temperature maps.

6.2 Final statistical parameters and discussion
The final ME is -0.05 °C, an intrinsic negligible negative bias; the final MAE is 0.75 °C; the final RMSE is 0.95 °C. Such values were found just evaluating the final temperature residuals (measured values minus final modelled values), whereas a jack-knife cross validation was not performed.

No station was rejected, if only 5% of the data (the stations with the highest, negative or positive final residuals), had been rejected, the model would have had better statistical parameters (ME -0.03 °C, MAE 0.67 °C, RMSE 0.77 °C) but it would have been less realistic.

If the final averaged residuals of our model are plotted in monthly maps, there are only two areas where the average station residuals are larger than 1.0 °C: the South West of Piedmont (Langhe and Monferrato) in winter and the Adige (Etsch) Valley in winter and summer. The South-Western Piedmont is hotter than reality, because the Po Plain effect was modelled with a linear regression between temperature and elevation: this area is located at approximately 500 m, thus the effect in the model is not well captured even though that area has a rather continentality. In the Adige Valley there are 5-7 stations with very highly negative residuals (about -2.5 °C) in winter and very highly positive ones (more than 2.0°C) in summer: this is probably due to the remarkable inversion effects in Adige Valley and in secondary valleys in that area. Also this effect is probably caused by the high continentality effect that is not properly captured by the model. A third area with significantly negative residuals was found, the Bernese Oberland: this area is all the year round hotter in the model than in reality: this is a very cold area (approximately 0.8°C every month), probably because this is an area particularly exposed to the Atlantic cold weather fronts.

Finally, the statistical parameters only for the Italian stations were evaluated: the result is a little bit worse because the model was planned for a bigger area: ME is 0.11°C and it means that the intrinsic negative bias for our model is caused by some cold areas over the Alps, MAE is 0.79°C and RMSE is 1.01°C.

6.3 HRT monthly 1961-60 maps
Fig. 40: January temperature map.

Fig. 41: February temperature map.
Fig. 42: March temperature map.

Fig. 43: April temperature map.
Fig. 44: May temperature map.

Fig. 45: June temperature map.
Fig. 46: July temperature map.

Fig. 47: August temperature map.
Fig. 48: September temperature map.

Fig. 49: October temperature map.
Fig. 50: November temperature map

Fig. 51: December temperature map
Fig. 52: Average yearly temperature map.

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