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GIS as a Tool for Investigation of Early Medieval Climatic Changes in the Kislovodsk Basin (Southern Russia)

Abstract: The paper details the results of using a special GIS-module to analyze climatic changes in the Kislovodsk basin. The main method is a computer simulation of micro-climatic conditions within grid cells of 500 x 500 m taking into account spatial and temporal changes in the global climate. The temperature of the Atlantic Ocean was raised in simulation by approximately 0.8 °C, leading to the climatic changes probably characteristic of this region during the Early Middle Ages. Based on this climatic model, the climate indicator variables for each site could be estimated and a hypothetical Medieval climate reconstructed for archaeological sites. Two major inhabited zones in the Kislovodsk basin were identified according to the altitude of the settlements. The chief result of this simulation is the hypothesis that in the Early Middle Ages the populated zones of the basin were suitable for agriculture apart from cattle farming.

Previous Investigations in the Kislovodsk Basin

Recently, the use of GIS in archaeological research has become increasingly common all over the world. In 1996, the Russian Academy of Sciences' Institute of Archaeology, led by Dr. G. Afanasjev, began work on an archaeological GIS "Kislovodsk". During the project, an archaeological survey was carried out near the town of Kislovodsk from 1996 to 2006. The area researched is a basin with natural borders where more than 830 archaeological sites were

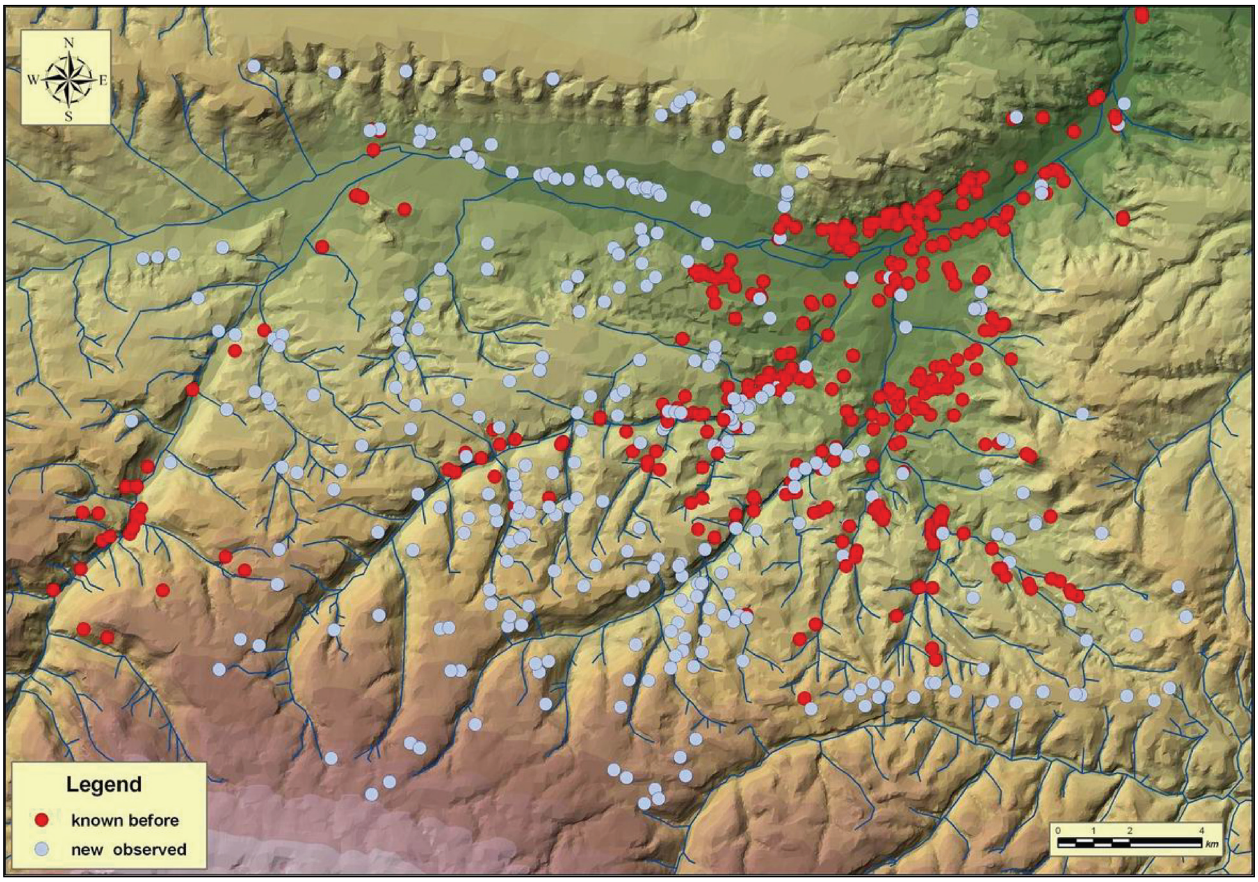

Fig. 1. Archaeological GIS "Kislovodsk". The distribution of the sites of all periods.

observed. Including the town and its surroundings, the region covered has a perimeter of 88 km, and an area of over 345 km^2. Such a high density of archaeological sites is unique in the Northern Caucasus *(Fig. 1)*.

Of the sites, around one third could be regarded as Early Medieval settlements and cemeteries, reflecting the highest level of population in the area's history. The majority of these sites can be dated to 400–750 AD based on burial data. Burial in catacombs is characteristic of the Iranian-speaking Alanic population. Their fortified and unfortified settlements (around 250 sites) cover the entire territory of the basin and reach an altitude of 1600 m above sea level, which is quite different from the modern distribution of settlements. In modern climate conditions, snow cover is usually present above 1200 m altitude from October to May, in the area where not only permanent settlements of the Alans, but also the remnants of agricultural landscapes and terraced fields can be observed. These facts led to the hypothesis that the climate in the Kislovodsk basin was different during the Early Middle Ages than at present.

Evidence for the Early Medieval Climate

Our hypothesis about the different climate in the basin in the Early Middle Ages was confirmed by several forms of evidence. First of all, it is supported by the palynological data obtained in the Taman peninsula, where a group of scholars made reconstructions of the climate and the landscape (Bolikhovskaja et al. 2002, 265). As a result, a specific stage of the Subatlantic period dating back to 600–1100 AD has been singled out, which was characterized by the most arid climate of the entire Holocene period. The predominance of a strongly arid climate in the North Caucasian piedmont between 600–1100 AD could also be proven by examination of the Caspian Sea level oscillations. L. N. Gumilev established that at around 500 AD, the level of the Caspian Sea was 4–5 m lower than at present (according to some data, 7–8 m lower), proven by underwater observation of the Derbent defensive wall constructed around 600 AD and now covered by sea (Gumilev 1966, 88).

This evidence corresponds well to the concept of the "Arkhyz interval", or a minor climatic optimum recorded across Europe between 600–1200 AD. Moreover, paleoclimatologists suppose an arid climate to be characteristic of the whole northern hemisphere in that period. For example, the period 400–800 AD is defined in geobotany as the "second xerothermic period" and characterized as extremely arid (Barash 1989, 18). Dendrochronological data obtained from archaeological sites in Germany also provide evidence for an extremely arid climate in the period 250–450 AD and around 700 AD (Schmidt / Gruhle 2003), as does an investigation of Swedish forests (Briffa 1994) and many other sources.

A new GIS Tool for Modeling the Paleoclimate

In order to investigate the microclimatic changes in the Kislovodsk basin, a new GIS module was prepared within the framework of the project led by G. E. Afanasjev in cooperation with the climatologist A. V. Kislov and the GIS-specialist A. V. Chernyshev. The module has already been described and published (Afanasjev / Kislov / Chernyshev 2002, 76–79). The following description was also published as a paper co-authored by G. E. Afanasjev and the present author (Afanasjev / Korobov 2007).

The team's main task was to make a reliable simulation of the microclimate under the influence of spatial and temporal shifts in the global climate. This required the following stages: the creation of a digital terrain model based on mid-scale topographic maps of the region; the estimation of the basic morphometric factors for a raster grid with cells 500 m square (aspect and slope, horizon exposition, the proportion of the sky above the horizon screened by the mountains, etc.); simulation of key microclimatic indicators for the year 2000 and evaluation of their consistency with the real data; establishment of landscape types and their boundaries based on the data from the microclimatic simulation, and their mapping; simulation of a hypothetical climate, evaluation and mapping of corresponding landscape conditions; converting databases and cartographic models into a special GIS.

Simulation of the local climatic features was carried out in the following way. Firstly, using a general circulation model (GCM) of the atmosphere, the global climate is reproduced. Then values from each region are transformed into regional models dependant on the region's relief. Finally, the meteorological values are adjusted to the specifics of the vegetation and top-soil. The model T21L15 was used as GCM (containing 21 harmonics in horizontal resolution of the equations of atmosphere hydrothermodynamics over sphere, 15 vertical σ-levels) based on a corresponding version of the model made by the Russian Federal Centre for Hydrometeorology (Kourbatkin / Djagterev / Frolov 1994). The temperature on the ocean surface during the simulation was prescribed monthly.

The testing ground used is situated in the GCM cell bordered by the lines of latitude ~ 44°–50° N and longitude 42°–48° E. It covers an area of 20–30 km^2, its altitudes range from 800 to 2400 m above sea level. The ground was divided into subcells of 500 m x 500 m; within each subcell, the topography, climate, and landscape were assumed to be constant. A digital terrain model was created based on contours from a digital map (scale 1:100,000) using the MAGSURF module developed by the Moscow State University's Automation Laboratory (Department of Cartography and Geoinformation, Faculty of Geography). From this terrain model, slope, aspect, and the proportion of the sky above the horizon screened by the mountains were computed for each subcell. In order to check the correlation between the information reproduced in the GCM cell and the local climate of each subcell, the data was refined to take into account the altitude and the relief key indicators by solving hydrostatic equations.

In the final stage, the distribution of temperature, air humidity and soil moisture in the surface boundary layer and active soil layer was calculated. These values were established by solving equations of the budget of energy and moisture in correspondence with the following variables: air temperature and humidity within the two layers of vegetation; soil temperature and moisture represented by a three-layer model. This accentuates relatively insignificant variations of climate, similar to those of the Subatlantic period. Their origin has not yet been comprehensively studied, but there are some factors generally regarded as having contributed to their formation, such as stochastic auto-oscillations within the oceanic-atmospheric system, and perturbations of the radiation regime caused by the fluctuations in solar activity and intense volcanic eruptions (Kislov 2001, 246–252). With the simulation methods for auto-oscillations currently available, no statistically reliable results for a long-term climatic model could be achieved. This is due to the fact that this kind of model is complicated to construct and requires a detailed record of past solar activity which does not exist.

Another, more simplified approach investigates the reaction of one part of the system (atmosphere or ocean) to the fixed status of the other. Assuming that both interaction of the atmosphere and the ocean, as well as the external factors, result in a certain temperature status on the ocean surface, then through simulation, it is possible to determine the status of the climate which corresponds to it. The difference between this and the modern climate is the climatic variation we are interested in. It is difficult to pinpoint the simulation results chronologically, but it seems that the warmer period observed in the Middle Ages is reasonably representative of the climate at that time. The basic climatic model was calculated using the approach described and this basic model was refined to reflect the local climatic variations of the region under investigation. It was posited that the temperature deviation on the ocean surface affected only the North Atlantic Ocean (latitude 30°–60° N). This is quite reasonable, since it is this region that really represents a key point as far as generation of climatic variability of various scales in the northern hemisphere is concerned. The spatial distribution of the temperature difference compared to the modern situation is similar to a dipole in physics, with positive deviations in the subtropics and negative ones in the moderate latitudinal zones, the total change of the temperature equalling zero. The maximal deviation value was less than 0.8 °C according to the simulation results.

The global model was calculated for the modern and the hypothetical Medieval situation. The model makes it possible to compare the simulated values and the actually observed values and hence evaluate the model's reliability. In the present study, regions of vegetation classes were defined based on the two variables total annual precipitation (ΣP) and

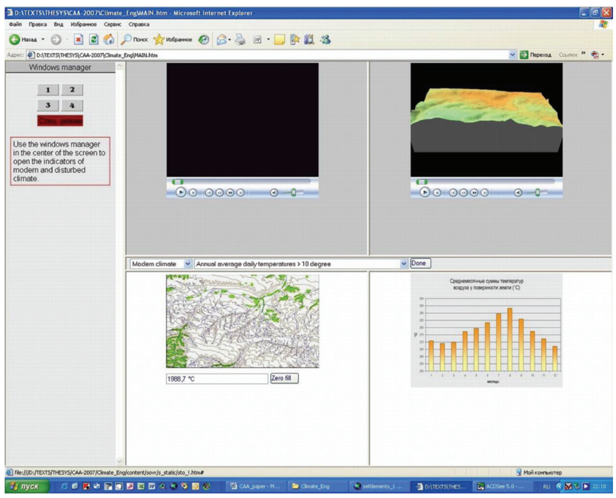

Fig. 2. The GIS module of the climate simulation shown as a series of multimedia windows.

the annual total of the average daily temperatures above 10 °C (Σt > 10 °C) (Grebenstchikov 1974). As it happened, the areas' contours often overlapped, meaning that different formations may have existed in the same climatic conditions. This conclusion raises problems when attempting a simple interpretation of the vegetation's reaction to climatic variations. To avoid these complications, some areas were combined. Using this scheme, it is possible to evaluate trends in vegetation variations caused by climatic changes.

In order to store the original information (relief structure, hydrographic network, landscape types) and the results of the climate simulations in the area under investigation, a special GIS was created. The system allows a virtual flight trajectory to be predefined, simulating a flight along this route viewing the 3D reconstruction of the terrain. The terrain reconstruction includes not only the relief but also spatial and temporal changes in climate indicators. The electronic map is linked with the database, so the user can click on any location in the cartographic image to obtain information about the climatic indicators at this point. Finally, a special function was used to generate two-dimensional graphics. The system appears as a series of multimedia windows *(Fig. 2)*.

Results of Modeling

Using the GIS module described above, around 3500 measurements of climatic indicators were made — seven for the real and seven for the hypothetical climate for each of the 249 settlements of Early Medieval origin. The following indicators were used:

- Annual average daily temperatures > 10°, °C
- Annual net radiation, hJ/m^2
- Annual precipitation, mm
- Annual number of precipitation days
- Annual number of days with daily average temperature > 10 °C
- Hydrothermal coefficient, mm/°C
- Aridity index

Then the values obtained from the GIS module were compared using descriptive statistics and the coefficient of correlation. The main procedure was cluster analysis which unites all the site data into four main groups according to climatic characteristics. A simple Euclidian distance calculation was

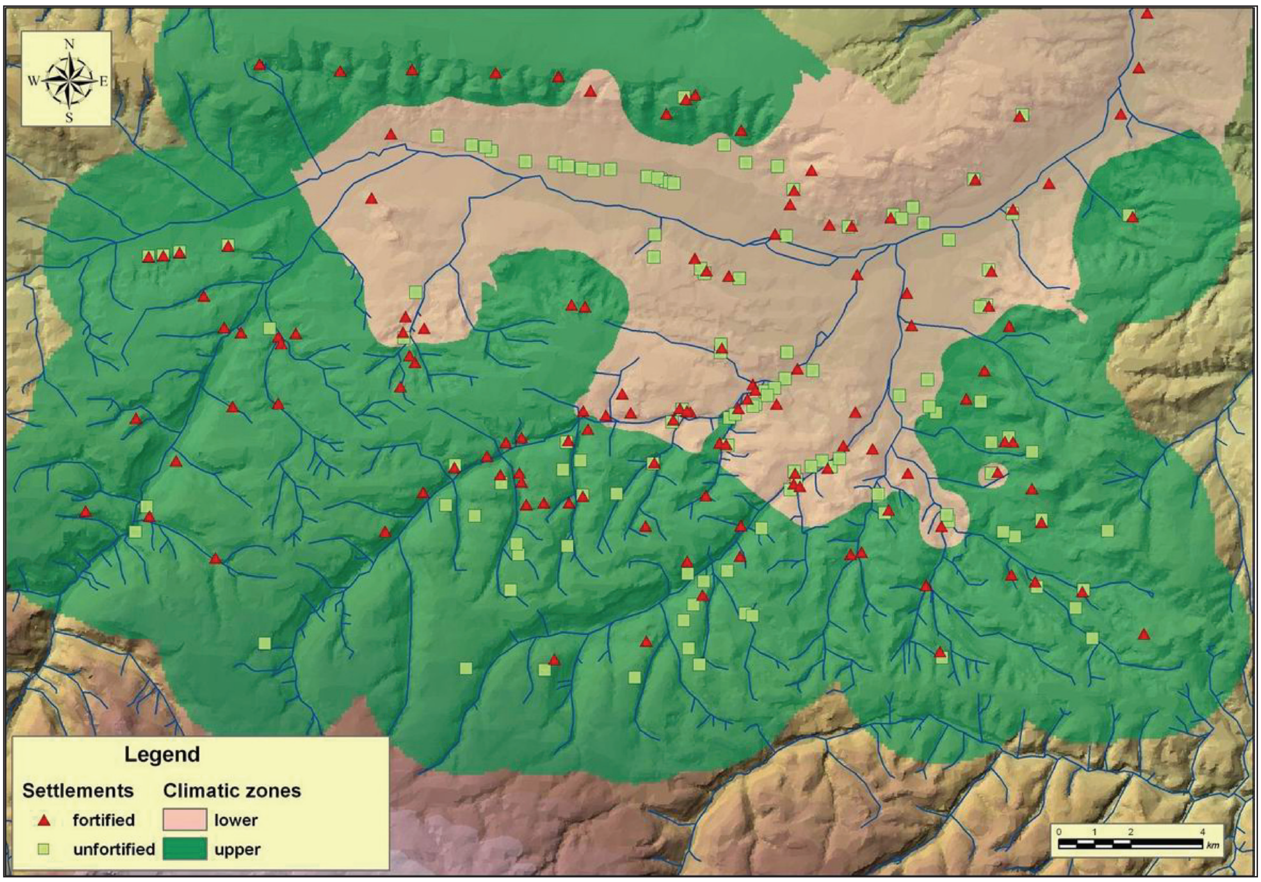

Fig. 3. The distribution of two main zones of habitation under modern climatic conditions.

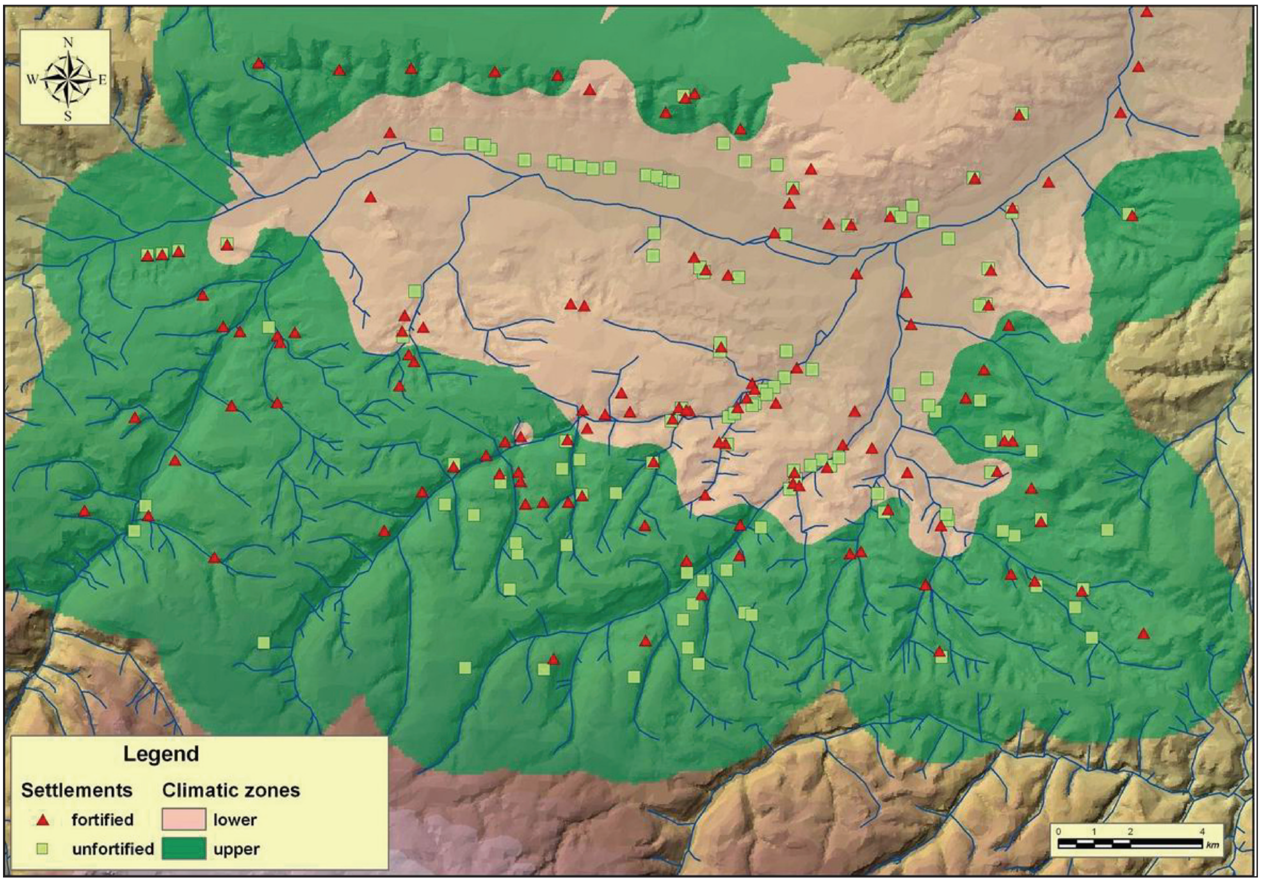

Fig. 4. The distribution of two main zones of habitation under the simulated climatic conditions.

used to group the 249 settlements described by the first five variables mentioned above (hydrothermal coefficient and aridity index were seen as non-independent and excluded from the analysis).

The clustering of the settlements under 'real' climatic conditions makes it possible to divide the sites into four clusters with the cut point at the distance of 108.87. The statistical characteristics of these clusters were graphed as box-and-whisker plots for comparison and then mapped in the GIS. We were able to divide the characteristics for the modern Alanic sites into two main groups. In the first group (clusters 1 and 3), there are 123 settlements with a higher annual temperature (2170–2390 °C) and lower annual precipitation (190–230 mm) and net radiation (1.70–1.90 hJ/m^2). They lay in the lower part of the Kislovodsk basin at elevations between 700–1220 m. It is evident that the geographical border of this group could be an isoline at 1020 m altitude *(Fig. 3)*, below which 107 of the settlements are found. The second group contained the 126 settlements of clusters 2 and 4, which had a lower annual temperature (1600–1950 °C) and higher annual precipitation (290–380 mm) and net radiation (2.05–2.30 hJ/m^2). These settlements were found in the upper zone of the basin, 119 sites were situated above 1020 m altitude.

Using the same procedure with 'disturbed' conditions simulated for an Early Medieval climate, the settlements were divided with the same cut-point distance of 108.87 into four clusters. After charting the climatic indicators as box-and-whisker plots, they were also combined into two main groups. As was the case under modern climatic conditions, the first group contained 132 settlements in the lower part of the Kislovodsk basin (clusters 2 and 3) with higher annual temperatures (2680–2900 °C) and lower annul precipitation (200–250 mm) and net radiation (1.60–1.80 hJ/m^2). The remaining 117 sites (clusters 1 and 4) had lower annual temperatures (2120–2390 ºC) and higher annual precipitation (320–400 mm) and net radiation (2.00–2.20 hJ/m^2). The geographical border between these two zones was the isoline at 1080 m altitude *(Fig. 4)* — i.e. a little higher than in modern conditions.

Comparing the two models obtained during the simulation, we could observe a significant difference between the distributions of the annual temperature variable. Though these two models ('real' and 'disturbed') are apparently very similar because of the presence in each of two main climatic zones (upper and lower), the absolute values of the annual average daily temperatures above 10 ºC are dramatically different. While in modern conditions the sum of the annual temperatures in the lower zone is around 2170–2390 °C, these same values are observed for the upper zone in the simulation (2120–2390 °C). The lower zone of the basin in the Early Middle Ages would seem to be much hotter than at present (2680–2900 °C), while the modern upper zone is much colder than in the Medieval past (1600–1950 °C).

Conclusions

Thus the analysis of modern climatic conditions and those simulated for the Early Middle Ages carried out with GIS and multivariate statistics leads to the obvious conclusion of the existence of two main inhabited areas in the Kislovodsk basin, each characterized by specific climatic conditions. At present, the lower area of the basin (below around 1020 m above sea level) has a warmer and less humid climate, and the upper area has a lower temperature, but higher precipitation and net radiation. By simulating climatic conditions for the Early Middle Ages (that is, an increase in the temperature of the Atlantic Ocean by 0.8 °C), it was possible to observe significant changes in the location of the two climatic regions, as well as in their characteristics. Simulated climatic changes representative of the true Early Medieval conditions show the inhabited area to be further up in the foothills, the border between the two areas being the line at 1080 m altitude. The upper area is characterized under the 'disturbed' climate by a similar climate to that found today in the lower area. This leads to the conclusion that in the Early Middle Ages, both populated zones of the basin were suitable for agriculture apart from cattle farming. Currently, agriculture can be developed only in the lower area. This can be proven by the distribution of the permanent settlements and terraced fields dated to the Early Middle Ages.

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