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TERRAIN MORPHOLOGY AS FACTOR OF LOCAL TEMPERATURES DISTRIBUTION IN UKRAINIAN CARPATHIANS

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Abstract. Ukrainian Carpathians like other mountainous areas are susceptible to the modern climate changes manifested mainly in accelerated warming. There are several main mechanisms of the orographic effects on temperature distribution, operating on different scales. The well-known and universally observed cooling with elevation is still often used as an over-simplified model of terrain relation to temperature regime, yet there are other significant orographic effects connected with the position of terrain features respective to incoming solar radiation angle and the large-scale movements of air masses. In Ukrainian Carpathians these effects are manifested mainly in more mild and less continental conditions on south-western macroslope that is also warmer due to larger solar radiation intake. Another important factor of temperature distribution is the formation of near-ground temperature inversions that often emerge in narrow valleys and inter-mountain troughs.

The mapping of land surface temperatures can be effectively achieved by applying spatial imagery with thermal infrared bands; in our case, Landsat 8 images allowed to obtain detailed maps of temperature distribution in Bystrytsia river basin for three different seasons of the year. An analysis has been performed of relationships between temperatures and a set of morphometric parameters, by means of *raster* package and appropriate functions of R software environment. Rather strong negative relationship between elevation and temperature has been revealed in all the three cases. Direct relationship between slope and temperature was not confirmed, while potential incoming solar radiation values for the date and time of the imagery appeared to have a moderate effect on temperature, its effect varying from season to season.

Key words: mountain climate; Carpathians; terrain morphology; temperature gradient; spatial analysis.

МОРФОЛОГІЯ РЕЛЬЄФУ ЯК ФАКТОР ЛОКАЛЬНОГО РОЗПОДІЛУ ТЕМПЕРАТУР В УКРАЇНСЬКИХ КАРПАТАХ

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Анотація. Українські Карпати, як і інші гірські райони, вразливі до сучасних змін клімату, які проявляються головним чином прискореним зростанням температур. Існує кілька основних механізмів орографічного впливу на розподіл температури, які діють у різних масштабах. Загальновідоме та повсюдно спостережуване падіння температур з висотою досі часто використовують як спрощену модель залежності температурного режиму від рельєфу місцевості, проте існують й інші значимі орографічні ефекти, пов’язані з положенням місцевості щодо кута падіння сонячних променів та великомасштабних рухів повітряних мас. В Українських Карпатах ці впливи

проявляються, здебільшого, дещо м'якшими та менш континентальними умовами південно-західного макросхилу, якому також властиві порівняно тепліші умови завдяки більшому надходженню сонячної радіації. Ще одним важливим чинником розподілу температур є утворення приземних температурних інверсій, які часто виникають у вузьких долинах та міжгірських улоговинах.

Картування розподілу температур підстильної поверхні можна ефективно здійснювати шляхом обробки та аналізу даних супутникового знімання у далекому (тепловому) інфрачервоному діапазоні спектра. У нашому випадку за допомогою зображень платформи Landsat 8 вдалось отримати детальні карти розподілу температур підстильної поверхні у басейні річки Бистриця протягом трьох різних сезонів року. Проаналізовано залежності між цими температурами та набором морфометричних параметрів за допомогою пакета *raster* та відповідних функцій програмного середовища R. В усіх трьох випадках виявлено доволі сильний негативний зв'язок між абсолютними висотами і температурою. Прямої залежності між величиною похилу поверхні і температурою не підтверджено. З іншого боку, значення потенційної сонячної радіації, що надходить на земну поверхню станом на дату і час знімків, певною мірою впливали на температуру підстильної поверхні, причому сила цього впливу змінювалась залежно від сезону року.

Ключові слова: гірський клімат; Карпати; морфологія рельєфу; градієнт температури; просторовий аналіз.

Introduction. Terrain is a well-known factor that influences the distribution of climate parameters, among which – the mean, maximal and minimal monthly and annual air and land surface temperature. Studies of the relationships between terrain characteristics and the distribution of air and ground temperatures are important for a wide range of applied fields, among which the agriculture (especially horticulture and viniculture), forestry and forest ecology, water management, etc. The importance of these studies will grow as the increasing rates of global warming pose the challenges to the adaptation of ecosystems, human populations and local economy to new climatic environment. It is natural that terrain influences on climatic parameters are more pronounced in mountainous areas that are characterized by large gradients of morphometric parameters. On other hand, mountainous areas are among the most vulnerable places concerning the climate changes and their consequences. Ukrainian Carpathians are definitely of such a kind, taking also into account deteriorating socio-economic situation in the region for the last several decades, poor environmental regulation, spontaneous forest cutting, recreation facilities development, poaching, unregulated tourism, etc. The aim of the present study is to characterize the main types and mechanisms of the relationships between terrain and climate, and to analyze the main features of the manifestation of these relationships in Ukrainian Carpathians, based on the analysis of published literature, as well as on our recent study of the distribution of land surface temperatures by means of spatial image data analysis. As terrain is directly discernable and easily mappable by modern remote sensing methods, these relationships can be the useful tool for detailed mapping of regional and local climate parameters (current as well as future prospective).

Firstly some comprehensive theoretical works on the topic should be mentioned. The book by R. Barry (Barry, 1992) presents an exhaustive analysis of factors and mechanisms of orographic effect on climate, including influences on atmospheric circulation and pressure fields, the redistribution of inbound solar radiation, and the formation of orographic precipitation. Some ecological consequences of these effects are also considered, like those reflected in the position of mountain treelines, determined by the combined effects of temperature regime, wind intensities and snow cover depth and duration of stay.

The book by A. Olenev (Olenev, 1987) is also noteworthy, as the author tries to make theoretical reflections on the whole complex of orographic effects on climate and landscape features conditioned on the latter. He notes first of all that the influences of relief on climate are determined in the first place by its orographic features irrespective of the relief genesis and rocks composition. Olenev introduces the notion of oroclimatogenic complexes as the total complexes of natural features that are conditioned by the orographic effects on climate. These as a type of natural complexes are characterized by a set of peculiar properties, namely: they don’t usually have precise boundaries; they can have a nested structure, with complexes formed by smaller terrain forms being nested inside those generated by the forms of higher orders; they do not form a continuous cover of land surface; they arise in certain zonal and sectoral conditions which together with orographic conditions determine the character and the intensity of oroclimatogenic complexes. Olenev classifies oroclimatogenic complexes by their main forming factors into several basic types, namely: altitudinal, windward, leeward, depressional, trough.

Methods. Considering specifically the orographic effects on temperature distribution, there are several main mechanisms operating on different scales. First of them is the well-known and universally observed cooling with elevation, connected with the physical process of adiabatic cooling of arising air with the drop in pressure. It even brings about an analogy of altitudinal zones with latitudinal ones. However, while temperature decrease with latitude is usually accompanied with an increase of its annual range (winter temperatures decrease faster than summer ones), the temperature ranges on high elevations are either similar to or somewhat smaller than those on adjacent low-lying areas. As an example, in Ukrainian Carpathians the vertical temperature gradient in January (the coldest month) ranges from 0.45°C/100 m in elevation levels 500–600 m to 0.3°C/100 m in elevation levels 1100–1200 m, while on April temperature gradient increases significantly, up to 0.7°C/100 m and 0.65°C/100 m on the elevation levels 500–600 and 1100–1200 m, respectively (Ukrainskie.., 1988). The altitudinal drop in mean temperatures is naturally reflected in the derivative ecological indices: thus, active temperatures drop on average by 100°C for every 100 m altitude (Klimat.., 1967).

It is known that climate becomes less continental with an increase in elevation, which is further supported by increases in precipitation with elevation. The annual temperature range in Ukrainian Carpathians decreases from 22–23°C on foothills to 17–20°C on high mountains (Ukrainskie…, 1988). Increased elevation not only usually lessens the annual temperature variability, but also shifts the seasonality in thermal conditions: summer temperature peaks shift to later in the year, spring being much colder than autumn. This also imparts to mountain climate some “maritime” features.

The monotonous dropping of temperatures with elevation, being the coarsest possible model of relationship between terrain morphology and temperature regime, is still sometimes used solely for the purpose of climatic regionalization. An example is the climatic zoning scheme proposed by M. Andrianov in (Pryroda.., 1968), that has been highly cited by Ukrainian authors for half a century. Its zones and their boundaries are based on the averaged values of altitudinal temperature gradients calculated from weather stations data. It was noted that the boundaries of these climatic zones, hardly tied to altitudinal values, often do not coincide with observed vegetation zones (Ukrainskie…, 1988). As noted in (Lookingbill & Urban, 2003), temperature estimates that has important implications for ecological analysis still frequently rely upon the simplifying assumptions associated with lapse rates.

Another kind of orographic effect refers to the position of terrain features respective to the large-scale movements of air masses. Mountains can influence the movement of atmospheric waves of different scales, the deformation of cyclones and atmospheric fronts, the cyclogenesis in the lee side of mountains, the formation of high-pressure ridges over the mountain ranges crossed by air flow, the increase of air convectivity, and some other effects (Barry, 1992). The barrier (windward and leeward) effects in Ukrainian Carpathians are manifested mainly in much larger precipitation values on south-western macroslope windward relative to wet air masses from Atlantic. There is also a manifestation of this effect in higher temperature gradients on south-western macroslope (on average 0.3°C higher annually than on north-eastern macroslope) (Klimat…, 1967). Barrier effect also somewhat affects seasonality in temperature: the differences in mean monthly temperatures between locations in similar elevations on different macroslopes is only 0.1–0.2°C in June, but increases to 0.6–1.1°C in August (Buchynskyi, Volevakha & Korzhov, 1971).

Terrain morphology directly affects the redistribution of solar radiation depending on slope and aspect. “Warming” effect of larger solar radiation on southern oriented slopes comparing to northern ones (in the Northern hemisphere) is well-known, some researches claiming that aspect differences can be even more important than elevation in controlling temperature (McCutchan & Fox, 1986).

There are also some more delicate effects of terrain aspect: for instance, differences in solar radiation incidence between northern and solar slopes are less noticeable in summer, and steep northern slopes in summer can be even warmer than southern ones. Due to convective processes, eastern slopes can receive more direct solar radiation in summer then western slopes. Complex terrain forms may have peculiar local climatic conditions influenced by their morphology. Thus, deep longitudinal valleys are mostly shadowed during mornings and evenings thus receiving relatively less total insolation, especially on summer. On the other hand, deep latitudinal valleys may be completely devoid of direct solar radiation on winter months (Buchynskyi, Volevakha & Korzhov, 1971).

To more precisely capture the effect of solar radiation redistribution on surfaces (slopes) of different slope and aspect, the potential relative radiation index can be calculated, which is a measure of how topography translates to spatial differences in relative radiation. It both accounts for hillshading and shadowing effects and integrates over time to account for the fact that solar position changes over the course of the day and year (Lookingbill & Urban, 2003).

Another mechanism of terrain influence on temperature distribution is the formation of near-ground temperature inversions that cause decline in temperature in lowest topographic locations compared to those on higher altitudes. This effect mostly concerns the distribution of minimal temperatures, but those can in turn affect the mean temperatures also. Because of it, minimal air temperatures in the region are usually observed on weather stations located in negative forms of terrain – troughs, valleys of small rivers, etc. (Klimat…, 1967). Frequent temperature inversions are the main cause of relatively small altitudinal temperature gradients in winters. Research of (Bolstad et al., 1998) showed that for a five-station network located within the research watershed covering 694–1439 m elevation range, mean daily minimum temperatures observed at the valley bottom station were generally lower than the mean daily minima at the higher elevation stations when averaged over the entire year and growing season (May through mid-October), even though the valley bottom was at an elevation 500 to 700 m lower. Daily minima averaged approximately 2°C lower at a valley bottom location than nearby sideslope measurement stations.

Temperature inversions in Carpathians are peculiar of narrow valleys and inter-mountain troughs (like Yasynia and Vorokhta troughs), where they can last in winters up to several days under anticyclonic conditions (Buchynskyi, Volevakha & Korzhov, 1971). In some extreme cases, inverse temperature gradients can reach 15°C/1000 m (Mukha, 2008). It appears that temperature inversions are more frequent during relatively cold winters with prevailing anticyclonic conditions. Our study (Mkrtchian & Shuber, 2009) showed that in January 1985, when mean winter temperatures in Western Ukraine were 1,5–6°C below norm, correlation between temperature and elevation was nearly absent. It is also reported that in the harsh winter of 1964 the mean January temperature in Pozhizhevska weather station lying near the crest of the highest Chornohora range at 1434 m was 3,3°C higher than that in Kolomyia lying at the foothills at 298 m altitude (Buchynskyi, Volevakha & Korzhov, 1971).

The study by (Laughlin & Kalma, 1990) reports that the spatial distribution of minimal temperatures in winter depends upon the genesis type of frost that can be either of the advective or of radiation type. Under advective frosts (that develop as a result of a large scale influx of cold air and are characterized by moderate-to-strong winds and a well-mixed atmosphere), differences in (minimum) air temperature at the local scale are usually small and exposed hilltops are usually slightly colder than protected valleys. On the contrary, under radiation frosts (that occur at night and result from strong long wave radiation cooling in calm, clear and dry atmospheric conditions) strong surface inversions develop and significant horizontal temperature differences in undulating or dissected terrain are observed, determined by the three-dimensional cold air drainage (which is affected by shelter and surface roughness) and subsequent cold air ponding; thus valleys and depressions are usually colder than hilltop sites (Laughlin & Kalma, 1990). To evaluate the frequency and intensity of cold air ponding under radiation frosts conditions, no local morphometric parameters would be sufficient, and spatial context should be taken into account. As (Dietrich & Böhner, 2008) note in more general context, the relation between a terrain segment and its environment further away plays a key role for topoclimate, therefore, the spatial relation to the surrounding area is absolutely indispensable for a sufficient characterization of a specific terrain segment

The phenomenon of temperature inversions is connected with the appearance of “warms belts” on slopes on certain altitudinal ranges. Contrary to the standard “linear” model of vertical zonality this assumes the bidirectional gradient of temperature, when it reaches maximal values inside the certain altitudinal range and drops above as well as below this range. This phenomenon is most characteristic of inversion episodes, when temperature inversion embraces the lower parts of long and high mountain slopes, whereas above the inversion layer an ordinary altitudinal gradient takes over. In locations with frequent inversions this can reflect in climatic parameters. Another cause of the formation of "warms belts" can be the larger values of solar radiation falling on steep mountain slopes of southern aspects, in comparison with lower lying neighboring flat areas. This phenomenon is well expressed and studied for the Transcarpatian region of Ukraine, which agriculture has been specialized in relatively heat-loving crops. It has been determined that most favorable conditions for viniculture and heat-loving fruit crops are located on southern slopes at 150–250 m elevation, while below as well as above this altitudinal range these conditions become significantly worse (Buchynskyi, Volevakha & Korzhov, 1971).

Many regional studies have been published that aim at the analysis of terrain-climate relationships on regional and local scales and the detailed characteristisation of regional and local climate based on information on terrain as a driving factor. Study of (Hiebl et al., 2009), aimed at the creation of a high-resolution (1×1 km) monthly temperature dataset for the Greater Alpine region using multilinear regression techniques, analyzed the relationships between temperature and a set of geographic factors, like latitude, longitude, elevation, and distances from the coast. The elevation appeared to be the single variable that has the strongest influence among all, explaining 69% of temperature variance averaged over the year, reaching the maximum explained value in May (85 %) and minimum in January (45%). A somewhat similar task has been set out by the CARPATCLIM project teem aimed at the creation of grids of daily distributions of a large set of meteorological variables and climatic indicators for the entire Carpathian Region with spatial resolution of 30 arc-second, employing records from 231 weather stations and 469 rain gauges (Spinoni et al., 2015). While the study of the relationships between land surface topography and climatic parameters was not the aim of the task, the data interpolation algorithm applied was based on regression-kriging in which explanatory variables (predictors) were the principal components derived from a set of elevation differences calculated in local neighborhood, supposed to reflect the orographic variability (so-called AURELHY method developed in 1980-th at the French Meteorological Service) (Spinoni et al., 2015).

In our study (Mkrtchian & Shuber, 2009) the terrain morphology information in the form of SRTM digital elevation model (DEM) was used for the purpose of the mapping of mean monthly temperature distribution for the Western region of Ukraine, which include Ukrainian Carpathians as well as some flat and moderately dissected plains. Mapping was performed with the interpolation of weather station data by the regression kriging method, that combines multiple regression modeling (which utilizes DEM-derived morphometric data interpreted as factors influencing temperature) with the geostatistical interpolation of regression residuals (Mkrtchian & Shuber, 2009). As was expected, the absolute elevations appeared to be the parameter most closely related to temperatures. Terrain ruggedness appeared to be the second most significant factor, yet its influence on temperature can be of opposite directions depending on synoptic conditions prevailing in the certain month. Regional aspect (calculated in the floating window with 3.6 km radius) also had varying influence on temperature field: areas with prevailing southern aspects were not always significantly warmer than areas with northern ones; eastern aspects were warmer than western in the periods with prevailing dry and sunny conditions, while on months with prevailing cyclonic circulation type (indicated by lowest mean atmospheric pressure) western aspects appeared to be slightly warmer than eastern ones.

The results of the study by (Lookingbill & Urban, 2003) suggest that temperature estimates that consider additional fine-scale topographic variability describe temperature more accurately for the study area (located in old-growth forest of the Oregon Western Cascades covering 6400 ha and ranging in elevation from 410 to 1630 m) than do estimates derived from simple lapse rate models. For daily maximum temperature, the simple lapse rate model is significantly improved upon by including radiation, while distance from stream appeared more important than any of the radiation proxies in explaining variability in daily minimum temperature (Lookingbill & Urban, 2003).

Results and discussion. Our recent research was aimed at mapping of land surface temperature for the Bystrytsia river basin located in Western Ukraine, part of which lies in the Gorgany range of Ukrainian Carpathians, reaching altitude of 1836 m (summit of mt. Syvulia Velyka) (Kovalchuk, Mkrtchian & Kovalchuk, 2018) (Fig. 1). The mapping was achieved using Landsat 8 imagery with two thermal infrared bands, that capture emissivity values closely related to land surface temperature. As the latter is not equivalent to an above-ground air temperature, the both are pretty well correlated and the land surface temperature easily measured with remote sensors can serve a good proxy to the temperature of air directly above land surface. The applied method of land surface temperature estimation consists of several successive steps which are described in (Kovalchuk, Mkrtchian & Kovalchuk, 2018). Three multispectral images referring to different seasons (autumn, winter and summer) were used to obtain three rasters of land surface temperature for the Bystrytsia river basin, referring to different seasons (autumn, winter and summer) (Tab. 1, Fig. 2). The big spatial detail of these temperature rasters allowed to perform a detailed analysis of relationships between temperature and a set of morphometric parameters.

Tab. 1. General characteristics of the scenes of Landsat 8 images used in the study

Date	Local time	Sun height	Cloud cover percentage of the scene	Air above-ground temperature (Ivano-Frankivsk weather station)
2013, October 5	12:16	35,07˚	6,73%	9℃
2015, February 13	11:14	24,99˚	0,67%	1.4℃
2016, August 10	12:14	53,17˚	7,89%	26℃

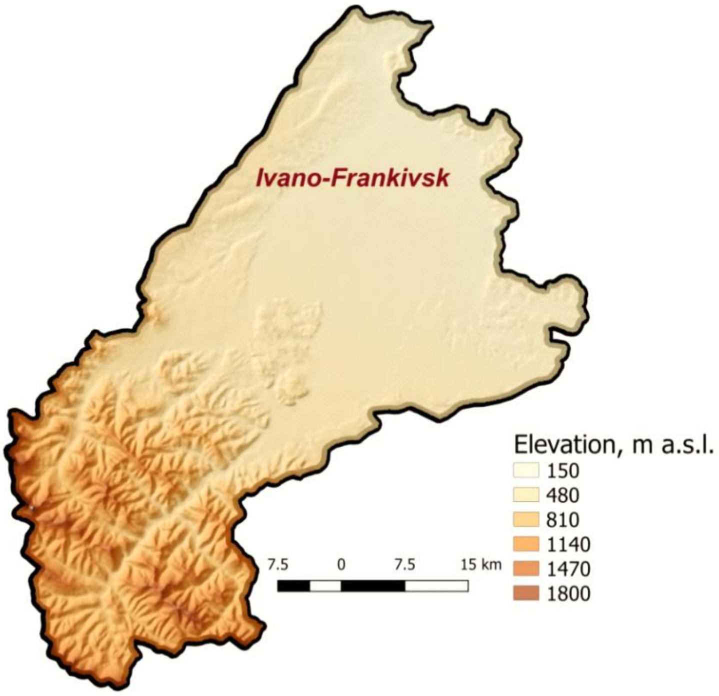

Fig. 1. The terrain of the Bystrytsia river basin

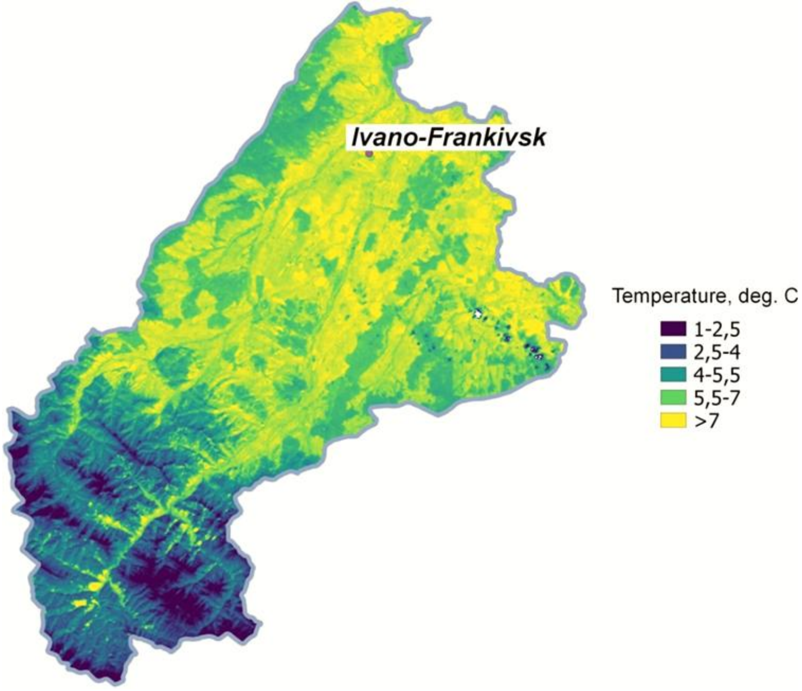

Fig. 2. Distribution of land surface temperature for the Bystrytsia basin for October 5, 2013

The analysis was performed in R language and free software environment for statistical computing. A set of morphometric parameters was generated for the analysis from SRTM DEM with *terrain* function of *raster* package. These parameters included elevation, slope, as well as the terrain indices according to (Wilson et al., 2007). The latter included TRI (Terrain Ruggedness Index) – the mean of the absolute differences between the value of a cell and the value of its 8 surrounding cells; and TPI (Topographic Position Index) – the difference between the value of a cell and the mean value of its 8 surrounding cells (Wilson et al., 2007). Additionally, potential incoming solar radiation for the date and time of the imagery have been calculated with the SAGA GIS. Relationships between the mentioned terrain morphometry parameters and land surface temperature were calculated with *lm* function of R, and the values of Pearson correlation coefficient were used to assess the strength of the relationship.

Results of the analysis are given in Tab. 2. For slope parameter, two different correlation coefficients were calculated: standard and partial, that takes into account the correlation between elevation and slope. As in many areas the latter values are strongly correlated (low elevations being occupied by plains and plain river valley bottoms, high elevations – by steep mountain slopes), strong correlation between elevation and temperature will also mean phony correlation between the temperature and the slope, even if the latter two are not interrelated at all. Partial correlation coefficient takes into account such a possibility and characterizes proper relationship between slope and temperature, elevation being equal.

Tab. 2. Correlation coefficients between terrain morphometry parameters and land surface temperatures, measured for the Bystrytsia river basin

Variable / ***Date***	Elevation	Slope		TRI	TPI	Insolation
		Standard	Partial			
2013, October 5	-0.86	-0,73	-0.08	-0,73	0.01	0.23
2015, February 13	-0.75	-0,62	-0.02	-0,61	0.1	0.26
2016, August 10	-0.76	-0,65	-0.08	-0.65	0.02	0.15

As can be seen from Tab. 2, negative relationship between elevation and temperature is rather strong in all the three cases. Relationship between slope and temperature also seem strong at a first glance (from a standard coefficient), but almost disappear when the partial correlation coefficient is calculated and the confounding elevation variable is accounted upon. Correlation coefficients with TRI index seem rather equal to standard coefficients with slope. And indeed, correlation coefficient between slope and TRI layers was as high as 0.998. Thus, TRI index (the mean of the absolute differences between the value of a raster cell and its neighbors) looks totally redundant, conveying in fact the same information as slope index. Correlation of temperature with TPI index was also rather non-existent, meaning that local morphoform in this area is not informative as a factor influencing temperature. Insolation appears to have a moderate effect on temperature, and this effect varies from season to season, being stronger in winter and weaker in summer. It should be mentioned that all the satellite data were taken around midday, thus better characterizing the distribution of maximum temperatures.

Conclusion. Terrain morphology is a well-recognized factor that strongly influences regional and local climate. This influence is rather complex and its analysis should not be reduced to mere calculation of regional lapse rates. The analysis for the Bystrytsia river basin revealed that slope angle was not noticeably related to land surface temperatures, the same being true for the indices of terrain ruggedness and topographic position that characterize local terrain morphometry. On the contrary, land surface temperatures appear to be significantly influenced by potential incoming solar radiation, the latter being a complex function of slope angle and aspect. It emphasizes the utility of process-based models in the study of relationships between local climate and topography. Other processes that relate to terrain morphology and affect temperature distribution are worth further studies, first of all – the influence of topography on the frequency and depth of temperature inversions that form in the terrain hollows and significantly influence the distribution of minimum temperatures. Further studies could also be directed towards the differences in relationships between the temperature and the terrain variables under the different weather conditions (e.g. prevailing cyclonic or anticyclonic conditions, cloud cover, wind speed and direction, etc.)

Taking into account the relationships between terrain morphology and climatic characteristics will allow to produce precise and accurate climatic surfaces that convey the regional and local distribution of climatic parameters, among which – those characterizing temperature regime. The distribution of near-surface air temperatures can also be inferred from the land surface temperature measurements taken from satellite-born remote sensors and preprocessed with appropriate algorithms. Combination of different data sources would possibly allow to obtain the most accurate land surface and near-surface air temperature maps applicable to a wide range of applied fields.

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