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PHYSIOLOGICALLY EQUIVALENT TEMPERATURE AS A FACTOR FOR TOURISM IN EXTREME CLIMATE REGIONS IN THE RUSSIAN FAR EAST: Preliminary results

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Abstract: Preliminary human-biometeorological estimation of climatic conditions throughout the southern part of the Russian Far East is carried out using the physiologically equivalent temperature (PET) based on the body-atmosphere energy balance. The results are presented in seasonal and annual bioclimatic maps for spatial estimation of bioclimate based on the climatic data to give adequate bioclimatic information for regions with a low density of weather stations, and may be used for needs of tourism and human well-being management. Areas with extreme and uncomfortable thermal conditions for all seasons and the year as a whole are identified. Temporal evaluation of PET for the city Birobidzhan, the administrative center of the Jewish Autonomous Region, is an example of detailed daily biometeorological reports of thermal bioclimate conditions and may be applicable by the residents and tourists in Birobidzhan. **Keywords**: climate and tourism, human energy balance, physiologically equivalent temperature, temperate monsoon climatic zone, Russian Far East.

Resumen: Son presentadas estimativas biometeorológicas humanas preliminares sobre las condiciones climáticas en la región sur del Extremo Oriente de la Rusia, con recurso al indicador de "temperatura fisiológicamente equivalente" (PET), el cual tiene por bases el equilibrio

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energético cuerpo/atmósfera. Los resultados son presentados en la forma de mapas bioclimáticos sazónales y anuales de estimativas espacial del bioclima. Estas estimativas se basan en datos bioclimáticos, y dan la información bioclimática adecuada para regiones con baja densidad de estaciones meteorológicas, y pueden ser usadas en los dominios del turismo y de la gestión del bienestar humano. Son identificadas las áreas con condiciones térmicas extremas y desconfortables, sea en las varias estaciones del año, sea globalmente para todo el año. La evaluación temporal del indicador PET para la ciudad de Birobidzhan, centro administrativo de la Región Autónoma Hebraica, es un ejemplo de relatorio biometeorológico diario detallado de las condiciones térmicas bioclimáticas, y puede ser aplicado por residentes y turistas en Birobidzhan. **Palabras clave:** clima y turismo, equilibrio energético humano, temperatura fisiológicamente equivalente, zona climática de monzón templada, Extremo Oriente de la Rusia.

Resumo: O presente estudo apresenta estimativas bio-meteorológicas humanas preliminares sobre as condições climáticas na região sul do Extremo Oriente da Rússia, com recurso ao indicador de "temperatura fisiologicamente equivalente" (PET), o qual tem por base o equilíbrio energético corpo/atmosfera. Os resultados são apresentados sob a forma de mapas bioclimáticos sazonais e anuais de estimavas espacial do bio-clima. Estas estimativas baseiam-se em dados bio-climáticos, e fornecem informação bio-climática adequada para regiões com baixa densidade de estações meteorológicas, e podem ser usadas nos domínios do turismo e da gestão do bem-estar humano. São identificadas as áreas com condições térmicas extremas e desconfortáveis, quer nas várias estações do ano, quer globalmente para todo o ano. A avaliação temporal do indicador PET para a cidade de Birobidzhan, centro administrativo da Região Autónoma Hebraica, é um exemplo de relatório bio-meteorológico diário detalhado das condições térmicas bio-climáticas, e pode ser aplicado por residentes e turistas em Birobidzhan. **Palavras chave:** clima e turismo, equilíbrio energético humano, temperatura fisiologicamente equivalente, zona climática de monção temperada, Extremo Oriente da Rússia.

INTRODUCTION

The meteorological environment, alongside with other natural conditions, is one of the most significant factors in the estimation of a region's possibilities for tourist activity (de Freitas, 2003). The assessment of a region's suitability for tourism and recreational outdoor activities assumes knowledge of the influence of climate and its thermal component on human well-being. There are three main facets of climate and weather that are of importance in tourism climate assessment: thermal characteristics, such as air temperature and /or humidity; the aesthetic or psychological aspects, such as clear blue skies; and physical factors (e.g., rain, cloudiness), where the first one is of primary significance (de Freitas, 2003; de Freitas et al., 2008).

Several different models and indices were developed during the second half of the 20th century to estimate the complex thermal influence of the atmospheric environment on the human body. The assessment of thermal bioclimate may be done by the use of climate indices, e.g. Heat stress index (Belding & Hatch, 1955), Discomfort index (Thom, 1959), Wind-chill index (Steadman, 1971) or similar ones that are based on atmospheric parameters such as air temperature, humidity, wind speed, etc. However, they do not include the effect of radiation fluxes, nor do they, amongst other limitations, account for the thermo-physiological regulatory processes, which are of a certain importance (Mayer & Höppe, 1987; Höppe, 1999; Matzarakis et al., 1999).

To estimate relations between the atmospheric environment and human health in a more sophisticated way, the heat balance of human beings is incorporated into the analysis (Burton & Edholm 1955; Budyko & Cicenko, 1960; Fanger, 1972; Höppe, 1999). Physiologically equivalent temperature (PET) is developed on the basis of the body-atmosphere energy balance and may be calculated by the RayMan model (VDI, 1994; VDI, 1998; Matzarakis et al., 2007b, 2010), which has been developed for applied climate studies. The main feature and advantage of RayMan compared to other similar models is the calculation of short- and long-wave radiation fluxes, the possibility to evaluate the thermal environment throughout the year for both cold and hot seasons, and the use of a commonly known unit (°C). The RayMan model and PET as well can be used for a variety of applications: for the assessment of climate in human biometeorology, for studies in applied climatology, for recreational issues and environmental medicine, for land use and planning purposes on various levels (Matzarakis et al., 2007b). PET is among the most sophisticated of the schemes currently available for integrating complex thermal body-atmosphere interactions and expressing the result as meaningful unitary index (VDI, 1998; Matzarakis et al., 1999; Höppe, 1999).

The aim of this paper is to present an application of the index of physiologically equivalent temperature in spatial-temporal assessment of the thermal environment for the extreme thermal climate of the Russian Far East useful for needs of tourist and recreation managing in the region. The study area is located in the temperate monsoon climate zone, which is characterized by an extreme continental regime of annual temperatures. Calculations of daily data for the weather station Birobidzhan reflect the temporal information about the thermal environment and describe the first attempt to develop a data base containing detailed daily biometeorological information about the thermal conditions. This analysis may be compared to the spatial visualization of monthly, seasonal or annual PET bioclimate maps, which are constructed on the basis of climatic values for the entire study region. Areas with extreme and uncomfortable thermal bioclimatic conditions and heat stress are identified.

METHODS

RayMan model and PET

The heat balance equation for the human body reads as follows (Höppe, 1993, 1999):

$$\mathbf{M + W + R + C + E_D + E_{Re} + E_{Sw} + S = 0}$$

where M is the metabolic rate (internal energy production by oxidation of food); W is the physical work output; R is the net radiation of the body; C is the convective heat flow, E_D the latent heat flow to evaporate water into water vapor diffusing through the skin (imperceptible perspiration), E_{Re} the sum of heat flows for heating and humidifying the aspirated air, E_{Sw} the heat flow due to evaporation of sweat and S the storage heat flow for heating or cooling the body mass. The individual terms of the equation may be positive in the case of an energy gain (M is always positive) and may be negative – in the case of an energy loss (W, E_D and E_{Sw} are always negative). The unit of all heat flows is given in Watt. All components required for the assessment of the impact of ambient thermal conditions on human comfort can be calculated using synoptic or climatological data – air temperature, air humidity, wind speed and short- and long-wave radiation – that are closely related to the thermo-circulatory system of the human body (VDI, 1998; Höppe, 1999).

The RayMan model is based on the energy-balance equation of the human body and is based on German VDI-Guidelines 3789 Part II (VDI, 1994) and VDI-Guidelines 3787 Part I (VDI, 1998). The model is developed for urban climate studies and has a broader use in applied climatology and tourism studies as well. Finally several thermal indices such as Predicted Mean Vote (PMV), Physiologically Equivalent Temperature (PET) and Standard Effective Temperature (SET*) may be calculated for the assessment of human bioclimate in a physiologically relevant manner as shown in several applications (Matzarakis et al., 1999; Matzarakis & Rutz, 2005; Blazejczyk & Matzarakis, 2007; Matzarakis et al., 2007b, 2010). All indices have the known grades of thermal perception for human beings and physiological stress (Höppe, 1999).

PET is defined as a certain air temperature related to fixed standard indoor conditions at which the heat balance of the human body is maintained with core and skin temperature equal to those under the conditions being assessed (VDI, 1998; Höppe, 1999). Compared to other thermal indices it has the advantage of using a commonly known unit (°C), which makes results easily understandable for people who may be unfamiliar with the human-biometeorological terminology. Another advantage of PET is that the values may be calculated for any day and any season of the year in different and extreme climates within easy and complex environments (Höppe, 1999; Matzarakis et al., 1999; Matzarakis et al., 2007b), widely applied in Europe (Blazejczyk & Matzarakis, 2007; Matzarakis et al., 2007a), in Japan (Matzarakis, 2008) and Australia (Shiue & Matzarakis, 2011).

PET can be adjusted to different grades of thermal perception and physiological stress. The baseline for a standard person is an internal heat production of 80 W of light activity, added to basic metabolism, and a thermal resistance of clothing of 0.9 clo (Table 1).

Table 1. Ranges of physiologically equivalent temperature (PET in °C) for different grades of thermal perception by humans according to Matzarakis and Mayer (1996)

PET (°C)	Thermal perception	Grade of physiological stress
	very cold	extreme cold stress
4		
	cold	strong cold stress
8		
	cool	moderate cold stress
13		
	slightly cool	slight cold stress
18		
	comfortable	no thermal stress
23		
	slightly warm	slight heat stress
29		
	warm	moderate heat stress
35		
	hot	strong heat stress
41		
	very hot	extreme heat stress

All meteorological parameters influence the human energy balance including air temperature, vapor pressure, wind speed, as well as short- and long-wave radiation parameterized by the mean radiation temperature (MRT) of the surroundings. Data on short- and long-wave radiation are generally not available in climate records. If radiation data is not available, MRT may be estimated using cloud cover, time of the year and type of surface cover (Matzarakis et al., 2007b).

PET may be quantified for a certain location; in this case results can be presented using the bioclimate diagram as a frequency of classes of thermal perception based on ten-day intervals in percentage of the class occurrence for the temporal evaluation. Information about every grade of physiological stress is available. Additionally the mean, maximum and minimum values of PET, frequency of cold days (days with PET < 0°C), thermal comfort and slight heat stress days (days with PET between 15 °C and 25°C), moderate and strong heat stress days (with PET > 30 °C and >35°C) may be calculated.

Study Area and Data

In the current study, the spatial distribution of PET is used to assess the thermal conditions of a meteorological environment in the Far-Eastern Federal District of the Russian Federation. The study area is situated at the northern latitude from 40° to 60°N and at the eastern longitude from 125° to 145°E in Khabarovsky Krai, Primorsky Krai (Primorye), Amursk Region, Jewish Autonomous Region (Figure 1) and is referred to as the southern part of the Russian Far East. The temporal assessment of PET for the evaluation of thermal component of urban climate is demonstrated in bioclimate diagram using data for the study site of Birobidzhan, the administrative center of the Jewish Autonomous Region.

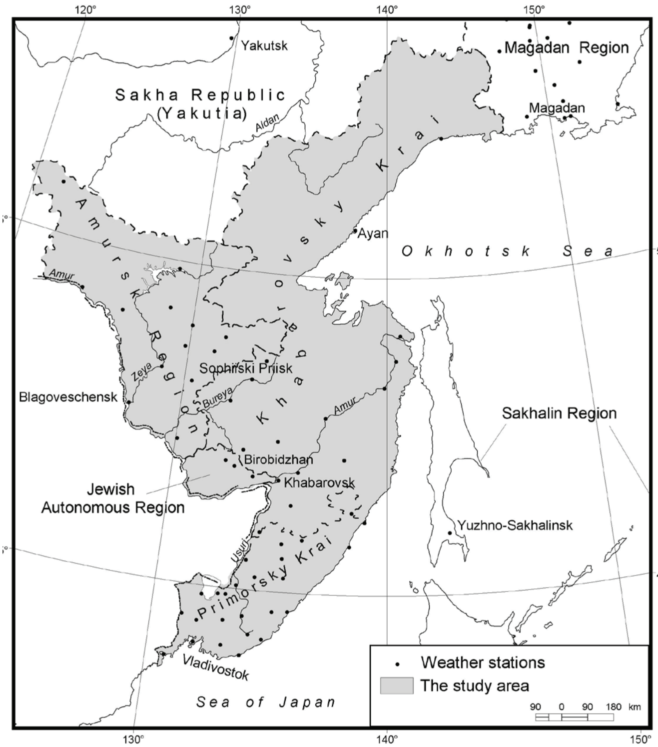
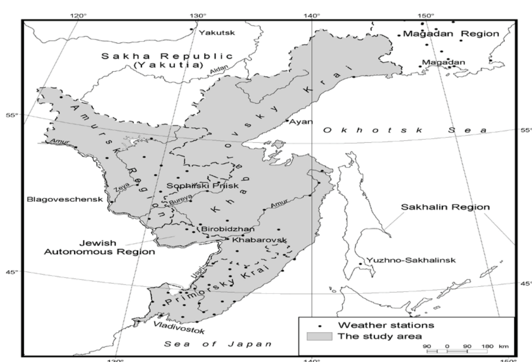
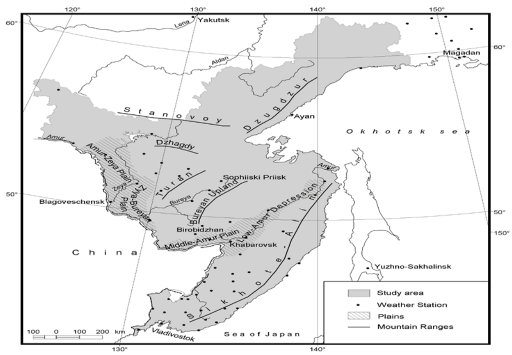


Figure 1. The southern part of the Russian Far East: administrative division. Showing the location of weather stations



The topography of the area varies, comprising extensive mountainous regions stretching mainly from south-west to north-east – Mountains Malyi Khingan, Sikhote-Alin, Dzugdzur; Bureyan Upland and other low- and middle mountains with a maximum 2078 m above sea level – as well as wide plains in the Amur River valley – Zeya-Bureya, Amur-Zeya and Middle Amur Plains and Low-Amur Depression (Figure 2).



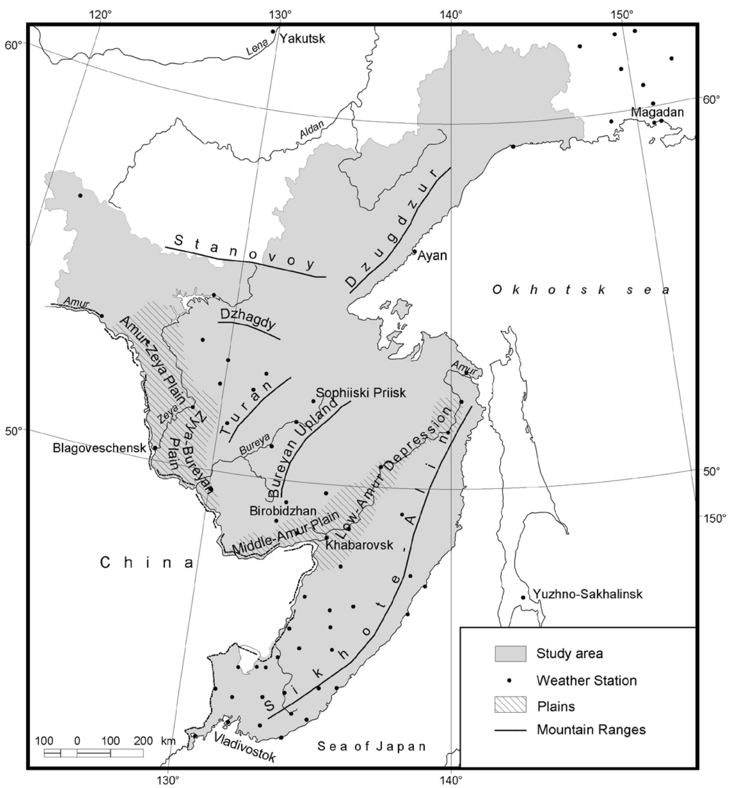


Figure 2. The southern part of the Russian Far East: topography

The study area is located in the temperate monsoon climate zone, which is characterized by an extreme continental regime of annual temperatures. The annual air temperature range (the difference between mean temperatures in months with maximal and minimal annual air temperature, e.g. January and July for continental climate) is near 45 °C -50°C, which underlines the continentality of Middle Siberia; the annual mean temperatures are between -7.3°C and 5.0°C (Table 2).

Table 2. The main climatic characteristics of the southern part of the Russian Far East

Weather stations	Elevation, m above sea level	Mean temperature, °C			Precipitation, mm		
		January	July	year	XI-III	IV-X	annual
Blagoveschensk	130	-24.1	21.4	0.1	42	626	681
Birobidzhan	80	-24.6	20.3	-0.1	120	710	830
Khabarovsk	88	-22.3	21.1	1.4	68	526	594
Vladivostok	13	-13.1	18.5	5.0	129	641	770
Sophiisky Priisk	326	-32.5	15.2	-7.3	58	663	721
Ayan	6	-19.2	11.5	-3.1	114	739	853

In winter, the southern part of the Russian Far East is influenced by the Siberian anticyclone, and a low-pressure area is developed over the northern Pacific Ocean; the situation is referred to as a winter monsoon with cold and sunny weather. The structure of the thermo-barical field of troposphere in summer is opposite to the winter. The Yakutian depression is located over the continent and the Pacific subtropical maximum is formed over the ocean. The situation is referred to as summer monsoon with hot weather and very high precipitation and humidity (Vitvitskyi, 1969). Annual precipitation varies between 400 mm and 1000 mm, and nearly 80 % of it falls during the summer monsoon from June to September (Table 2).

Several authors (e.g., Gorbatcevich, 1894; Matukhin, 1971) have highlighted the extreme bioclimate for this area: the conditions in the southern Far East with long cold winters are similar to those in Siberia and in summer the conditions are similar to those of the warm, humid tropics. Human discomfort in the monsoon climatic conditions of the Far East is influenced by a combination of the low temperatures and wind in winter and the high air temperatures with high relative humidity creating an unpleasant, sultry feeling, in summer (Grigorieva, 2007).

Standard climate data, such as air temperature, relative air humidity, wind speed and cloud cover is used to quantify the spatial distribution of thermal bioclimatic conditions. This data is available through the International Water Management Institute World Water and Climate Atlas (New et al., 2002) the climatology was interpolated from a data set of station means for the climate normal period from 1961 to 1990 and was constructed of a 0.1° latitude / longitude data set of mean monthly surface climate.

The use of PET for the evaluation of the thermal component of urban climate for recreation and health purposes in a bioclimate diagram is demonstrated for the city Birobidzhan, the administrative center of the Jewish Autonomous Region, situated in the southern part of the study area. Standard meteorological data (air temperature, wind speed, air humidity and cloud cover) at 3 pm of the weather station Birobidzhan (48°52'N, 131°02'E, 80 m above sea level) was processed for the 10-year period from January 1997 to December 2006. Thermal-physiological conditions here are expressed using the bioclimate diagram as frequency classes of thermal perception based on ten-day intervals in percentage of the class occurrence. Physiological and meteorological fundaments of RayMan model are described in Methods (Matzarakis et al., 2007b).

In the view of limited access to meteorological data of high time resolution, temporal assessment for Birobidzhan was done using available data for a 10-year period (from January 1997 to December 2006) that does not coincide with data used for the spatial estimation of thermal conditions in the period from 1961 to 1990. These two parts of the work – maps and diagram – are independent of each other and may be calculated using different data, when the purpose of the work is to give a general view of the thermal bioclimate of the region.

RESULTS

Spatial patterns of PET

The spatial visualization of average thermal conditions for human-biometeorological significant analysis may be obtained from the spatial distribution of PET. For this purpose monthly, seasonal and annual PET bioclimate maps are constructed which include a combination of climate parameters. Thus, instead of a daily resolution we present mean monthly and seasonal conditions useful for general assessment of thermal bioclimatic conditions. Extreme conditions can be available from the temporal distribution of PET at the bioclimate diagram on the example of Birobidzhan.

The map for the winter period (December, January and February) shows that PET values vary from -15 °C to -40 °C, increasing from south-east to north-west of thermo-physiological extreme cold stress level (Figure 3). Low values in the north-western part of the study area (up to -45°C in high mountains) reflect the great continentality of this region. The coastal locations along the coastline of the Japanese sea show the maritime influence of the Pacific Ocean with relatively high values near -15°C in the far south.

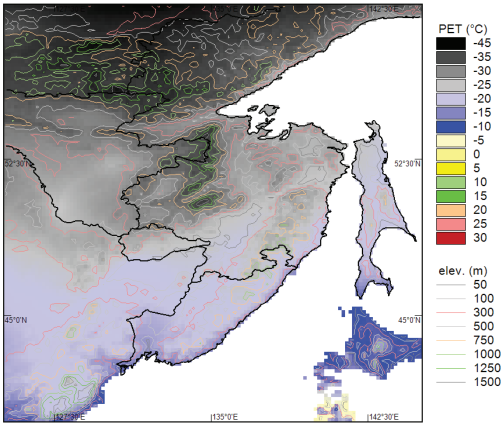


Figure 3. Physiologically equivalent temperature for winter (December, January, February) in the Far East Russia for the period 1961-1990, using mean monthly data

In spring (March, April and May), as shown in Figure 4, PET values vary from -5 °C to +15 °C and range from the thermo-physiological extreme cold stress level in the north and in the mountainous regions (e.g. in Dzugdzur Mountain Range along the coasts of the Okhotsk sea PET reaches -5 °C to -10 °C) to slight cold stress in the southern continental regions. The plains show relatively high PET values that are close to favorable bioclimate conditions.

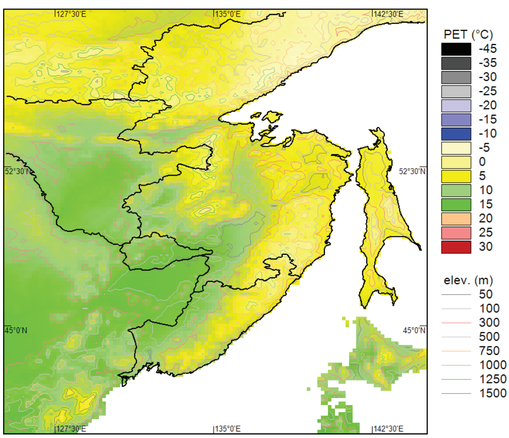


Figure 4. Physiologically equivalent temperature for spring (March, April, May) in the Far East Russia for the period 1961-1990, using mean monthly data

In the summer months (June, July and August), PET conditions may reach values from 5 °C to 25 °C (Figure 5). Particularly in summer, the dependence of PET values on the location results in a marked variation of PET values calculated for different places. Locations in the plains with slight heat stress show much higher thermal stress than mountainous areas. Favorable conditions with thermal comfort (PET values without thermal stress) are obtained only in higher elevated areas but only in the central part of the study area; the northern mountains are situated in the zones with thermal moderate cold stress even in the summer period.

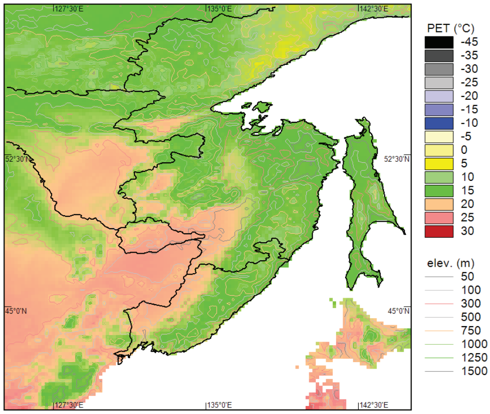


Figure 5. Physiologically equivalent temperature for summer (June, July, August) in Far East Russia for the period 1961-1990, using mean monthly data

In autumn (September, October and November), PET varies from -30 °C to 0 °C (Figure 6). The spatial distribution is similar to that in summer. The highest values are found in the southern locations along the coast of the Japanese Sea. The coldest areas are in the elevated regions of the north-west and in the mountains. As a whole, autumn is much colder than spring, a phenomenon that may be explained by the cold (air temperatures are very close to winter values) and windy November.

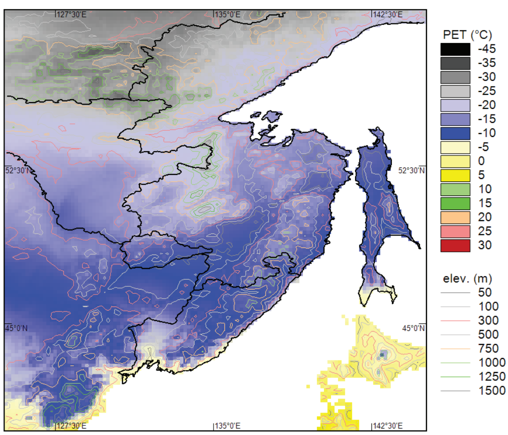


Figure 6. Physiologically equivalent temperature for autumn (September, October, November) in Far East Russia for the period 1961-1990, using mean monthly data

In all seasons, the lowest PET values are observed in elevated areas, e.g. in Sikhote-Alin and Dzugdzur; the highest in the continental lowlands near the Middle Amur and in the far south along the coast of the Japanese Sea.

Finally a map for the annual distribution of PET was constructed confirming the main features of seasonal peculiarities (Figure 7). The main territory of the study area is under the influence of strong cold stress, PET varying from -5 °C to 5 °C, with spots of PET equal to -10 °C in elevated regions. The northern part has conditions with strong annual cold stress (PET = -10 °C).

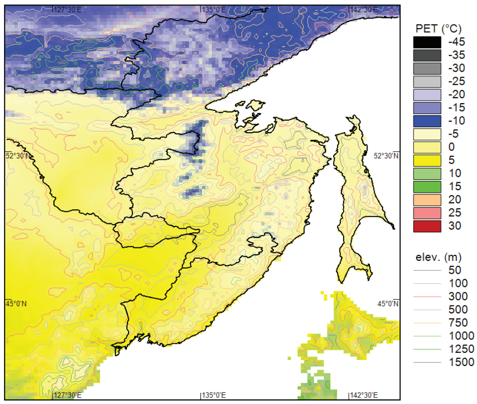


Figure 7. Physiologically equivalent temperature in Far East Russia for the period 1961-1990, annual results, using mean monthly data

Temporal patterns of PET for Birobidzhan

For the analysis of the general bioclimate conditions based on PET values of daily temperatures (3 pm) for the period January 1, 1997 to December 31, 2006, a bioclimate diagram was calculated including 10-day interval frequency classes of thermal perception for the city of Birobidzhan (Figure 8).

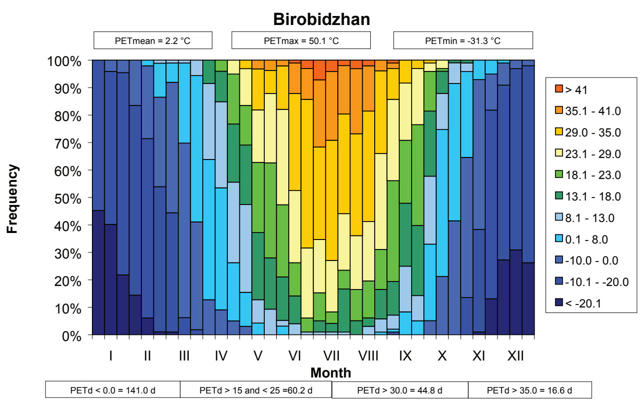


Figure 8. Bioclimate diagram of PET for Birobidzhan for 1997-2006, using meteorological data at 3 pm

It is shown that for extreme climatic conditions in the city (absolute minimum and maximum air temperatures are -49 °C and +40 °C consequently) the range of PET for grades of thermal stress moves to lower values compared with the European areas (Blazejczyk & Matzarakis, 2007; Matzarakis et al., 2007a). This illustrates the variability of PET over the 10-day intervals within the study period.

Figure 8 depicts that for the whole decade there were conditions of PET with thermal comfort (between 18 °C and 23 °C) when comfortable thermal perception occurs with frequencies from 4 % to 37 % of all classes. Conditions with PET higher than 29 °C are observed for the middle of May, higher 41 °C of extreme heat stress in the last days of June, conditions with PET less than 0 °C of extreme cold are observed from the beginning of October to the end of March, less than -20 °C of very extreme cold – from middle of November to beginning of March.

The results allow us to evaluate not only the mean conditions but also the maximum and minimum values and threshold classes to describe the climatic conditions in a more sophisticated way. The thermal diagram (Figure 8) holds additional information about mean PET (2.2 °C), the absolute maximum (50.1 °C) and the minimum (-31.3 °C) value at noon for the study period. It shows the number of cold days with PET < 0 °C, the 141 days occurred mostly from November to February. Period with thermal comfort and slight stress with PET between 15 °C and 25 °C lasts during 60.2 days from May to the beginning of June and from the last week of August to mid-September.

Heat stress with PET > 30 °C occurs on 44.8 days and is mainly in the period from June to August. Extreme PET > 35 °C at noon was also obtained on hot days in the summer period for a total of 16.6 days, presenting a pronounced thermal stress level. Thus, all information needed for the description of the thermal bioclimate regime is presented in terms of extremes and frequencies.

DISCUSSION

A human-biometeorological assessment of climatic conditions in the southern part of the Russian Far East is carried out by using the physiologically equivalent temperature based on the body-atmosphere energy balance. Results are presented as bioclimatic maps for spatial assessment of climate and they can be used for several applications related to biometeorological and climate change issues, first of all in recreation and tourism estimations. The limitation of the maps due to the monthly resolution can be improved by the graphical evaluation of temporal behavior of PET for the selected city Birobidzhan.

As was shown earlier (Matzarakis et al., 1999), one of the main advantages of PET is that it may be used for any time of the year in different climates and for temperate climate as well. We use it successfully for the bioclimatic evaluation of a temperate monsoon climatic zone, which is characterized by an extreme thermal regime at the Russian Far East. The spatial patterns are constructed to get general (on the climatic data) and more or less adequate bioclimate information about areas with a low density of weather stations. They allow us to identify regions with extreme and uncomfortable thermal conditions for all seasons and months. We believe that this approach provides a method for using meteorological information to assess, for example, the heat (or cold) waves that may influence human mortality and morbidity in the study area.

We may compare spatial distribution of PET with other regions of the world, i.e. with Europe (Blazejczyk & Matzarakis, 2007; Matzarakis et al., 2007a), with Japan (Matzarakis, 2008). The PET conditions in winter in the studied locations in Russia are considerably lower in comparison to Northern Europe. Only PET values for the extreme southern part of the study area are similar to those of Northern Europe and Japan. In summer, the PET conditions in the southern and central parts of the study area are more similar to the conditions in central and Northern Europe and Japan.

The bioclimate diagram for Birobidzhan gives an example of human-biometeorological analysis of thermal conditions in the selected location which may be useful for the specific purposes in applied (urban) climatology, for tourists and as additional information in everyday weather news. It would be very interesting to compare these results with the bioclimate diagrams of PET for other locations, for example with Freiburg (Matzarakis et al., 2006), but for this purpose PET for both weather stations must be calculated using the same period of meteorological data.

CONCLUSION

Physiologically equivalent temperature is well suited for the human-biometeorological estimation of the thermal environment in different climates, including the extreme climate regimes of the Russian Far East. Spatial visualization of seasonal PET using bioclimate maps results in a general evaluation of thermo-physiologically relevant information. Temporal assessment of PET using bioclimate diagram of Birobidzhan gives detailed analysis of the thermal conditions for the selected location, describing the first attempt to develop a data base containing detailed daily human-biometeorological information, which can be used by both local residents and tourists in a city.

We believe that this approach represents a method to attain general and more or less adequate bioclimate information for areas with a low density of climate stations. There are no similar studies for regions with an extreme regime of annual temperatures, and the present study is trying to fill this gap. Bioclimatic maps are of interest because they can be applied in tourism and recreation for the selection of holiday destinations, in climate and health research for analyzing thermal stress situations, and in climate change investigations and their relation to human biometeorology. This approach of PET estimation based on RayMan model provides a method for using meteorological information to assess, for example, the heat (or cold) waves that may influence human mortality and morbidity in the study area. Research based on more detailed meteorological daily (and hourly) data for other locations at the Far East Russia could be the subject of future work.

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