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ARTICLE

Problems and Opportunities for Biometeorological Assessment of Conditions in Cold Season

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ABSTRACT

The article is devoted to a discussion of the possibilities of biometeorological assessment of the severity of weather conditions during the cold season. The relevance of the study is ensured not only by the fact that residents of a number of states, whose total number is more than 27 million people, live in these extreme climatic conditions, but also by the need to improve biometeorological approaches to assessing the impact of these conditions on the body and health of the population. This study examined biometeorological characteristics that illustrate a measure of cold stress. These include the Siple wind-chill index; Bodman winter severity index; Arnoldi weather hardness coefficient; Mountain wind chill index; weather hardness coefficient according to I.M. Osokin. The results of a comparison of winter severity assessments based on the values of the calculated Siple and Bodman indices made it possible to establish that the Bodman index is more acceptable when assessing mildly severe winters. The most adequate for assessing the "severity" of the cold period against the background of a decrease in air temperature and an increase in wind speed is the Siple index. The need to provide the countries of the world with high-quality hydrometeorological and biometeorological forecast information is justified and relevant. In this regard, these studies are very promising.

Keywords: Biometeorological indices; Severe weather; Cold period of the year; "rigidity" of weather conditions; Cold stress; Biometeorological assessment

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1. Introduction

As we all know, weather conditions in their totality and duration have a very tangible effect on the human body. In this regard, the main task of biometeorological research is not only a comprehensive study of the above impact, but also the identification of the principles of possible adaptation to it. The idea of the impact of weather conditions on the human body and the development of diseases in it was expressed in the ancient world [1]. It is enough to mention the works of the ancient Greek scientist, doctor, thinker Hippocrates (about 460 B.C. - about 370 B.C.). Subsequently, biometeorological research continued, and their results are available in the works of a number of prominent scientists, such as Avicenna (Ibn Sina) (10-11th century), Paracelsus (Theophrastus von Hohenheim) (15-16th century), A.I. Voeikov (19-20th century) and others [2].

The problems of the impact of weather conditions on the human body are dealt with by the World Meteorological Organization (WMO), one of the areas of activity of which is the development of effective measures to reduce the risk of adverse effects of weather conditions on public health. It is worth mentioning that the issues of developing high-quality forecasts of various hazards associated with weather and extreme weather conditions, including natural disasters or severe weather events, as well as rapid changes in weather conditions, including sudden cold spells or warming of particular relevance. Of course, experts from the World Meteorological Organization understand "severe weather conditions" to mean a slightly wider range of dangerous weather-related phenomena, which include not only low temperatures, but also tropical cyclones, hurricanes, dust storms, etc.

Besides, the first severe weather forecasting project was started in 2006 in southeast Africa with the direct participation of 5 countries: Bostwana, Madagascar, Mozambique, the United Republic of Tanzania, and Zimbabwe. The Regional Specialized Meteorological Center in Pretoria (South Africa) provided these pages with forecast products related to severe weather conditions, and the Regional Specialized Meteorological Center in Reunion (France) provided support in the field of tropical cyclone forecasting, using Eumetsat satellite information. Later, in 2008, the project covered 16 African countries. The obvious success of this project was noted at the Fifteenth World Meteorological Congress (Cg-XV, 2007), during which a joint decision was made to expand the project and its implementation throughout Africa and other countries of the World Meteorological Organization. In subsequent years, the project was extended to other subregions of the world, receiving further development. For this reason, the Eighteenth World Meteorological Congress (Cg-XVIII, 2019) emphasized the role of cascaded severe weather forecasting from global to regional and national levels through the World Meteorological Organization's Global Data and Forecasting System (GDPFS) centres.

Thus, currently, about 80 countries from 9 subregions of the world participate in the WMO Severe Weather Forecasting Program (SWFP), aimed at strengthening the capacity of National Meteorological and Hydrological Services (NMHSs) in developing countries, including least developed and island countries, to provide improved forecasts and severe weather warnings. This SWFP program is based on a global data processing system, including forecasting weather conditions based on a "cascade forecasting process" (from global to national to regional levels). The SERCOM/SC-DRR Advisory Group on Severe Weather Forecasting (AG-SWF) held an extraordinary remote meeting on June 30, 2023.

It is important to emphasize that the implementation of the SWFP Program is largely consistent with the development plan of the World Meteorological Organization, contributing to the achievement of the following strategic goals:

1) Strengthen national early warning systems for weather hazards and increase the coverage of effective responses to weather hazards and associated risks.

2) Increasing the value of meteorological information and introducing innovations in the provision of meteorological information, meteorological services and decision support.

3) Availability of using the results of numerical analysis and forecasting of the Earth's climate sys-

tem in spatiotemporal terms and within the framework of the Global Data Processing and Forecasting System of the World Meteorological Organization.

4) Meeting the needs of developing countries for quality hydrometeorological information as part of providing them with the necessary weather, climate, hydrological and environmental services. Undoubtedly, WMO activities under the SWFP play a very important role in reducing the social and economic impacts of global hazards and threats associated with severe weather and its various phenomena.

There is no doubt that WMO's SWFP activities play a very important role in reducing the social and economic impacts of global hazards associated with severe weather and its various phenomena. Against this background, regional or local problems of severe weather associated with the impact on the human body of various combinations of meteorological elements, including air temperature and wind speed, which together reduce human thermal sensations, deserve special interest.

In addition, by actively working to improve the quality of early warning systems for weather hazards at different levels, including regional and national, the SWFP provides significant support for the United Nations 2030 Agenda for Sustainable Development in accordance with the goals of "sustainable development" and the Sendai Framework for Disaster Risk Reduction for the period 2015-2030. This study aims to investigate the impact of extreme cold conditions caused by winter low temperatures on population health from various severe weather phenomena.

2. Materials and methods

To achieve the goal of the study, reference materials were used in the work, containing long-term (1890-1960; 1960-1990; 2000-2020) numerical characteristics of the climate of a number of territories located at high latitudes (60-80 degrees north latitude). A number of numerical characteristics were considered, illustrating the thermal structure of the environment affecting the human body, known as biometeorological indicators. Thus, more than 30 biometeorological indicators are usually used for scientific research and calculations, divided into 7 main groups [3]. The first group, which includes temperature and humidity indicators, includes the effective temperature of still air, ET; and discomfort index, *DI* (*DY*). The second group, containing temperature-wind indicators or cold stress indices, includes the wind-cold index according to Siple [3-5], *W(K)*; winter severity index according to Bodman (*S*); Arnoldi weather stiffness factor, T; Hill wind chill index, *H*; weather stiffness coefficient according to I.M. Osokin [6-9], S_0. The third group contains temperature-humidity-wind indicators for shady spaces, including equivalent effective temperature, *ET* (taking into account the influence of wind) or *EET*; normal equivalent-effective temperature (taking into account the influence of wind for a dressed person). The fourth group of biometeorological indicators—temperature-humidity-wind—includes radiation equivalent effective temperature, *REET*; biologically active temperature, *BAP*; and reduced temperature index according to V.N. Adamenko and K.Sh. Khairullin, Tpr; heat balance of the human body according to V.I. Rusanov, *Qs*; thermal insulation properties of clothing, *C*. The fifth group of indicators includes the indices of pathogenicity and climate variability: the index of pathogenicity of the meteorological situation according to V.G. Boxsha, *I* [10-12]; weather class of the moment according to V.I. Rusanov, *KPM*; biological index of changing weather conditions according to V.Sh. Belkin, *BISM*; meteorological health index according to O.G. Bogatkin, *MIZ*; indicator of tension of thermoregulation mechanisms according to B.A. Eizenshtat, *G*; heat load index according to K.Ya. Kondratiev, *N*. The sixth group of biometeorological indicators consists of climate continentality indices according to L. Gorchinsky, *Kg* or according to S.P. Khromov, *Khr*. It was proposed to supplement the groups of biometeorological indicators with a group that would contain numerical characteristics of the level of pollution of the surface air layer [1]. So, in the seventh group of biometeorological indicators, it is recommended to include the total index of atmospheric pollution, *API*; atmospheric pollution potential, *PZA*; climatic potential of self-purification of the atmosphere according to T.S. Selegey, *Kmp* or according to I.L. Linevich, *Km*.

3. Results

As it seems to the authors, when examining the signs of severe weather, that is, the measure of the severity of weather conditions and bearing in mind the regional or local characteristics of territories located in the temperate and arctic latitudes of the Northern Hemisphere, we will consider biometeorological characteristics illustrating the measure of cold stress (the second group of biometeorological indicators), which, reducing a person's heat sensation, thereby limiting his capabilities. The indicators mentioned above include indicators such as wind-cold index according to Siple, *W(K)*; winter severity index according to Bodman (*S*); Arnoldi weather stiffness factor, *T*; Hill wind chill index, *H*; weather stiffness coefficient according to I.M. Osokin, S_0.

Obviously, when assessing human heat sensations, the characteristics of the intensity of the wind flow are essential. In this regard, Paul Siple (1957), an Antarctic researcher, proposed introducing the so-called wind-cold index, *W(K),* to assess the impact of negative air temperature and wind speed on the thermal state of the human body (Equation 1):

$$W\left(K\right)=\left(\sqrt{100V}+10,45V\right)\left(33-t\right) \tag{1}$$

where *W(K)* wind-cold index, points

V wind speed, m/s

t air temperature, °C

In fact, the Siple wind-cold index allows one to estimate the intensity of heat loss by the human body due to the combined effect of wind speed with various variations in air temperature values. In the scientific literature, there are explanations regarding the extreme values of the Siple index: at *W(K)* < 50, the biometeorological conditions of the cold period correspond to very warm conditions ("hot"); at *W(K)* > 1000, very cold conditions are observed ("very cold"). In this connection, in order to be able to compare the assessments of wind-cold conditions in the winter period based on the calculations of the Siple index with the values of other indices, the authors proposed a detailed scale of gradations for the Siple index values (**Table 1**).

Table 1. Siple index scale, *W(K),* to characterize the conditions of the cold period.

Siple index value, W(K)	Characteristics of the conditions of the cold period of the year
< 50	very warm conditions
50-200	warm conditions
201-350	cool conditions
351-500	slightly cold conditions
501-800	moderately cold conditions
801-1000	cold conditions
1001-2000	very cold conditions
2001-3000	harsh conditions
3001-4000	very harsh conditions
4001-7000	extremely harsh conditions
> 7001	extremely harsh conditions

In addition to the Siple index, one of the most well-known indices, the Bodman index (*S*), is successfully used to assess the severity of winter conditions, which makes it possible to identify the "severity" of winter weather in accordance with the "severity" score scale (**Table 2**).

Table 2. Bodman index scale, (*S*), to assess winter severity conditions.

Bodman index value, (S)	Characteristics of winter conditions
< 1.0	rough, soft
1.1-2.0	little-severe
2.1-3.0	moderately severe
3.1-4.0	severe
4.1-5.0	very harsh
5.1-6.0	hard-severe
> 6.1	extremely severe

When calculating the values of the Bodman index, *(S),* they rely on the assessment of the duration of the cooling process of a vessel with water having an initial temperature of +30 °C and cooled to a temperature of +20 °C (Equation 2):

$$S=\left(1-0,004t\right)\left(1+0,272V\right) \tag{2}$$

where *S* wind-cold index, points

V wind speed, m/s

t air temperature, °C

Studies by a number of authors have shown [4-6] that assessments of the "severity" of winter weather based on the Bodman index, (*S*), imply a significant variability in the range of air temperature values, that is, with the same score of "severity" of winter weather calculated for a certain value of wind speed, the values of air temperature can vary by 10-15 °C. Due to the fact that these circumstances could not but affect the accuracy of assessments of the biometeorological conditions of winter weather, I.M. Osokin proposed a refinement of Equation (2) by introducing additional coefficients and changing the constants in front of the temperature and wind speed:

$$S = (1 - 0,006t)(1 + 0,20V)(1 + 0,0006H_k)H_b A_c \quad (3)$$

where S wind-cold index, points

V wind speed, m/s

t air temperature, °C

H_k absolute height of the terrain, m

H_b relative humidity factor

A_c coefficient taking into account the role of daily air temperature amplitudes

However, refinements of Equation (2) introduced by I.M. Osokin, did not allow for improving the quality of assessments of biometeorological conditions of the winter period, since the calculations of the "hardness" of winter weather for settlements located in different geographical areas, carried out using the refined Equation (3), showed fairly close results [7,8].

Refinements of Equation (3) introduced by I.M. Osokin, include the altitudinal characteristics of the area, as well as coefficients taking into account relative humidity and daily temperature amplitudes. However, despite the physical validity of their introduction, the above clarifications are apparently not quite mathematically correctly reflected in the final form of the Equation (3). In this connection, Equation (2) is more applicable, the calculation results of which are most consistent with the real conditions of the winter period.

In addition to the indices described above, which describe the severity of winter weather conditions, the weather "severity" coefficient is also known according to I.A. Arnoldi, *T*. [9]. The usefulness of this coefficient is due to the fact that, being an empirical indicator, it allows one to evaluate the "hardness" of winter weather, based on the correspondence of an increase in wind speed by 1 m/s to a conditional decrease in air temperature values by 2 °C (Equation 4):

$$T = t - 2V \quad (4)$$

where T weather "hardness" coefficient according to I.A. Arnoldi, points

V wind speed, m/s

t air temperature, °C

It is important to note that the values of the described I.A. Arnoldi, *T*, correlate with physiological data [10-14], and the degree of functional stress of thermoregulation systems, as studies have shown, depends on air temperature. And, if the actual load on the apparatus of thermoregulation of the human body is determined by the air temperature, then, based on Equation (4), the wind speed has a greater mathematical significance for estimating the numerical values of the coefficient *T*. So, in accordance with observations of the state of the body at various combinations of air temperature and wind speed in the cold period, in the framework of calculating the coefficient *T*, it was found that at air temperature values:

from 0 to –15 °C	the tension of the thermoregulatory apparatus of the human body is weak;
from –16 to –29 °C	average;
from –30 to –45 °C	strong;
from –46 °C or more	excessive.

A positive point is also the fact that this coefficient I.A. Arnoldi, *T*, not only characterizes the measure of the severity of winter conditions, but also makes it possible to justify the needs of a person in clothing that allows him to provide thermal comfort when working outdoors. However, the established discrepancy between the results of observations and the mathematical expression (Equation 4) undoubtedly significantly reduces the accuracy of the I.A. Arnoldi, *T*, results.

The Hill Wind Chill Index is also used to describe the severe biometeorological conditions of the winter period.

There are two mathematical equations for calculating the numerical values of the wind chill index. For the case of dry cooling, Equation (5) is applied:

$$H = \left(0,13 + 0,47V^{0,5}\right)\left(36,6 - T_H\right) \quad (5)$$

where	H	wind (dry) cooling index, W/m^2
	V	wind speed, m/s
	T_H	air temperature, °C

Based on the analysis of the results of calculating the values of the wind (dry) cooling index, H, human heat sensations have the following gradations:

0.35-0.5	hot
0.6-0.9	comfortable
1.0-1.7	cold
1.8-2.3 or more	extremely cold

According to experimental data, possible frostbite of parts of the human body, including limbs, is observed at values of the wind (dry) cooling index, H, equal to or more than 0.7 W/m^2 [15].

The second mathematical equation for calculating the Hill wind chill index takes into account the correction for water vapor pressure and is determined by the Equation (6):

$$H_W = H + \left(0,085 + 0,102V^{0,3}\right)\left(61,1 - e\right)^{0,75} \quad (6)$$

where	H_W	wind cooling index, W/m^2
	H	wind (dry) cooling index, W/m^2
	V	wind speed, m/s
	e	water vapor pressure, hPa

The wind chill index described above, which takes into account the elasticity of water vapor, characterizes the intensity of heat loss in a moist moving air stream. At the same time, the numerical values of the H_W index, located in the range from 4.5 to 5.5 W/m^2, characterize the uncomfortable weather conditions of the winter period; with a value of the H_W index > 8.0 W/m^2, absolutely uncomfortable winter conditions are established.

Gradations of the values of the Hill wind cooling index, taking into account the elasticity of water vapor, H_W, W/m^2, are presented below:

3.5-4.4	comfortable
4.5-5.5	cold (discomfort)
5.6-7.9	extremely cold
8.0 or more	absolute discomfort

4. Discussion

For a more detailed study and assessment of the applicability of the most adequate biometeorological indicators considered above, a summary table was compiled containing calculated and empirical data (**Table 3**).

Table 3. The results of assessing the applicability of biometeorological indicators of the severity of winter conditions in comparison with empirical data.

Wind speed, m/s	**Air temperature, °C**	**Results of calculations of biometeorological indices**				**The results of observations of human heat sensation, perceived air temperature, °C**
		Siple index, *W(K)*		Bodman index, *S*		
1	0	809	cold conditions	0	mild conditions	–0.8
2	–10	1505	very cold conditions	1.6	little-harsh	–14.1
3	–15	2335	harsh conditions	2.0	little-harsh	–21.5
4	–20	3275	very harsh conditions	2.3	moderately severe	–28.9
5	–25	4330	extremely harsh conditions	2.6	moderately severe	–36.2
8	–30	7050		3.6	severe	–45.4
12	–35	10400	extremely harsh conditions	4.9	very harsh	–54.8
20	–40	17929		7.5	extremely severe	–61.5

Analysis of the obtained results of comparison of estimates of the severity of the winter period based on calculations of such well-known biometeorological indicators as the Siple index *W(K)* and the Bodman index, *S*, with the results of observations of various human heat sensations for some combinations of wind speed (m/s) and air temperature, (°C), presented in **Table 3**, made it possible to establish the following very revealing points:

- with slight frosts in combination with low wind speeds, the Bodman index, *S*, is most accurate for assessing the severity of winter conditions;

- more adequate estimates of the "hardness" of the cold period against the background of lower air temperatures and increased wind speed are given by the Siple index, *W(K)*.

5. Conclusions

Thus, as a result of a comparative analysis of a number of biometeorological characteristics illustrating the measure of cold stress and reducing a person's sense of heat, it was found that for milder winter conditions with slight frosts and low wind speeds, the Bodman index is the most acceptable for biometeorological assessment. However, for extremely cold conditions of the winter period against the background of increased surface wind speeds in combination with frosty temperatures, a more adequate assessment of the "severity" of the cold period can be obtained using the Siple index.

In addition, important results of the study include the ranking and comparative assessment of a number of biometeorological indicators used to study the cold period of the year for the weight and reliability of the numerical estimates of the severity of weather conditions in the cold period of the year obtained with their help. The author's scale of gradations of the values of a number of biometeorological indices is also proposed, including the addition of the known gradations of these indices.

The above conclusions and results of the study confirm the need for further study of known biometeorological indicators to identify opportunities for their effective use, as well as to develop new principles and options for assessing the severity of cold period conditions. Since the noted problem [15-19], which consists in providing a sufficiently large number of countries in the world with high-quality hydrometeorological and, in particular, biometeorological forecast information, is relevant at the present time and is unlikely to lose its significance in the near future, the research described above should be continued.

Author Contributions

The authors of this article fully formulated the idea, made calculations, wrote the text, took care of the design of the article.

Conflict of Interest

There is no conflict of interest.

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