COMPARATIVE ASSESSMENT OF THE IMPACT OF WEATHER AND CLIMATE CONDITIONS IN THE ARCTIC REGION BY BIOCLIMATIC INDICES

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There are single and multi parameter bioclimatic indices that enable assessment of the impact of weather and climatic conditions on health of a human being. This study aimed to comparatively assess health risks in the Arctic's open area using the bioclimatic indices. Relying on the data from the Central Siberian Department for Hydrometeorology and Environmental Monitoring (Krasnoyarsk) that describe the weather on Cape Chelyuskin in 2010–2022, we assessed the temperature, the integral indicator of body cooling conditions (IIBCC), the wind chill factor (WCF), the effective (ET) and the net effective temperature (NET), and the universal thermal climate index (UTCI). It was found that the WCF temperature can characterize the degree of frost risk as established by the IIBCC: the indicator has the critical frost risk period lasting November through April, and the respective risk level by WCF is "discomfort" (coolness) and "very cold", that by UTCI — "extreme stress", by ET — "caution — frostbite of exposed skin" (shorter), by NET — "threat of frostbite" (longer). The IIBCC and the UTCI show that the risk of cold injury in the conditions of Cape Chelyuskin is year-round: according to the IIBCC, its level changes between moderate (4–6 months) and critical (4–6 months), and according to UTCI, it may be very strong (4 months), and very strong and extreme (8 months). We have proven the advantages of UTCI over other integral indicators in assessment of the cold-related health risk and updated the basis for the hygienic requirements regulating practice of work in the open or in unheated enclosed spaces during the cold season.

Keywords: Cape Chelyuskin, bioclimatic indices, cold injury risk

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СРАВНИТЕЛЬНАЯ ОЦЕНКА ВЛИЯНИЯ ПОГОДНО-КЛИМАТИЧЕСКИХ УСЛОВИЙ В АРКТИКЕ ПО БИОКЛИМАТИЧЕСКИМ ИНДЕКСАМ

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Влияние на здоровье погодно-климатических условий определяют по одно- или многопараметрическим биоклиматическим индексам. Целью работы было провести сравнительную оценку риска для здоровья на открытой территории в Арктике по биоклиматическим индексам. По данным метеорологического центра "Среднесибирское управление по гидрометеорологии и мониторингу окружающей среды» (г. Красноярск) за 2010–2022 гг. на мысе Челюскин оценили температуру, интегральный показатель условий охлаждения организма (ИПУОО), ветро-холодовой индекс (ВХИ), эффективную (ЭТ) и эквивалентно-эффективную температуры (ЭЭТ), интегральный индекс теплового комфорта (UTCI). Определено, что температура ВХИ может характеризовать степень холодового риска, установленную по ИПУОО. Периоду критического холодового риска по ИПУОО (ноябрь–апрель) соответствует риск по ВХИ, оцениваемый как «дискомфорт» (прохлада) и «очень холодно», по UTCI — «экстремальный стресс»; по ЭТ — «осторожно — обморожение открытых участков кожи» (более короткий); по ЭЭТ — «угроза обморожения» (более длительный). ИПУОО и UTCI указывают на круглогодичный риск холодовой травмы в условиях мыса Челюскин: по ИПУОО — умеренный (4–6 месяцев) и критический (4–6 месяцев), по UTCI очень сильный (4 месяца), а также очень сильный и экстремальный (8 месяцев). Доказано преимущество использования UTCI для оценки холодового риска для здоровья. Актуализируется вопрос нормирования гигиенических требований к режиму работ на открытой территории или в неотапливаемых помещениях в холодный период года.

Ключевые слова: мыс Челюскин, биоклиматические индексы, риск холодовой травмы

Вклад авторов: Р. С. Рахманов — разработка дизайна и концепции исследования, написание статьи; Е. С. Богомолова — редактирование, утверждение окончательного варианта статьи; Д. А. Нарутдинов — сбор материала, участие в статистической обработке материала; С. А. Разгулин — подбор литературных данных, участие в статистической обработке материала.

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The meteorological factors of the environment can have a pathological, sanogenic, stable and unstable, direct and indirect effect on an individual [1–3]. Therefore, the approach practiced to determine their significance for human health involves assessment of one factor or multicomponent physical quantities (expressed as bioclimatic indices), which allows establishing health risks related to morbidity, mortality, injuries, as well as describe meteorologically conditioned sensations in zones of comfort and discomfort and under extreme conditions [4–9].

Studies by various researchers prove that it is air temperature and wind speed that influence safety of work outdoors or the risk of frostbite associated therewith when the weather conditions are severe [10–12].

At the same time, air humidity or radiation temperature are two other major factors determining how safe it is to work in the open. For example, when the air temperature is extremely low and wind speed and humidity are high, clothing loses its heat insulation properties, which dramatically increases the risk to human health [13, 14]. Radiation temperature (average temperature of radiation, including short-wave and long-wave radiation of the atmosphere) is one of the key components shaping the pattern of heat exchange between a person's body and the environment [15–16].

The purpose of this study is to comparatively assess weather and climatic conditions in the Arctic by bioclimatic indices, factoring in various combinations of air temperature, radiation temperature, air humidity and movement speed.

METHODS

The basis for the study were the weather and climatic conditions at Cape Chelyuskin (77.717,104.300). Using the data reflecting physical factors (temperature, relative air humidity, air speed (wind), all registered on a daily basis) collected by the Central Siberian Department for Hydrometeorology and Environmental Monitoring in 2010–2020, we calculated the daily average monthly indicators describing the conditions in the open:

– temperature;

– two parameter indicators (factor in temperature and wind speed), which are the integral indicator of body cooling conditions (IIBCC) and the wind chill factor (WCF);

– three parameter indicators (also factor in relative air humidity), which are the net effective temperature (NET) as per the Missenard's formula and the effective temperature (ET) under the Robert Steadman's formula;

– four parameter indicator (factors in radiation temperature), which is the universal thermal climate index (UTCI).

The IIBCC score was calculated as prescribed by the regulations (MR 2.2.7.2129-06). The health risk criteria levels are as follows: ≤ 34 — no risk; < 34 – ≤ 47 — moderate risk; < 47 – ≤ 57 — critical risk; > 57 — catastrophic risk. The IIBCC score allows determining the safe duration of work in the open: when the level of risk is moderate, it is safe to work outdoors for 60 minutes, when it is critical - for 1 minute only, and catastrophic risk level means it is safe to work outdoors for no more than half a minute.

The wind chill factor (°C) reflects the time of onset of hypothermia (without frostbite) in uncovered parts of a human body in cold environments. An environment is considered to be cold when the temperature there is +10 °C and below. For work that involves light physical exertion an environment with the temperature of +10 °C or below is a cold one. The pattern of establishing the health risk by WCF is as follows: from –10 to –24 °C — uncomfortable, chilly; from –25 to –34 °C — very cold, skin surface hypothermia; from –35 to –59 °C — extremely cold, possible hypothermia of the exposed parts of the body in 10 minutes; from –60 °C down — extremely cold, possible hypothermia of the exposed parts of the body in 2 minutes.

NET (°C) is used to establish thermal comfort/discomfort zones: from –24 °C and below (threat of frostbite); from –18 °C through –24 °C (very cold); from –12 °C through –18 °C (cold); from –6 °C through –12 °C (moderately cold); from –6 °C through 0 °C (very cool); from 0 °C to +6 °C (moderately cool) [17, 18].

We used the Steadman's formula to calculate the effective temperature (ET, °C). Subzero temperatures indicate the likelihood of frostbite (below –50°C — possibly in less than 5 minutes; from –38 °C to –50 °C — possible in 10–15 minutes; from –28 —C to –38 °C — possible after 20–30 minutes of exposure; from -28 °C to –27 °C — no danger for a properly dressed person) [19].

Using UTCI, we assessed the risk to health associated with the cold by stress, which can be weak (from 0 to +9.0 °C), moderate (from –13 to 0 °C), severe (from –27 to –13 °C), very severe (from –40 to –27 °C), extreme (below –40 °C) [15, 20] and non-existent (from +9.0 to +18.0 °C). The UTCI values were calculated with the help of BioKlima 2.6 software [21].

To calculate the indicators, it was necessary to determine the daily average wind speed by months, which was done using the Beaufort scale (0 to 12 points), and the average daily relative humidity of the air, which could be dry (55.0% and below), moderately dry (56.0–70.0%), moderately humid (71.0–85.0%) and highly humid (85.0% and above) [22, 23].

We used the Statistica 6.1 software (StatSoft; USA) to statistically process the database. The mean values and standard errors (M ± *m*) were determined and Student's *t*-test employed. The differences were considered significant at $p < 0.05$.

RESULTS

The air in December through April (5 months) was moderately humid, and in May through October (6 months) — highly humid. In November, the air humidity level fluctuated between "moderately humid" and "highly humid" marks (Table 1). Compared to April, the relative humidity in May was greater ($p = 0.001$), same as for October and November ($p = 0.001$), which provoked special interest. Relative humidity reached its maximum in July and was decreasing afterwards.

The wind was moderate (4 points) throughout the year. There were no statistically significant differences identified by months of the year.

By average monthly temperatures, weather conditions in the Arctic allowed labeling it as "cold environment" throughout the year. The temperature in the open was above zero only in July and August; in June and September, it fluctuated between above zero subzero values (Table 2).

Temperature calculations factoring in the complex influence of various physical factors led to a conclusion that all the values obtained were below the outdoor temperatures considered.

All bioclimatic indices shared a distinctive feature: the temperature difference was decreasing January through August and then increasing again towards January (Table 3). Another feature was the dynamics of differences between WCF and ET values and temperature in the open. If the former follow a clear "decrease-increase" pattern, the latter's dynamics relative to the former fluctuates noticeably: in January–April, the temperatures were higher than those accepted for the former, in May and October they were equal to each other, and in June–September the values were lower.

As for the health risk criteria, the data were as follows: IIBCC signaled of the year-round risk of frostbite in exposed parts of the human body, with the values of this index reaching the top of the "moderate risk" span in April and November (Table 4); according to the WCF, hypothermia is a possibility 8 months in a year, with the most severe period ("extremely cold") lasting for 2-4 months; ET alarmed of a risk of frostbite during the winter months and in March, and NET cautioned of the risk of frostbite during 8 months of a year; the UTCI, same as IIBCC, indicated a year-round health risk associated with the cold.

DISCUSSION

According to regulations documents, the duration of warm and cold periods of the year is determined by the outdoor temperature, same as patterns of work in the open and work management conditions for cold environments. It also affects the body's energy expenditure and the need for proteins, fats and carbohydrates, as well as morbidity [13]. Extreme weather

Table 1. Average monthly wind speed and relative humidity at Cape Chelyuskin

Month of the year	Assessed indicators, M ± *m*	
	Relative humidity, %	Wind speed, m/s
January	81.1 ± 0.5	6.4 ± 0.5
February	81.6 ± 0.4	6.5 ± 0.4
March	81.6 ± 0.4	5.9 ± 0.4
April	81.5 ± 0.5	5.8 ± 0.3
May	88.5 ± 0.7	5.7 ± 0.2
June	89.2 ± 0.9	5.8 ± 0.2
July	90.5 ± 0.9	6.1 ± 0.2
August	89.6 ± 1.0	5.9 ± 0.3
September	88.5 ± 0.6	6.0 ± 0.3
October	85.1 ± 0.6	6.2 ± 0.3
November	81.1 ± 0.3	6.4 ± 0.4
December	82.1 ± 0.3	5.8 ± 0.3

conditions, including "cold waves", modify morbidity, mental health and mortality [24–26].

Some researchers believe that for cold conditions, it is best to rely on IIBCC and WCF in establishing the impact of bioclimatic factors of weather on a body [27]. Regression models of frostbite risk built on the values of temperature, wind speed and air humidity indicate that, for work done outdoors, the key factors are temperature and wind speed [10]. It is likely the reason behind the recommendation to rely on IIBCC and WCF for any practical purpose.

However, the "cold indices" do not allow establishing the degree of bioclimatic comfort peculiar to an environment. For this purpose, ET and NET can be used [17, 18].

Our data show that air humidity matters in assessing severity of the weather. For example, the ET value depends thereon: with the air moderately humid, the ET was higher than the temperature according to the WCF, and it decreases as the humidity increases. The NET indicator, which also accounts for air humidity, shows temperatures lower than those by WCF: the difference between them was 6.8 °C only in January, and during the remaining months it ranged from 10.4 °C to 11.7 °C.

However, all three indices (WCF, ET and NET) give different assessments of the impact of outdoor weather conditions on health of a human being. The WCF shows that for 8 months a year the conditions range from "discomfort" to "extremely cold", while 4 months present no risks. This index is a recommended basis for the work conditions management routines, including work outdoors, in cold environment, with temperatures below +10 °C. But such conditions are already uncomfortable, which translates into the need for protection from the cold.

According to the Steadman's ET formula, there is a risk of cold injury only 4 months in a year. The comfort zone range considered in the context of this indicator is 17.2 to 21.7 °C [28], so it can be assumed that during the remaining months, when the temperature fluctuates between –4.1 and –25.0 °C, the conditions are also not comfortable for a person and can cause cooling of the body.

According to the Missenard's NET index, the period of cold in the considered area lasts longer, with its conditions more severe: it is significantly cold there for 8 months of a year, and the remaining 4 months are not warm but also cold.

The effect of cold and the pathogenesis associated therewith are based of body cooling. The related changes can be both functional and pathological. Compensatory reactions to local cooling cause reflex-driven shifts in the work of cardiovascular, respiratory and endocrine systems, with the gravity of such shifts depending on the body part undergoing cooling (more for face, less for hands). When the cold affects face, respiratory organs, arterial vessels shrink in the limb circulatory and coronary systems, which leads to the elevation of blood pressure. Chronic exposure to cold impairs motor activity, coordination and the ability to perform precise operations; the inhibitory processes in the cerebral cortex intensify and, following respiratory failure and oxygen deficiency,

Table 2. Annual temperature indicators, outdoor and by bioclimatic indices

Month of the year	Evaluation criteria					
	T, °C	IIBCC, points	WCF, °C	ET, °C	NET, °C	UTCI, °C
January	–26.0 ± 1.1	50.8 ± 0.8	–38.9 ± 1.7	–34.5 ± 0.4	–45.7 ± 1.3	–48.8 ± 1.4
February	–24.5 ± 1.0	50.2 ± 0.7	–37.0 ± 2.1	–33.1 ± 0.3	–49.2 ± 1.1	–49.7 ± 1.3
March	–22.9 ± 1.2	49.1 ± 0.8	–34.5 ± 2.3	–31.0 ± 0.3	–46.1 ± 1.2	–46.7 ± 0.9
April	–16.3 ± 0.4	45.9 ± 0.4	–26.0 ± 2.0	–24.1 ± 0.4	–37.3 ± 0.9	–41.0 ± 1.1
May	–8.0 ± 0.5	42.0 ± 0.4	–15.4 ± 2.8	–15.2 ± 0.4	–26.9 ± 0.6	–32.0 ± 0.6
June	–0.3 ± 0.2	38.5 ± 0.2	–5.8 ± 2.5	–6.8 ± 0.4	–16.5 ± 0.5	–23.1 ± 0.8
July	1.4 ± 0.2	37.9 ± 0.2	–3.7 ± 2.5	–5.0 ± 0.4	–14.5 ± 0.3	–21.7 ± 0.6
August	2.1 ± 0.4	37.4 ± 0.4	–2.8 ± 2.0	–4.1 ± 0.4	–13.2 ± 0.5	–20.2 ± 0.7
September	–0.05 ± 0.4	38.5 ± 0.4	–5.5 ± 2.0	–6.6 ± 0.4	–16.1 ± 0.7	–23.1 ± 1.1
October	–6.8 ± 0.6	41.8 ± 0.5	–14.3 ± 2.2	–14.3 ± 0.4	–25.4 ± 0.9	–32.3 ± 1.2
November	–17.0 ± 0.8	45.9 ± 0.6	–27.1 ± 1.9	–25.0 ± 0.4	–38.4 ± 1.1	–42.0 ± 1.3
December	–22.3 ± 0.7	48.7 ± 0.5	–33.6 ± 2.3	–30.3 ± 0.4	–45.3 ± 0.7	–45.8 ± 0.9

Table 3. Fluctuations of temperature by bioclimatic indices relative to the temperature registered in the open

Month of the year	Absolute values of bioclimatic temperature fluctuations			
	WCF, °C	ET, °C	NET, °C	UTCI, °C
January	–12.9	–8.5	–19.7	–22.8
February	–12.3	–8.4	–24.7	–25.0
March	–11.6	–8.1	–23.2	–23.8
April	–9.7	–7.8	–21.0	–24.7
May	–7.4	–7.2	–18.9	–24.0
June	–5.5	–6.5	–16.2	–22.8
July	–2.3	–3.6	–13.1	–20.3
August	–0.7	–2.0	–11.1	–18.1
September	–5.5	–6.6	–16.1	–23.1
October	–7.5	–7.5	–18.6	–25.5
November	–10.1	–8.0	–21.4	–25.0
December	–11.3	–8.0	–23.0	–23.5

"polar hypoxia syndrome", "chronic hypoxic syndrome" or "cold hypoxia" may develop [11, 12, 23, 29–31] . Cold violates nutrient metabolism, which increases the risk of diseases and disorders [14].

According to two bioclimatic indices (IIBCC and UTCI), the risk associated with cold is real all the year round, i.e., frostbite can develop in uncovered areas of the body. But, on the one hand, the first bioclimatic index does not produce the equivalent temperature value determined based on temperature and wind speed. This value is taken from the table given in Appendix 6 to MR 2.2.7.2129-06 approved by the Chief Sanitary Officer of the Russian Federation. However, this table presents a fairly wide range of equivalent temperatures, which complicates selection of specific values. On the other hand, it does not account for the influence of air humidity and radiation temperature. Our data suggests that it corresponds to the equivalent temperatures determined with the help of the WCF formula.

The universal thermal climate index has given the lowest equivalent temperature values and shown a longer period of severe ambient conditions at Cape Chelyuskin. Against the temperature by WCF, the minimum difference therewith was 9.9°C (in January), the maximum — 18.0 °C (July and October). In general, the average annual temperature by WCF was 2.1 times lower than that by UTCI: –20.4 ± 4.0 °C versus –42.8 ± 3.3 °C (p = 0.008).

It looked interesting that the temperature values according to UTCI and Missenard's NET in December — March were almost equal.

Thus, based on the data describing Cape Chelyuskin, we have shown the advantages of using UTCI to assess the risk to human health associated with cold; this index can be used to predict the risk considering the severity of weather and climatic conditions. In addition, we generated the data in the context of assessment of the average values of physical indicators describing the conditions outdoors. A combination of maximum/minimum air humidity, extreme physical factor values (in this case, minimum temperature, maximum wind speed) and radiation temperature make the negative effect on the body much more pronounced. Probably, it is necessary to evaluate the influence of weather factors by extreme (unfavorable) values, as pointed out by other researchers [32].

This study updates the basis for the hygienic requirements regulating practice of work in the open or in unheated enclosed spaces during the cold season.

CONCLUSIONS

The temperature determined by the WCF formula (in degrees Celsius) can reflect the degree of cold risk established by the IIBCC in points. The latter indicator has the critical frost risk period lasting November through April, and the respective risk

Table 4. Characteristics of the risk criteria as factored by various bioclimatic indices

№	Index	Type of risk	Months of the year / number of month
1	IIBCC	Moderate	IV–XI (8–6)
		Critical	XII–III (4–6)
2	WCF	lacking	VI–IX (4)
		Discomfort, chill	V, X (2)
		Very cool	III–IV, XI–XII (4–2)
		Extremely cold	I–II (2–4)
3	ET	Lacking	IV–XI (8)
		Be careful — frostbite of exposed skin is possible after 20–30 minutes	XII–III (4)
4	NET	Cold	VI–IX (4)
		Very cold	Нет
		Threat of frostbite	X–V (8)
5	UTCI	Strong	VI–IX (4)
		Very strong	V, X (2)
		Extreme	XI–IV (6)

level by WCF is "discomfort" (coolness) and "very cold", that by UTCI — "extreme stress", by ET — "caution — frostbite of exposed skin" (shorter), by NET — "threat of frostbite" (longer). The IIBCC and the UTCI show that the risk of cold injury in the conditions of Cape Chelyuskin is year-round: according to the IIBCC, its level changes between moderate (4–6 months) and critical (4–6 months), and according to UTCI, it may be very strong (4 months), and very strong and extreme (8 months).

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