UDC 613.1, 574.24
DOI: 10.21668/health.risk/2022.3.02.eng

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Review

SPECIFIC ENVIRONMENTAL HEALTH CONCERNS AND MEDICAL CHALLENGES IN ARCTIC AND SUB-ARCTIC REGIONS

J. Reis[1], N.V. Zaitseva[2], P. Spencer[1]

[1]RISE, Specialized Group on Environment and Health, Strasbourg, France
[2]Federal Scientific Center for Medical and Preventive Health Risk Management Technologies, 82 Monastyrskaya Str. Perm, 614045, Russian Federation

This systematic review surveys the results of studies that address the manifold influences of climate change on the health of populations in the Arctic and sub-Arctic regions. The review includes papers available in PubMed (maintained by The United States National Library of Medicine at the National Institutes of Health), Scopus (the largest abstract and citation database of peer-reviewed literature), WoS (the abstract and citation database of peer-reviewed literature) and BVS (Virtual Health Library) that were published between 1960 to 2021.

The review covers pressing environmental, sanitary-hygienic and social issues and identifies priority risk factors for human health and that of wildlife. Global pollution and communicable diseases are shown to pose threats for indigenous people living in the Arctic. These threats are likely to be greater than those faced by populations living elsewhere in the world.

We conclude that because climate is changing faster in the Arctic than anywhere else on the planet, there is an urgent need to address the issue. Global pollution and communicable diseases pose threats to public health, including the health of indigenous people living in the Arctic and sub-Arctic regions. It is necessary to intensify cooperation among different states to reduce external influences on the Arctic environment and to prioritize public health.

Keywords: *Arctic and sub-Arctic regions, global climate change, public health, risk factors, sanitary-epidemiological situation, ecological situation, local and imported threats, health losses.*

Most indigenous populations of the Arctic and sub-Arctic Regions are adapted to harsh natural environments, but these regions are subject to the effects of especially rapid climate change. Climate-related changes in circumpolar regions are affecting not only regional wildlife and human health but, from changes in permafrost, also threaten life across the planet. We examine some characteristics of Arctic and sub-Arctic regions from a geographical, demographic and cultural perspective and address the environmental chal-

Jacques Reis – Doctor of Medical Sciences, Associate Professor (e-mail: jacques.reis@wanadoo.fr; tel.: +33 (0) 3-88-27-28-71; ORCID: https://orcid.org/0000-0003-1216-4662).

Nina V. Zaitseva – Academician of the Russian Academy of Sciences, Doctor of Medical Sciences, Professor, Scientific Director (e-mail: znv@fcrisk.ru; tel.: +7 (342) 237-25-34; ORCID: http://orcid.org/0000-0003-2356-1145).

Peter Spenser – Professor (e-mail: spencer@ohsu.edu; tel.: +1 503-494-1085; ORCID: https://orcid.org/0000-0003-3994-2639).

lenges and health threats faced by their populations.

Our research goal was to perform a systematic review of relevant studies that address environmental, sanitary-hygienic, social and other factors creating public health risks in the Arctic and sub-Arctic regions. The review aimed to reveal pressing challenges and issues that seek solutions as a top priority.

Materials and methods. The review included research articles published between 1960 and 2021 that are available in *PubMed* (maintained by The United States National Library of Medicine at the National Institutes of Health), *Scopus* (the largest abstract and citation database of peer-reviewed literature), *WoS* (the abstract and citation database of peer-reviewed literature) and/or *BVS* (Virtual Health Library). Articles addressed issues associated with climate change, pollution, and the influence on health and psychological state of populations living in the analyzed regions.

Results and discussion. *Geographic presentation of the Arctic and sub-Arctic regions.* The Arctic, following a geographical definition, is the region north of the Arctic Circle (about 66° 34' N latitude), the approximate southern limit of the midnight sun and the polar night. For ecologists, it is the region in the Northern Hemisphere where the average temperature for the warmest month (July) is below 10 °C (50 °F); the northernmost tree line roughly follows the isotherm at the boundary of this region. Whatever the definition, the Arctic region is a unique area among Earth's ecosystems consisting of the Arctic Ocean and adjacent seas, which contain seasonal sea ice in many places, and of land characterized by seasonal variation of snow and ice cover, with predominantly treeless permafrost (permanently frozen underground ice) containing tundra. The continental part of the Arctic belongs to Canada, Denmark (Greenland), Finland, Iceland, Norway, the Russian Federation, Sweden and the United States of America (Alaska). These eight countries have membership of the Arctic Council together with six Permanent Participants drawn from peoples indigenous to the Arctic. The sub-Arctic zone of the Northern Hemisphere refers to regions immediately south of the Arctic Circle or regions similar to these in climate or conditions of life. The sub-Arctic region (50°N and 70°N latitude) covers much of Alaska (USA), Canada, Iceland, the north of Scandinavia, Siberia (Russia), the Shetland Islands (UK), and the Cairngorms (Scotland, UK) [1].

The Arctic and sub-Arctic Regions have a very low population density. Permanent residents number ~4 million people, of whom approximately 500,000 are Indigenous Peoples[1]. Some population groups number > 100,000 inhabitants (e.g., Anchorage, Archangelsk, Reykjavik, Murmansk). The population is increasing in Alaska and Iceland and declining in the Russian Federation[2].

The Arctic states initiated a scientific and thereafter political cooperation in the late nineteen eighties to address an alarmingly fragile environmental state resulting from the arrival and accumulation of chemical and radionuclide pollution[3]. Despite the geopolitical differences of Members, the Arctic Council was formally established in 1996. Today, the Arctic Council is the leading intergovernmental forum promoting cooperation, coordination and interaction among the Arctic States, Arctic Indigenous peoples and other Arctic inhabitants. The Council addresses common Arctic issues, in particular those relating to sustainable development and environmental protection. The six Permanent Participants

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[1] Permanent Participants. *Arctic Council Secretariat*. Available at: https://www.arctic-council.org/about/permanent-participants/ (June 08, 2022).

[2] IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. In: H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría [et al.] eds. Cambridge, UK and New York, NY, USA, Cambridge University Press, 2019, pp. 3–35. DOI: 10.1017/9781009157964.001

[3] The workhorses behind the success. *Arctic Council Secretariat*. Available at: https://www.arctic-council.org/news/the-workhorses-behind-the-success (June 08, 2022).

representing Arctic Indigenous Peoples include: the Aleut International Association, the Artic Athabaskan Council, the Gwich'in Council International, the Inuit Circumpolar Council, the Russian Association of Indigenous Peoples of the North, and the Saami Council. Thirteen non-Arctic states, as well as intergovernmental and interparliamentary organizations and non-governmental organizations have been approved as Observers to the Arctic Council[4].

An extreme environment challenged by climate change. The Intergovernmental Panel on Climate Change (IPCC)[5], a body of the United Nations responsible for advancing knowledge on human-induced climate change, issued a 2019 Special Report dedicated to the Polar Regions, the Ocean and Cryosphere in a Changing Climate. The Report noted that global warming has led to widespread shrinkage of the cryosphere (frozen components of the Earth system), with mass loss from ice sheets and glaciers (*very high confidence*), reductions in snow cover (*high confidence*) and Arctic Sea ice extent and thickness (*very high confidence*), and increased permafrost temperature (*very high confidence*).

Earlier, in April 2006, the impact of the progressive loss of Arctic Sea ice from global warming was powerfully illustrated by a photograph of an apparently stranded white polar bear on the front cover of *Time*, an American news magazine read around the world[6]. Titled "*Be worried. Be VERY worried*", this iconic illustration represents well the environmental and ecological challenges in the Arctic. "*Global warming is already disrupting the biological world, pushing many species to the brink of extinction and turning others into runaway pests. But the worst is yet to come*"[7]. Indeed, in 2013, Fitzgerald [2] stated, "*If trends continue and the ice continues to disappear, the effect on polar bears would be devastating*."

The remarkable degree of specialized adaptation to life on the sea ice that allowed the bears to be successful is the very reason that these animals are so vulnerable to the effects of climate change. Polar bears have few alternatives if their habitat (sea ice) and their access to ringed seal prey rapidly disappear. Predictions that polar bears may be able to adjust and sustain themselves on alternative food sources are not based on reality. Spring breakup of sea ice is happening much earlier and the Fall freeze-up is getting later, thereby prolonging the open-water period when the bears are shore bound. If these trends advance, and the ice continues to decline, the effect on polar bears could be devastating.

The plight of the polar bear may be more nuanced in that regional changes may actually favor survival. Studies (1990–97 and 2012–16) of the world's most northerly polar bear population in Kane Basin[8], which is transitioning to a seasonally ice-free region because of climate change, showed some beneficial effects, including range expansion, improved body condition, and stable reproductive performance, albeit in the setting of increased geographic and functional isolation [3, 4]. However, the authors concluded: "*The duration of these benefits is unknown because, under unmitigated climate change, continued sea-ice loss is expected to eventually have negative demographic and ecological effects on all polar bears*" [4].

The impact of climate change on biodiversity must take into account adaptation of the fauna in the northern terrestrial ecosystems, structured by a history of biotic and abiotic changes that overlie a complex geo-

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[4] Arctic Council Observers. *Arctic Council Secretariat*. Available at: https://www.arctic-council.org/about/observers/ (June 08, 2022).

[5] The intergovernmental body of the United Nations responsible for advancing knowledge on human-induced climate change.

[6] TIME. Available at: http://content.time.com/time/magazine/0,9263,7601060403,00.html (June 08, 2022).

[7] Bjerklie D. Global Warming: Feeling the Heat. *Time*, 2006, vol. 167, no. 14. Available at: https://content.time.com/time/subscriber/article/0,33009,1176986,00.html (дата обращения: 08.06.2022).

[8] An Arctic waterway lying between Greenland and Canada's northernmost island, Ellesmere Island.

graphic arena. Since the Pliocene, Holarctic ecosystems have faced shifting climates (glacial and interglacial stages), resulting in cyclic animal distribution and demographics, with episodic dispersal / isolation and diversification of the fauna [1]. One example of this phenomenon is the apparent development of brown bears derived from a population of polar bears (*Ursus maritimus*) likely stranded by receding ice at the end of the last glacial period [5]. The Ancient Greeks named two constellations seen in the Northern Hemisphere, Ursus Minor and Ursus Major [6], and the word "Arctic" derives from the Greek "*arktikós*", meaning "of the Bear".

The Arctic climate and physical system is characterized by the cryosphere, defined by the IPCC as "*the components of the Earth System at and below the land and ocean surface that are frozen, including snow cover, glaciers, ice sheets, ice shelves, icebergs, sea, river and lake ice, permafrost and seasonally frozen ground*"[9]. The cryosphere, which represents 10 % of the Earth surface, has a major role in the climatic system owing to its high surface reflectivity or albedo. The increased melting of snow and ice induces a positive feedback, which in turn leads to more warming. This effect is named the snow- or ice-albedo feedback[10].

Climatologists have a special interest in the cryosphere as it acts as an historical archive of climatic behavior. Ice drilling and the analysis of ice cores in Greenland have allowed scientists to reconstruct previous periods of climatic changes [7], the evolution of global temperature over the past two million years, the cycles of nitrogen, carbon and methane, and even information on the former vegetation [8].

In the Arctic, the Greenland Ice Sheet covers an area of 1.7 million km^2, a sixth of the Antarctic Ice Sheet (12.3 million km^2, excluding the ice shelves). In the Arctic Ocean, sea ice reaches an average maximum of ~15 million km^2 at the end of winter, while Antarctic Sea ice reaches about 19 million km^2, usually in September. Thus, the Arctic ice sheet is an important contributor to the cryosphere.

Permafrost describes frozen soil (sand, ground, rock or sediment) – sometimes hundreds of meters thick. To be classified as permafrost, the ground has to have been frozen (when its temperature remains at or below 0 °C) continuously for at least two years. Since Arctic permafrost stores almost 1700 billion tons of carbon, it is an essential climate parameter[11]. The rise in global temperatures, which is higher in the Arctic than elsewhere, is causing the subsurface ground to thaw[12]. This releases greenhouse gases (carbon dioxide and methane) produced by biological material (e.g., remains of vegetation) and abruptly changes the landscape (ground subsidence)[10]. Climatologists closely monitor and model the climate change-associated evolution of permafrost (extension, thawing). It is estimated that, by 2011, up to two-thirds of the near-surface permafrost could be lost as a result of atmospheric warming[11].

The Arctic cryosphere, fragile and unique, is heavily impacted by climate change. In less than half a century, from 1971 to 2019, the Arctic's average annual temperature rose by 3.1 °C, compared to 1 °C for the planet as a whole. Stated otherwise, the Arctic is the fastest warming region on the planet, a phenomenon termed "Arctic amplification"[13]. On

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[9] IPCC, 2019: Summary for Policymakers. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. In: H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte, P. Zhai, M. Tignor, E. Poloczanska, K. Mintenbeck, A. Alegría [et al.] eds. Cambridge, UK and New York, NY, USA, Cambridge University Press, 2019, pp. 3–35. DOI: 10.1017/9781009157964.001

[10] The cryosphere in the climate system. *Copernicus Europe's eyes on Earth*. Available at: https://climate.copernicus.eu/climate-indicators/cryosphere (June 08, 2022).

[11] Permafrost thaw: it's complicated. *ESA*. Available at: https://www.esa.int/Applications/Observing_the_Earth/FutureEO/Permafrost_thaw_it_s_complicated (June 18, 2022).

[12] The Arctic is warming four times faster than the rest of the world. *American Association for the Advancement of Science*. Available at: https://www.science.org/content/article/arctic-warming-four-times-faster-rest-world (June 18, 2022).

[13] Deshayes P.H. Arctic warming three times faster than the planet, report warns. Available at: https://phys.org/news/2021-05-arctic-faster-planet.html (April 28, 2022).

20 June 2020, a temperature of 38 °C was recorded in the Russian town of Verkhoyansk, a new Arctic high-temperature record according to the World Meteorological Organization (WMO)[14].

In summer 2019, hundreds of large wildfires ravaged the Arctic region (Russia, Alaska and Greenland). Wildfire burned an area covered with grass, shrubs, and peat for several weeks in the mountain slopes about 150 kilometers northeast of Sisimiut, Greenland's second-largest city. In Siberia, wildfires burned almost three million hectares of land, according to Russia's Federal Forestry Agency. The numerous fires produced plumes of smoke that reached the cities of Kemerovo, Tomsk, Novosibirsk, and the Altai regions, some even the North Pole and Mongolia! These fires were caused by record-breaking high temperatures and lightning, fueled by strong winds. In June 2019 alone, they released harmful pollutants, toxic gases and around 50 megatons of carbon dioxide into the atmosphere[15]. Summer 2020 set new emission records when wildfires in the Arctic Circle exceeded 2019 records for carbon dioxide emissions[16].

Dust and dust storms, which are commonly associated with deserts, also occur at high latitudes (≥ 50 °N and ≥ 40 °S, including the Arctic as a sub-region ≥ 60 °N). The sources of this High Latitude Dust (HLD) are various [9]. In Greenland, its origin is linked to glaciers grinding and pulverizing rock, which produces a fine-grained silt: the glacial flour. In the south, soil surface conditions are favorable for dust emission during the whole year. Human activities also generate dust; examples include mineral-rich dust from year-round mining operations and pavement traction sanding of roads in wintertime. At high latitudes, winds are occasionally strong enough to send plumes of sediment along coastal regions. Dust storms have often been observed in Greenland and were documented in its peninsula of Nuussuaq by the Copernicus Sentinel-2 satellites on 1 October 2020.

HLD impacts northern high latitudes of Alaska, Canada, Denmark, Greenland, Iceland, Russia, Sweden and Spitsbergen, Norway. Dust particles have numerous climatic and ecological impacts, ranging from the formation of clouds to alterations of atmospheric chemistry, marine environment, and bio-productivity. These alterations influence air quality and human health, acting at different levels (local, regional, and global) through climate change, air pollution, and deterioration of nutrient sources.

A holistic approach to the consequences of rapid climate changes in the Arctic and sub-Arctic regions and ecosystems is mandatory. Considering the Arctic biophysical system, Box and collaborators [10] propose the following indicators: air temperature; tundra biomass; local hydrology and permafrost thaw; increased ignition of wildfires; increased shrub biomass; timing mismatch between plant flowering and pollinators; increased plant vulnerability to insect disturbance; shifting animal distribution and demographics. Regular updates of these indicators can serve as reference points to assess environmental impacts associated with climate change.

The 2019 IPCC Special Report dedicated to the Polar Regions, the Ocean and Cryosphere in a Changing Climate focused mainly on climate-related modifications of the Arctic ecosystem and the several services provided by the ocean and the cryosphere to people. The services include food and water supply, renewable energy, cultural values, tourism, trade, and transport. Negative im-

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[14] WMO recognizes new Arctic temperature record of 38 °C. *World Meteorological Organization (WMO)*. Available at: https://public.wmo.int/en/media/press-release/wmo-recognizes-new-arctic-temperature-record-of-38ºc (April 28, 2022).

[15] Siberian wildfires. *ESA*. Available at: https://www.esa.int/ESA_Multimedia/Images/2019/07/Siberian_wildfires (April 28, 2022); Huge fires in the Arctic and Siberia. *Eumetsat*. Available at: https://www.eumetsat.int/huge-fires-arctic-and-siberia (April 28, 2022).

[16] Copernicus reveals summer 2020's Arctic wildfires set new emission records. *Copernicus Europe's eyes on Earth*. Available at: https//atmosphere.copernicus.eu/copernicus-reveals-summer-2020s-arctic-wildfires-set-new-emission-records (April 28, 2022).

pacts of the Arctic induced by climate change, which are already observable, concern the ocean (sea level, ocean pH, temperature, kelp forest), the landscape (ground subsidence) and several ecosystems (rivers and streams). Impacts on human activities include a positive effect on tourism (Alaska and Scandinavia) and a negative impact on agriculture and infrastructure everywhere. The Report failed to address the health impact of climate change, in particular the impact on resident indigenous populations.

The threats of local and imported chemical pollution. In addition to climate change, global chemical contamination reaches the polar regions, allowing Sonne and coauthors to evoke "*the Arctic as a sink for pollutants*" [11]! Even though some sources of pollution are local (e.g., from mining and pesticide use), the majority arises from transport of sources located in lower latitudes through air, water (ocean currents) and terrestrial routes. For example, mercury (Hg) contamination was transported to the Arctic via the atmosphere, dominated by sources from East Asia [12]. These long-range environmental transportations (LRET) are major contributors to Arctic pollution by emerging organic contaminants (EOCs) and persistent organic pollutants (POPs), such as industrial organochlorines, polybrominated biphenyls (PCB) and diphenyl ethers (PCDE), polyfluorinated compounds (PFACs), and dioxins [13, 14]. The question of the effect of climate change on the transportation (LRET) and fate of these pollutants has arisen recently [11], and its remobilization has been confirmed [14]. The wide dispersal of pollutants, notably in the air and by sea, exposes the whole ecosystem and explains biotransformation, bioaccumulation and biomagnification. This adversely impacts Arctic fauna (zooplankton, marine invertebrates, fish, sea birds), notably mammals (e.g., seals, sled dogs, whales, polar bear). For example, POPs have multiple organ-system effects across taxa, including neuroendocrine disruption, immune suppression and bone density decrease [11].

Health challenges for the Arctic and sub-Arctic populations. From the nineteen fifties to 1990 in Alaska[17] and Canada [15], basic infectious diseases of humans included: Tuberculosis, Poliomyelitis, and parasitosis (worms, trichinosis, echinococcus linked with mammal flesh contamination). Eye-diseases (conjunctivitis, corneal opacities and blindness caused by UV light), poor diet and nutrition, addictions (alcoholism), and biting insects (requiring the use of DDT) were also prevalent. Sewage and waste disposal in permafrost areas presented additional health risks, including survival in very low ambient temperatures (-50 C°).

At the end of the 20th Century, the National Environmental Health Action Plan for Sweden [16] addressed new health concerns that included environmental pollutants, such as methyl mercury, brominated flame retardants, and radionuclides released from the Chernobyl Nuclear Power Plant in Soviet Ukraine.

Climate as a factor influencing public health. In 2010, Arbour and colleagues[18] (2010) provided a major introduction to some health issues in the Arctic, with a public health perspective.

Air temperature is a major meteorological factor influencing the human body. A change in air temperature alters the heat exchange between a person and the environment. Heat is primarily emitted through skin (approximately 82 %) and respiratory organs (13 %), and its emission depends on heat insulation by clothing. Wind increases heat emission. When air temperatures are low, wind can lead to body overchilling; wind stimulates more intense skin evaporation when air temperatures are high[18] [17]. A strong wind can provoke a hypertensive crisis and a stroke[19]. A drastic change in a

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[17] Public Health Problems in Alaska. *Public Health Reports*, 1951, vol. 66, pp. 911–950.

[18] Boksha V.G., Bugutskii B.V. Meditsinskaya klimatologiya i klimatoterapiya [Medical climatology and climatic therapy]. Kiev, Zdorov'ya, 1980, 262 p. (in Russian).

[19] Grigor'ev I.I. Pogoda i zdorov'e [Weather and health]. Moscow, Avitsenna, YuNITI, 1996, 96 p. (in Russian).

wind direction can result in greater blood pressure variability[20] [18].

Air humidity strengthens impacts exerted by air temperature: the higher the air humidity, the more intensely the body reacts to it, both under high and low temperatures[21]. High air humidity combined with a low ambient temperature intensifies heat exchange and body chilling; when the temperature is high, air humidity helps promote body overheating that can result in heatstroke [19]. Elevated air humidity increases the likelihood of airborne diseases and exacerbates diseases of the respiratory and musculoskeletal systems [20].

Atmospheric pressure and changes thereof can promote physiological alterations expressed as headaches and functional disorders of the cardiovascular system (changes in blood pressure, vascular crises and internal bleedings, etc.) [21–23].

The Arctic and sub-Arctic climate typically involves the body being simultaneously exposed to several adverse weather-related factors. This is proposed to promote development of "polar strain syndrome" or "northern stress". This poly-syndrome includes several basic components such as oxidative stress, insufficient detoxification and poor functioning of the barrier organs, disorders of northern-type metabolism, northern tissue hypoxia, immune deficiency, blood hypercoagulation, poly-endocrine disorders, regenerative-plastic failure, impaired electromagnetic homeostasis, functional dissymmetry of interhemispheric communication, desynchronosis, psychoemotional strain, and meteoropathy. Chronic stress stimulates depletion of the body's functional reserves and often induces a cascade of deadaptation disorders that ultimately leads to pathology [24]. There is also a concept of a "geographic latitude syndrome", which describes differences in risk of morbidity and mortality among populations with respect to their distance from the Equator[22].

Living in the Arctic or sub-Arctic region can adversely affect human health. When comparing disease incidence rates among people living beyond the Polar Circle (68º N latitude) with those among populations living in the temperate region in Russia (56º N latitude), experts established the former to be higher both among children (by 1.5 times) and among adults (by 1.3 times). For children, there is a higher prevalence of respiratory diseases, diseases of the eye and adnexa, diseases of the musculoskeletal system and connective tissue, and endocrine, nutritional and metabolic diseases. The prevalence of circulatory diseases, diseases of the musculoskeletal system and connective tissue, and diseases of the eye and adnexa, is higher among adults living beyond the Polar Circle [25]. In addition, comparison of disease incidence among populations living in municipal settlements located beyond the Polar Circle (67° N latitude) and the temperate region in Russia (54° N latitude) showed that diseases of the musculoskeletal system were 2.5–2.6 times more frequent among adults living beyond the Polar circle; diseases of the eye and adnexa 2.7–2.0 times more frequent; diseases of the genitourinary system 2.6–2.4 times more frequent; diseases of the digestive system 1.5 times more frequent; and diseases of the circulatory system 1.3–1.6 times more frequent [26].

Primary hypertension was established to be much more frequent at higher latitudes[23] than at middle ones. Frequency increases as the period of living in polar regions lengthens [27–29]. Primary hypertension is peculiar in the Arctic and sub-Arctic region not only because it develops at a considerably younger

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[20] Kucher T.V., Kolpashchikova I.F. Meditsinskaya geografiya [Medical geography]. Moscow, Prosveshchenye, 1996, 160 p. (in Russian).

[21] Koiranskii B.B. Okhlazhdenie, pereokhlazhdenie i ikh profilaktika [Chilling, overchilling and their prevention]. Leningrad, Meditsina, 1966, 247 p. (in Russian).

[22] Gundarov I.A., Zil'bert N.L. Izuchenie regional'nykh razlichii v zabolevaemosti i smertnosti naseleniya s pozitsii sindroma geograficheskoi shiroty [A study on regional differences in population incidence and mortality considering the latitude syndrome]. *Vestnik AMN SSSR*, 1991, no. 11, pp. 52–56 (in Russian).

[23] High latitudes is a conventional denomination for polar regions on the Earth located to the north from approximately 65° N latitude and to the south from 65° S latitude.

age but also in regard to its clinical signs[24] and rapid progression. At high latitudes, primary hypertension tends to be more severe, more often involves hypertensive crises with a considerable increase in both systolic and diastolic blood pressure, and drastic disorders of higher nervous activity often result in strokes and myocardial infarctions [30–32]. There is even a peculiar "northern" primary hypertension described in the literature; the disease is associated with apparent weather sensitivity, crises typically developing as per the cerebral and cardiac types, strokes and myocardial infarctions [29].

O.N. Popova confirmed in her research work [33] that geographical latitude affected external respiration functioning in people who were born and lived beyond the Polar Circle. She established changes in the functional state of the respiratory system (lung vital capacity, inspiratory and expiratory reserve volumes being authentically higher than the physiological standards, an increase in lung volume). All these changes were compensatory and adaptive responses of the body under exposure to extreme weather and climatic factors. A moderate edema of inter-alveolar septa is considered the morphological basis of this functional shift; its occurrence in northern people was confirmed by electron microscopy.

According to K.N. Dubinin [34], impacts exerted by latitude on the endocrine system have been confirmed by multiple research works. They show that the "hypophysis–adrenal" system is activated at higher latitudes, thyroid hormones tend to be more labile, and the limits of the thyrotrophic hormone content shift towards smaller values. Adaptation strain in people living on the European North is combined with low levels of total triiodothyronine (T3) against an increase in concentrations of the most active free T3.

E.V. Tipisova established in her research [35] that men who lived in mid-latitude areas (59° 13' N latitude) had minimal activity of the "hypophysis – thyroid gland" system (triiodothyronine, free thyroxine) in comparison with that detected in people living in the Arctic area (66° N latitude) and close to it (64° N latitude). In addition, men who lived at 64–65° N latitude had lower reserve capabilities of the "hypothalamus – hypophysis – thyroid gland" system against more apparent activation of the "hypothalamus-hypophysis–adrenal cortex" system in comparison with people who permanently resided beyond the Polar circle. Prolactin content tended to decline and estradiol acted as an adaptation factor in the regulation of the "hypothalamus – hypophysis thyroid gland" system.

V.N. Petrov [25] showed that geographical altitude had its influence on a growing number of diseases of the eye and adnexa among people living beyond the Polar Circle due to low oxygen levels in ambient air. This results in oxygen deficiency in vessels that supply blood to the optic nerve, retina and lens leading to declining adaptation capabilities of the visual organs, especially during the polar night. Changes of the circulation in the central ophthalmic artery indicate there are certain vascular shifts and impaired cerebral hemodynamics.

Effects on health produced by the midnight sun, polar night and the day/night cycle. In the Arctic and sub-Arctic, an apparent change between day and night is absent for a long period of the year; there is also the polar night and midnight sun (contrasting seasons of light aperiodicity). These are specific northern factors typical for territories located higher than 67–68° N latitude. A.V. Enikeev and colleagues [36] showed that the polar night and midnight sun, as well as the long-term absence of a stable day/night cycle, could affect human health considerably by creating health risks for the respiratory organs, endocrine and circulatory systems.

Effects produced by the polar night on the respiratory organs were confirmed by

[24] Khamnagadaev I.I. Rasprostranennost' arterial'noi gipertenzii, ishemicheskoi bolezni serdtsa i ikh faktorov riska sredi sel'skogo korennogo i prishlogo naseleniya Severa i Tsentral'noi Sibiri [Prevalence of primary hypertension, ischemic heart disease and their risk afctors among rural indigenous people and alien population in the North and Central Siberia]: the thesis of the dissertation … for the Doctor of Medical Sciences degree. Tomsk, 2008, 49 p. (in Russian).

Yu.F. Shcherbina [37] who established that the external respiration apparatus had to work under greater strain during the polar night than during the midnight sun against apparently declining effectiveness of alveolar ventilation and reserve respiration capabilities. In addition, according to A.B. Gudkov [38], lung vital capacity became greater during the polar night than in the midnight sun, and large and middle-sized bronchi became more patent for airflow. This was a relevant compensatory and adaptive response of the body aimed not only at providing intensified metabolism but also at heating and moistening inhaled air.

V.N. Chesnokov established [39] that the polar night strained the adaptive mechanisms of the cardiovascular system. This strain became apparent through a growing contribution made by the cardiac and vascular components to the provision of adaptive reactions of the cardiovascular system. V.N. Pushkina[25] mentioned in her work that there was a strain in the blood supply to the brain against the elevated tone of cerebral vessels during the polar night.

According to data provided by Yu.Yu. Yuriev and E.V. Tipisov [40], as well as by A. Kauppila with colleagues [41], contrasting seasons of light aperiodicity affect the endocrine system by changing hormonal concentrations in the body. Thus, as daylight hours become longer, the “hypophysis–gonads” system is activated in people living in the Far North; this may result in various imbalances associated with both elevated activity of the system and depletion of its reserves.

K.E. Kipriyanova and colleagues [42] revealed both considerably elevated levels of testosterone and estradiol and abnormally low concentrations of globulin that bound sex hormones and total and free testosterone fractions in people living in the Far North under longer daylight hours.

E.V. Tipisova established in her study [35] that an elevated blood insulin level and a decrease in available adrenal cortical reserves was an adaptive reaction in men (living in the European North) under shorter daylight hours; these reserves recovered when daylight hours were the shortest. She also detected advanced adaptive reactions of the endocrine system in male children and adolescents.

K.N. Dubinin noted [34] that a specific hypophysis-thyroid system and dependence of thyroid gland hormones on photo periodicity had common adaptation significance for the human body under harsh climatic conditions in the European North.

V.N. Pushkina[26] confirmed that psychoemotional stress occurred during a period of the “biological polar night”. This stress became apparent through elevated situational and personal anxiety, poorer health and lower activity against an obvious growth in aggressive reactions [39, 43].

Climate change has increased injuries, accidents and drownings. Rising ambient temperatures have disrupted ice formation and breakup patterns, leading to unsafe and unpredictable travel conditions which, in turn, have increased rates of injuries and death [44]. This was documented in Inuit communities of Canada: Search and Rescue (SAR) records from 1995 to 2010 showed an estimated annual SAR incidence rate of 19 individuals per 1,000. The incidence rate was six times higher for males than females; land-users aged 26–35 years had the highest incidence rate among age groups. Critical risk factors were environmental (weather and ice) conditions, particularly related to travel on sea ice during winter, as well as age and sex. In contrast with other studies, A. Durkalec and colleagues [45] noted that intoxication (alcohol) was the least common factor associated with SAR incidents. A study of over 4000 winter drownings in 10 Northern Hemisphere countries showed an exponential increase in regions with warmer winters (air temperatures near 0 °C). Risk factors were environmental conditions (winter air

[25] Pushkina V.N. Khronofiziologicheskie pokazateli funktsional'nogo sostoyaniya organizma studentov v usloviyakh Pripolyar'ya [Chronophysiological indicators of the body fucnitonal state in students living in reigons near the Polar Circle]: the thesis of the dissertation ... for the Doctor of Biological Sciences degree. Arkhangelsk, 2013, 37 p. (in Russian).

temperatures were between -5 °C and 0 °C, unstable ice), subject age (children and adults up to the age of 39), indigenous traditions and human behavior (livelihood requiring extended time on ice) [46].

Infectious diseases in the Arctic and sub-Arctic regions are impacted by climate change. Surprisingly, interest on the occurrence and distribution of communicable diseases in the Arctic and sub-Arctic is recent. In 2014, Hedlund and coauthors [47] underlined that few studies were available from Siberia and Alaska, and none from Greenland or Iceland. These authors suggested systematic surveillance with monitoring of extreme weather events after having reviewed the impact on common infectious diseases. These included food-borne diseases (salmonellosis, campylobacter), rodent-borne diseases (e.g., nephropathia epidemica), airborne diseases (respiratory pathogens) and vector-borne diseases (tick-borne encephalitis, TBE or borreliosis). The spirochete *Borrelia burgdorferi,* which causes Lyme disease, is the most common vector-borne disease (VBD) affecting humans in the temperate Northern Hemisphere. The number of Lyme disease cases in Europe was ~ 35,000 in the late 2000s [48]; left untreated, infection can spread to the joints, heart and nervous system.

Climate-sensitive infectious diseases in the Northern/Arctic Region, including borreliosis, leptospirosis, TBE, Puumala virus infection, cryptosporidiosis, and Q fever, show significant relationships with climate variables related to temperature and freshwater conditions. Whereas these infectious diseases represent increasing threats for humans, the risk of leptospirosis may decrease with increasing temperature and precipitation. "*At whole-region scale, the incidences of TBE are negatively correlated with all (hydro-) climate variables, while those of borreliosis are positively correlated with all climate variables*". This is notable because these diseases share the same vector, namely Ixodidae ticks [49]. Thus, the same vector can transmit a pathogenic bacterium (*Borrelia* spp.) and a neurotropic Flaviviridae virus (such as TBE).

Weather conditions, rainfall, moisture (at least 85 % relative humidity) and temperature affect the life cycle and habitat of Ixodes ticks. These factors contribute to the geographic expansion in association with vegetation communities and wild animal hosts (deer, other cervids, birds, and rodents), which carry tick vectors to new areas [48, 49]. For example, the sheep tick *Ixodes ricinus* has spread to the northern regions of Sweden and Norway [49]. In addition to this expansion, an increase in the incidence of tick bites has been linked with the increased annual temperature. Human contact with wild fauna due to urbanization and green zones in towns, as well as changing patterns of human behavior (increasing number of trekkers, wildlife and pet lovers), has augmented the risk of exposure to tick-borne pathogens [48].

The health of wildlife also has relevance to human health. Muskoxen and caribou (reindeer) are infected by a helminth parasite (*Varestrongylus eleguneniensis*, lungworm) that has rapidly extended its geographical range at high latitudes in the central Canadian Arctic; this is attributed to faster warming at high latitudes and altitudes, which allows the establishment of lungworms and their gastropod intermediate hosts [48]. Although not in direct relation with climate change, the propagation and geographic extension of Chronic Wasting Disease (CWD, an infectious and degenerative prion disorder) in the cervid population (deer, elk, moose, and caribou) is a major concern in Arctic areas. CWD, which was discovered in the 1980s in the western United States (U.S.), had expanded by 2012 to 19 U.S. states and 2 provinces in Canada [50] and, by 2021, to 26 U.S. states and 3 Canadian provinces [51]. After a decade of surveillance, the first case of CWD in reindeer was diagnosed in Norway in 2016, since that time, other cases have been reported in Norway, Sweden and Finland. Besides the threat to the cervid population across the Arctic region, the potential risk of transfer of a contagious prion to humans via food is considered. Ruscio and coauthors [52] recommend a regional One Health approach to assess interactions at the human–animal–environment interface to augment understanding of, and response to, the complexities of climate change on the health of Arctic inhabitants.

Specific health risks related to permafrost thawing due to global warming. While organic matter in thawing permafrost is subject to microbial activity, with consequent release of greenhouse gases (carbon dioxide and methane), human health may also be impacted by the additional release of chemical and radioactive materials deposited in permafrost in recent times [53]. Biological risks associated with the permafrost thawing rank at the highest degree of uncertainty since all biological items are frozen before decomposition or degradation. This led Abramov and coauthors [54] to write "*Permafrost is used as a paleoarchive*". The story of preserved mammoth bodies, commonly found in Siberia permafrost, is known worldwide. Less widely known is that diverse microorganisms (Archaea, Bacteria and Eukarya), as well as viruses, are also isolated in permafrost. Some such organisms have been cultured, which demonstrates the preservation of life forms in permafrost [54]. A question of utmost importance is the potential health impact on modern humans if the multitude of unknown microorganisms that have been sequestered in permafrost for tens to hundreds of thousands of years were to be released into the environment[26].

The discovery of the H1N1 virus, which caused the global Spanish influenza epidemic, illustrates well the threats of sequestered microorganisms. The pandemic killed 20 to 50 million people in 1918–1919 [55]. Some key researchers, starting with Johan Hultin in 1951, have unsuccessfully attempted to obtain the 1918 virus from bodies of victims buried in permafrost at Alaska's Brevig Mission burial site. He was again involved in 1997, at age 72, during his second trip to the Brevig Mission burial ground. He provided unfixed lung tissue to U.S. scientists Dr. Jeffery Taubenberger and Dr. Ann Reid who isolated RNA material. With genomic RNA of the 1918 virus isolated from archived formalin-fixed lung autopsy materials, the sequencing the genome of the 1918 virus was at last possible [56]. Microbiologist Dr. Peter Palese and his New York team created the plasmids used by Dr. Terrence Tumpey at the U.S. Center for Disease Control & Prevention to reconstruct the 1918 pandemic virus [57].

Contrary to the H1N1 influenza virus, which has been reconstructed, some viruses can "*survive intact in ice patches for at least this period and retain their infectivity*" [58]. This was demonstrated for the caribou feces-associated virus (aCFV) that was probably present in the animal's plant diet and isolated from a 700 ± 40 year-old caribou fecal sample [59].

The study of the Siberian permafrost virome allowed the detection of a giant virus, named *Pithovirus sibericum*, which was isolated from a > 30,000 year-old radiocarbon-dated sample. A previous study reported the detection of genomic signatures of a tomato mosaic tobamovirus in 140,000 year-old glacial ice in Greenland, but did not address the question of viability [60].

The risk of mammalian infectious diseases linked to the release of microbes in thawing permafrost was realized in 2016 when *Bacillus anthracis* (anthrax bacterium) killed thousands of reindeer and affected dozens of humans in the Yamal peninsula in the northern part of Russia's Western Siberia. After 70 years free of anthrax, this outbreak was related to former severe and recurring regional epizootics of anthrax in the early 20th century. The activation of spores in 2016 had several causal factors, including 6 years of relatively warm weather followed by cold years during which a thick snow cover prevented soil from freezing. The summer 2016 heat wave accelerated the permafrost thaw, and the situation became even worse due to a reduced rainfall in July 2016 (less than 10 % of its 30-year mean value) [61].

[26] Permafrost thaw could release bacteria and viruses. *ESA*. Available at: https://www.esa.int/Applications/Observing_the_Earth/Permafrost_thaw_could_release_bacteria_and_viruses (June 26, 2022).

Arctic pollution impacts humans through water and food consumption. Awareness of the human impact of pollution in the Northern Hemisphere led to the creation of a dedicated research program in 1997. The Arctic Monitoring and Assessment Programme (AMAP) launched ongoing surveillance of environmental POPs in the Arctic ecosystem. In 1998, 2002, and 2009, AMAP published reports on the results and the health risks of POPs for Arctic populations [62].

The cultural behaviors of indigenous populations are a key to understanding the routes by which pollutants can enter the body. The first example is the population living in the Faroe Islands who traditionally consume marine mammals (whales), seabirds and other seafood and, in Greenland even polar bears. These animals are contaminated with pollutants such as mercury, metals and POPs (e.g., PCB, organochlorine pesticides), and consuming their flesh exposes subjects to pollutants with neurotoxic [63, 64], genotoxic and reproductive toxic potential [62, 65]. Human plasma organochlorine levels were elevated in an Arctic population, and the mean plasma concentration of DDE, the breakdown product of DDT, was found to be elevated in subjects with idiopathic Parkinson disease (PD). The age-adjusted prevalence of PD in the Faroe Islands (209 per 100,000 inhabitants) and in Greenland (187.5 per 100,000 inhabitants) is higher than in a Baltic Sea Island in Denmark (98.3 per 100,000 inhabitants); patients were younger in Greenland and a higher proportion of patients had cognitive decline [63, 64].

Exposure to methyl mercury from marine mammals and other seafood can affect human brain development. The average mercury concentration of hair was greater in children (5 micrograms/g) than their mothers (1.5 micrograms/g) in a traditional Inuit community in Qaanaaq (Greenland). While the children were clinically unremarkable, neuropsychological tests showed possible exposure-associated deficits. Additionally, in conjunction with data from other studies (Faroese Islanders), peak latencies on brainstem auditory evoked potentials tended to be prolonged at increased exposure levels [66].

In the same study, Inuit had significantly lower sperm DNA damage. Further studies are required to elucidate whether the serum POP-related effects on hormone receptors and / or AhR are explanatory factors. 'The Arctic dilemma' is that along with the intake of the Greenlandic traditional diet that contains POPs, there is also a number of important nutrients, such as trace elements/antioxidants and marine unsaturated fatty acids that have favorable health effects. However, several studies suggest that an increase in Western food items in the diet can lead to other health risks, such as the metabolic syndrome and its sequellae, namely body weight increase, hypertension, diabetes type 2, cardiovascular disease, and cancer, including breast cancer.

Further studies are required to elucidate these phenomena, including research focused on biomarkers of exposure and effects, epigenetic changes and the determination of relevant genetic polymorphisms, case-control as well as generation studies. There is also a need for the development of new biomarkers to study the potential POP effects that inhibit the immune system and affect the development of the central nervous system. Although the traditional Greenlandic diet, together with cigarette smoking, is associated with a high POP intake relative to that of Europeans, male Inuit have significantly lower levels of sperm DNA damage. A possible explanation is the relatively rich selenium and n-3 unsaturated fatty acids in the Arctic diet [62]. However, the exposure of pregnant women in Greenland to metal pollutants (tested in blood) over the admitted normal range, can "*adversely influence fetal development and growth in a dose-response relationship*". Abnormal fetal outcomes have been noted, including reduced birth weight, reduced head circumference, and preterm birth [65].

The second example of cultural tradition of many northern indigenous peoples is related to diet and water consumption. In addition to a cultural preference, drinking untreated water (e.g., from lakes, ponds, rivers, melted snow or ice) is not an uncommon practice, especially when northern residents are visiting cabins, hunting, fishing, trapping, and gathering [67]. For the Indigenous Peoples of North-Western Siberia, typically in the season of fishing or reindeer slaughter, "*This diet provides a ready-made set of macro- and micro-elements necessary for life in the challenging conditions of the Arctic*" [68]. An example of the benefit of traditional food is the consumption of reindeer venison meat, which has been shown to reduce hypertension and the risk of chronic non-obstructive bronchitis. Nowadays, as shown by Bogdanova and coauthors [69], the consumption of traditional reindeer food has decreased by almost 50 %, in part from the export of such products and the effects of climate change, which modifies seasonal fishing and disrupts the traditional migration routes of the reindeers [68]. The safety of food and water in relation to chemical/microbiological contamination is a major issue for Arctic populations, as are waterborne illnesses.

Suicide in the Arctic as an additional risk factor. We discovered the drama of suicide among adolescents when one of us (JR) visited the cemetery of Ammassalik-Tasilaq (Greenland) in summer 1994. Catherine Enel, a late French ethnologist who lived in the community explained the suicidal ideation of local adolescents and evoked Robert Gessain who, with alarm about the fate of the Inuit population, wrote in 1969 "*The Ammassalimiut will culturally disappear from the world, leaving more numerous descendants. Cultural death and population explosion, ethnocide and genoboom, are the by-products on these Arctic shores of Western expansion*"[27]. In fact, suicidal behaviors and thoughts are a major public health issue across Arctic States and their northern regions [70]. Excess risk is related to ethnicity (indigenous groups), age and sex. The suicide rate in the Norwegian Sami people is higher among males aged 15–24 and more than double in males than females. The mean age-standardized suicide rate shows great variations in the Arctic States for the decade 2000–2009. In the Western countries (Europe and America), the median age is < 20 years: suicide impacts a young population. To the contrary, in the Russian Federation, as well as in Greenland and Nunavut (Canada), where the indigenous population constitutes the majority of inhabitants, suicide occurs more in older people (> 40 years). Young and coauthors [70], who emphasize the need for suicide prevention, propose few explanations for the problem of suicidal behaviors and thought from a circumpolar perspective.

Conclusion. The Arctic and sub-Arctic populations are victims of the Anthropocene Epoch of human activity and the extension of a Westernized lifestyle that endangers local resources and indigenous cultures.

What can be done? Bring better research and information to allow remediation and resilience!

How? Increased cooperation among states is mandatory, as underlined by Margareta Johansson, a research coordinator in the Department of Physical Geography and Ecosystem Science at the University of Lund (Sweden) who concluded her document with the following sentence: "*the climate knows no national borders*"[28]. As climate changes faster in the Arctic than elsewhere, global pollution and infectious diseases threaten to challenge the health of its indigenous peoples to a degree perhaps greater than faced by humans in other parts of the world.

Funding. The research was not granted any financial support.

Competing interests. The authors declare no competing interests.

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Received: 17.07.2022
Approved: 25.09.2022
Accepted for publication: 27.09.2022