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Review

Emerging Environmental and Weather Challenges in Outdoor Sports

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Abstract: Given the climatic changes around the world and the growing outdoor sports participation, existing guidelines and recommendations for exercising in naturally challenging environments such as heat, cold or altitude, exhibit potential shortcomings. Continuous efforts from sport sciences and exercise physiology communities aim at minimizing the risks of environmental-related illnesses during outdoor sports practices. Despite this, the use of simple weather indices does not permit an accurate estimation of the likelihood of facing thermal illnesses. This provides a critical foundation to modify available human comfort modeling and to integrate bio-meteorological data in order to improve the current guidelines. Although it requires further refinement, there is no doubt that standardizing the recently developed Universal Thermal Climate Index approach and its application in the field of sport sciences and exercise physiology may help to improve the appropriateness of the current guidelines for outdoor, recreational and competitive sports participation. This review first summarizes the main environmental-related risk factors that are susceptible to increase with recent climate changes when exercising outside and offers recommendations to combat them appropriately. Secondly, we briefly address the recent development of thermal stress models to assess the thermal comfort and physiological responses when practicing outdoor activities in challenging environments.

Keywords: global warming; outdoor sports; thermal stress; environmental physiology; microclimatology; modeling

1. Introduction

1.1. Practicing Sport Activities in a Challenging Environment?

It is popularly perceived that regular physical activity reduces the risk of developing chronic diseases (*i.e.*, cardiovascular, overweight and obesity, type 2 diabetes, hypertension and certain types of cancers [1,2]) and improves psychological well-being [3,4]. In this vein, outdoor sports practice offers a preeminent gateway to a healthy active lifestyle [2,5], and is undergoing unprecedented popularity (e.g., +26% increase in USA outdoor runners population over 5 years from 2007 to 2012, leading to >53 millions of practitioners) among recreational and competitive individuals. This is notably the case for activities such as running/jogging, triathlon (traditional/road, non-traditional off-road), marathon, adventure racing, trail running, trekking/climbing (traditional/ice/mountaineering), biking (road, mountain, BMX), skating (in-line and on-ice), skiing (cross-country, biathlon, alpine/downhill; including snowboarding), swimming, windsurfing and surfing (including wakeboarding, stand up paddling), scuba diving/snorkeling, kayaking and rafting, team sports (e.g., soccer, ice-hockey) and tennis. Additionally, acceleration in sport technology development (e.g., specific clothing, global positioning system) facilitates practice of these outdoor activities without any specific pre-conditioning.

Outdoor sports participants may experience exertional hyperthermia (*i.e.*, core temperature >39 °C), when practicing in warm-to-hot ambient conditions, or hypothermia (*i.e.*, core temperature <35 °C) in cold or cool-windy environments. Thus, when exposed to environmental thermal stress, the likelihood of practitioners facing health risks increases. According to the laws of thermodynamics, the body loses heat when environmental temperatures are lower and vice versa [6]. Heat transfer in either direction occurs by convection (sensible heat flux), conduction (contact with solids), evaporation (latent heat flux), radiation (long- and short-wave) and respiration (latent and sensible) [7]. Environmental factors related to heat transfer are a combination of air temperature, wind speed, relative humidity and radiation. In addition, there are individual factors (e.g., age, gender, morphology, fitness) [8,9] which can interfere with physiological thermoregulation [6].

Physiological responses to exercise in challenging environments vary substantially among participants, with also periodic reports of severe or, albeit rare, near-catastrophic incidents of environment-related illnesses in a restricted number of practitioners. Even though compliance with heat-, cold- and altitude-related guidelines (e.g., use of fixed Wet Bulb Globe Temperature (WBGT) cut-offs to decide whether or not to suspend football or tennis matches) [10–14] would not guarantee full protection it will, however, reduce potential risks for most individuals.

1.2. Climate Change Consequences on Outdoor Sports Practice

Noticeable climatic changes occur around the world, as evidenced for instance by a global annual average temperature increase of ~1 °C over the last century, also majoring the number of episodes of extremes of heat and heavy precipitations. As such, it becomes a priority, not only to re-emphasize current but also, to provide additional recommendations in order to address and minimize risks of environmentally prompted illnesses and in extreme situations deaths due to outdoor sports participation. Weather forecasts in many parts of the world now routinely provide detailed information on levels of ozone and particulate air pollutants, of pollen and of exposure to ultraviolet radiation (UVR), along with warnings of when high or low temperatures may become hazardous to health. The appropriateness of outdoor environments for sport activities practice has hitherto been mostly assessed in terms of air temperature and one of a variety of expressions for humidity (e.g., relative humidity) for warm conditions, air temperature combined with air velocity for cold conditions [7], and other basic weather parameters (*i.e.*, vapor pressure, solar and thermal radiation), all being easily recorded from simple and rather inexpensive instruments. The influence of other meteorological factors (e.g., atmospheric pressure, precipitation and cloud cover) on outdoor sports performance is, however, often disregarded. Moreover, internal metabolic heat production [15], which closely depends on the exercise type, duration and intensity, as well as the aforementioned individual parameters and the clothing insulation are likely introducing large errors into any prediction of any adverse weather effect [16]. Thus, accurately modeling thermal stress requires consideration of the physical environment along with the physiological and psychological attributes of practitioners [17,18]. This has led to the development of various indices (e.g., WBGT or Modified discomfort index) attempting to describe thermal stress (see [19]). However, after nearly 50 years of experience with heat budget modeling (*i.e.*, heat exchange between the human body and the thermal environment [9]) and easy access to both computational power and meteorological data, it is surprising that the use of simplistic indices such as WBGT [20] continue to be widely recommended by major sports governing bodies (IOC, FIFA) [13]. A better understanding on thermal balance regulation during exercise in various outdoor environmental conditions is vital in furthering the validity of available models and improving outdoor recreational and competitive settings.

Comprehensive reviews have been published on thermal strain when exercising in the heat [12,21], in cold [10,22], at altitude [10]; on specific environmental-related risks (*i.e.*, pollution [23], allergen [24], UVR [25]); as well as on mechanisms of thermoregulation through sweating [26], clothing properties and metabolic heat production [27]. This has led to comparisons of selected simple thermal indices [19] and more complex approaches (see [28,29]). However, to our knowledge, no appraisal has yet focused on an integrated view of the various environmental-related parameters for outdoor sports participation, with special reference to global warming. Therefore, the aims of this review are twofold: first, we summarize the major environmental-related risk factors (and associated challenges) that are susceptible to increase with recent change in climate when practicing outdoor sport activities. In addition, we re-emphasize general recommendations to prevent the associated risks. Secondly, we briefly address the recent development of thermal stress models to assess the thermal comfort and physiological responses when exercising outside in challenging environments.

2. Environmental-Related Risk Factors

2.1. Heat

Global warming leads to an increased incidence of heat waves (*i.e.*, extended periods of extreme high temperatures), which substantially deteriorates human health [30–32]. While elderly—and to a lower extent, children—are primarily affected by heat stress during their outdoor sport practice, other outdoor recreational and competitive individuals may also be at risk.

As intense or prolonged exercise is completed in both cool (e.g., 8 °C–18 °C) [33–35] and hot/humid ambient conditions [36,37], the development of heat illnesses varies on a severity scale continuum [38] (mainly due to overlapping diagnostic features) ranging from mild (heat rash, syncope and cramps) to serious (heat exhaustion, injury and stroke) [12,33]. Exercise-associated muscle cramps, also called heat cramps, are painful spasms of skeletal muscles occurring in the heat [39]. Occurrence of heat cramps is more common in long distance runners [40] as well as in athletes engaged in prolonged, high-intensity sports (*i.e.*, tennis, American football and soccer) [41,42]. The main factors thought to be responsible for the development of heat cramps are muscular fatigue, body water loss and large sweat [Na^+] loss [42,43].

While exertional hyperthermia is defined as an elevation in core temperature above 39 °C [44–46], heat exhaustion commonly refers to a mild-to-moderate illness (*i.e.*, inability to sustain cardiac output) occurring at moderate (>38.5 °C) to high (>40 °C) core temperatures [44,46,47]. The latter is frequently accompanied by hot skin and a dehydration state. Heat injury is a moderate-to-severe illness (*i.e.*, injury to an organ (e.g., liver, kidney, gut, muscle)), which in most cases occurs with high core temperatures. Heat stroke is a severe illness in outdoor sport participants characterized by central nervous system dysfunction (e.g., confusion, disorientation, impaired judgment) and is usually accompanied by a core temperature above 40.5 °C. Heat stroke can be complicated by liver damage, rhabdomyolysis (breakdown of muscle tissue), widely distributed blood clotting (disseminated intravascular coagulation), water and electrolyte imbalances, and kidney failure [34,48–51].

Although any sport practitioner can sustain heat-related illnesses, a variety of factors substantially increases development risks [12]. In general, obesity (*i.e.*, a body mass index >30 kg m^{-2}), low physical fitness levels, non-heat acclimatization [33,36,44,52], dehydration (*i.e.*, elevated urine specific gravity, hematocrit, hemoglobin or serum osmolality) [52,53], with a previous history of exertional heat-related injury [43,46,54,55], sleep deprivation [54], sweat gland dysfunction, sunburn, viral illness, diarrhea, age >40 yr, male [54], Caucasian [56], are factors increasing the risk of heat-related illness. Furthermore, individuals with sickle cell trait (*i.e.*, higher prevalence in Blacks and certain Asian populations) [57], those having genetic predisposition to malignant hyperthermia or taking certain medications (e.g., antidepressant [58]), also have increased risks during outdoor practice.

Recommendation/Heat Stress

Development of cardiorespiratory fitness (e.g., training at intensities ranging between 70%–80% of maximal heart rate, 2–3 times a week for 30–45 min [59]), implementation of preventive countermeasures including pre-cooling (external (application) and internal (ingestion) of cold modalities including air, water and/or ice, separately or in combination [60]), heat acclimatization (exercising 60–90 min, every second day in hot conditions to induce profuse sweating and core temperature elevation (>1 °C), for at least one but ideally two weeks; [61]) and individualized hydration strategies (starting practice euhydrated, maintenance of fluid balance; limiting body weight loss < 2%; [12]) and salt balance (consuming a solution containing 0.5–0.7 g L^{-1} of sodium; [12]) would reduce the risk of heat-related illnesses [12,62]. Taking into consideration local weather data, training and competition should be preferably scheduled during the cooler hours of the day (e.g., early morning) during particularly hot (>30 °C) and humid (80% RH) months, with extended recovery periods (3–6 h) between practice sessions [12]. Near-maximal exertion should be avoided before acquired physical fitness and heat acclimatization (increased sweating and skin blood flow responses, plasma volume expansion and hence improved cardiovascular function) are sufficient to support high-intensity, long-duration exercise training or competition [63,64]. Practically, acclimatization requires gradually increasing the duration and intensity of exercise during the initial days (~3–5 days) of heat exposure [65], while exercising heart rate being the most accurate means of judging exercise intensity. Encouraged behaviors include (i) unlimited fluid access (although hydration recommendations still needs to be agreed on [66]); (ii) longer and/or more frequent breaks into practice facilitating heat dissipation, shorter exercise times decreasing heat production; and/or (iii) postponing training sessions or competition when environmental risks are high [12]. Removal of extra clothing limiting sweating would also reduce heat storage and improve heat balance.

2.2. Ultraviolet (Exposure)

Outdoor sport training sessions and competitions usually take place during the peak hours of UVR, *i.e.*, between 10 a.m. and 4 p.m. [67]. Reportedly, small doses of UVR from the sun help the body to produce vitamin D [68]. However, too intense, intermittent- and total cumulative-exposure to UVR have been associated with the development of both melanoma and non-melanoma skin cancers [69–71], while the number of malignant melanoma cases over the last 40 years has doubled every 7–8 years [72,73]. Apart time spent outside from an early age [70,74], numerous factors predispose outdoor sport participants to UVR injury (e.g., sunburns). Firstly, by enhancing the photosensitivity of the skin, sunburn risk is increased by heat and/or exercise-induced sweat production, thereby contributing to UVR-related skin damage [70,75]. Secondly, specific environments such as altitude [76] add to the exposure risk [70]. For example, skiing for durations as short as 6 min is enough to reach "minimal erythema dose" level [77], as UVR reflection is received both from the sky and the snow (the ground) [76,78]. In many aquatic sports, water is also reflecting a significant portion of UVR [70]. Skin areas presenting the highest risk for UVR exposure include the face, neck, hands, legs, and feet (dorsal); moderate risk areas are the thorax, thighs, arms, and forearms. Finally, initial erythema (*i.e.*, skin redness caused by congestion of the capillaries in the lower layers of the skin) becomes evident typically 3 to 5 h after significant sun exposure (e.g., midday during 15–30 min for an individual with fair skin), and reaches maximum severity 12 to 24 h post-exposure before gradually resorbing over the next 72 h [79].

Recommendations/Ultraviolet

Awareness of appropriate attitudes to face sun exposure is paramount to limit risks of skin cancer development in outdoor sport participants. The reality, however, is that sunscreen preparation and/or solar UVR protective textiles are currently underused [80] and their use is even forbidden by some official competition rules and regulations. For instance, it was not allowed to apply sunscreen on the thighs and shoulders to mark competition numbers onto the skin during the Hawaii ironman triathlon [81], while the use of hats and sunglasses is forbidden for field hockey and soccer players [82]. Such restrictions result from a lack of information related to the preventive effectiveness of sunscreen. While several educational interventions can increase adherence to sun safety behaviors and practices in coaches and their athletes [83–85], most of previous sun protection prevention programs [83,84,86] have demonstrated low success rates. Referring to the Global Solar UV Index would help to handle UVR risks more efficiently. Recommendations for reducing exposure to UVR generally include: (i) avoiding sun (especially during the peak UV exposure hours; *i.e.*, between 10 a.m. and 4 p.m.) and using shaded areas not only for athletes but also those who are not actively practicing; (ii) wearing protective clothing (*i.e.*, long pants, long-sleeves shirts, hats and sunglasses); (iii) applying sunscreen preparations (*i.e.*, sun protection factor 15+). One practical tip is the establishment of visual cues around locker rooms, reminding athletes to apply sunscreen. Furthermore, developing different sunscreens that are specific to competition needs of each individual athlete would undoubtedly enhance compliance. Finally, annual pre-season dermatologic screenings are valuable prevention initiatives.

2.3. Lightning and Severe Wind

Although rare, participants engaged in mountainous ultramarathons, for instance "Ultra trail du Mont Blanc, Tor des Géants or Hard Rock", may suffer from lightning strikes [87,88], whose timing occurrence (*i.e.*, afternoons during summer months) often corresponds with the peak of sport participation on possible remote locations. Lightning could potentially lead to lethal injuries [89,90] through its electrical current, heat production, and concussive force [91]. Among the different types of lightning contacts [87,92], side flash (*i.e.*, lightning hitting an object before jumping to the nearby individual), for instance standing under a tree for protection in a storm, is the most frequent [93]. Other types include direct strike (*i.e.*, lightning hitting an individual) and contact (*i.e.*, lightning hitting an object in contact with an individual). Lightning injuries comprise dermatologic manifestations (e.g., Lichtenberg figures, superficial erythema and blistering, and punctuate, contact and linear first or second degree severity burns [91,92,94]) as well as musculoskeletal (multiple fractures including shoulder dislocations and cervical spine fractures [92]), cardiopulmonary (temporary cardiac or respiratory arrest, ventricular fibrillation and prolonged cardiac arrest) and neurologic (confusion, amnesia, temporary deafness or blindness, and temporary unconsciousness [91]) disorders. Among long-term squeals of lightning strikes are post-traumatic headache, sleep disorders, irritability, psychomotor impairment and sympathetic nervous system dysfunction [87,93,95,96].

Wind is a by-product of weather generally associated to thunderstorms [97]. With the exception of hurricanes, tornados or cyclones, wind is generally described as straight-line air movements, down- (*i.e.*, horizontal downdrafts >4 km) and micro-burst (*i.e.*, outwards winds at the earth's surface with or without rain) and gust front (*i.e.*, when the front of rain-cooled air collides with warmer air of the thunderstorm inflow) [97]. Severe winds generally develop prior to a thunderstorm [97]. To date, three levels of advisement for wind have been issued: advisory (*i.e.*, sustained wind or wind gusts ranging 40–60 km h^{-1} for an hour or longer), watch (*i.e.*, range: 61–85 km h^{-1}) and warning (*i.e.*, >85 km h^{-1}) [97]. Whereas outdoor sporting event's officials seem to have a handle on the wind impact for optimal performance in individual sports [97], it does not seem that participant (or even spectator) safety is a major concern.

Recommendations/Lightning and Severe Wind

Before engaging in outdoor sport activities, individuals must be aware of weather reports and the possible occurrence of thunderstorms in relation to the location of their practice or competition playgrounds. When practicing, the best way to avoid lightning strikes is to use the 30 s–30 min rule [98]; which requires counting the time between seeing the lightning and hearing the thunder from the flash; a time ≤30 s requires to actively seek shelter (building or a metal-roofed automobile but not a golf car or a bus stop [91]) within 30 min. This safe location must be identified before exercise starts. Activities may resume after a 30 min period free of either last thunder or lightning flash.

2.4. Air Pollution

Air pollution is a growing environmental burden worldwide, which is thought to be the result of climate changes (hotter ambient temperatures exacerbate the harmful effects of ozone and air pollution), arising from greenhouse gas CO_2 accumulation [99]. Despite this, international competitions are often organized in large cities. For instance, at the occasion of the Beijing Olympics some visiting athletes were seen wearing a mask to protect them from heavy dust and pollution. Air pollution is a heterogeneous mixture of gases (e.g., ozone, carbon monoxide, sulfur dioxide, nitrogen oxides) and air-suspended mixture of solid and liquid particles, namely particulate matter [100–102]. In addition to commonly reported symptoms including cough, throat irritation, chest discomfort, skin or eyes irritations, these pollutants are likely to cause a myriad of other adverse effects in urban outdoor practitioners, affecting their health substantially. This would possibly include deteriorated lung function [103,104]; increased levels of inflammatory markers and altered immune function in the pulmonary system [103,105]; myocardial infarction, stroke, atherosclerosis, bronchitis and asthma [106–111]. As ventilation rate and breathing frequency are elevated during exercise and breathing switches from a nasal to a mouth-predominance [112], this results in a large air pollution inhalation when exercising outdoors [113,114]. Furthermore, a possible link between air pollution exposure and adverse effect on cognition (e.g., via an exercise-induced decrease in human Brain-Derived Neurotrophic Factor serum concentration) has recently been highlighted (see [23,115] for details) but its effect on impaired outdoor sport performance has not been elucidated yet.

Recommendations/Air Pollution

Both animal and human researches [116–118] suggest that a higher fitness level might attenuate the deleterious effects of polluted air [119–122], through cardio-protective effects of physical exercise [1], potentially reducing the likelihood of air pollution-related mortality [121,122]. By practicing outdoor activities away from congested traffic and preferably in the morning (especially in summer months since elevation in ambient temperature increases air pollution-induced lung inflammation, and impairs exercise capacity [115]) will minimize the negative effect of exposure to polluted air on health. In the meantime, air quality indices (e.g., the Air Quality Index) have been developed to inform practitioners about the level of the various pollutants in the ambient air, thereby helping them to engage or not in physical activities.

2.5. Cold

More than 34 million individuals are traveling to mountainous areas every year (e.g., recreational and competition winter sports participants) and routinely face environmental challenges such as extremely cold temperatures (−1 °C per 150 m ascent) and changing ice or snow conditions [123]), thereby placing themselves at risk of cold injuries. With higher mortality rates in winter compared to summer [124,125], it is paramount to evaluate the consequences of exercising in cold conditions. Cold-weather environments include low air or water temperature (or both), strong winds, low solar radiation and often rain/water exposure, which considerably increase convective heat transfer coefficient [126,127]. Cold-related injuries can be classified into three categories: hypothermia (low core temperature, <35 °C), frostbite (freezing injuries of the extremities), and nonfreezing injuries of the extremities (for details, see [128]). Cold-induced asthma and acute cardiovascular events such as myocardial infarction [22] represent secondary outcomes. In addition, hands losing their dexterity or less sensitive fingers, impaired coordination, visual acuity, general alertness or reflexes are other negative manifestations of cold exposure. In cold environment, practitioners are more liable to make mistakes or wrong cognitive choices, as their decision-making deteriorates (e.g., rugby players dropping the ball on the coldest match days) [123], potentially increasing the risk of being injured as well. Prolonged exposition to cold environments can cause hallucinations, while the combination of cold and hypoxia exacerbate the magnitude of physiological adaptations [123]; for instance, hypoxia is known to increase cutaneous vasoconstriction during prolonged cold exposure [129]. Finally, "cold urticarial" arises during re-warming after cold exposure.

Although being more frequently observed in alpine, and some endurance or team sports [128], nonfreezing (or cold-wet injuries such as chilblains [130,131] and trenchfoot [130,131]) injuries are typically not a major concern for the great majority of athletes. This is because these injuries typically develop after at least 12 h of skin exposure to cold-wet (≤10 °C) conditions. Depending of the degree of core temperature decrease, hypothermia is classified as "mild" (35 °C to 33 °C), "moderate" (32 °C to 29 °C), and "severe" (<28 °C) [132,133]. Frostbite is a localized freezing of body tissues which occurs when tissue temperatures fall below 0 °C [134–137]. As frostbite progresses from distal to proximal and from superficial to deep tissues, the mostly exposed zones include nose, ears, cheeks-though the cornea and wrists, while even clothed hands and feet can be affected [138,139]. Similar to hypothermia, frostbite has defined stages, delineated by the depth of tissue freezing: frostnip (superficial skin <10 °C), mild (<−2 °C and extracellular ice crystals form), and severe (resulting in microvascular collapse at the arteriole and venule levels and conducting to tissue death) frostbite [132,134–137].

In all cases, individual factors modify the magnitude of the responses to cold exposure and thereby modulate the injury risk [132]. The main predisposing factors for hypothermia when exercising outdoor include health status (e.g., diabetes, hypoglycemia) [133,140], rain, wind [126], altitude, wet clothing, anthropometry (*i.e.*, low subcutaneous body fat [141–143], large surface area-to-mass ratios [144]), fatigue, age, gender and ethnicity. In particular, gender differences in thermoregulatory responses during cold exposure are primarily attributable to body fat content, subcutaneous fat layer, muscle mass, and surface area-to-mass ratio [145]. Physiological and anthropometric differences also suggest 2–4 times higher frostbite risk in exercising blacks Afro-Americans compared with whites Caucasian [146,147]. Due to differences in body composition and anthropometry, children are usually at a greater risk of hypothermia than adults during outdoor practice; however, the elderly (>60 yr) also have elevated risks because their physiological and behavioral responses to cold may become blunted with age [148,149]. Finally, while physical training and level of fitness only have minor influences on thermoregulatory responses to cold [148,150], improved physical fitness allows sustaining higher metabolic rates for longer exercise durations, and may therefore contribute to the maintenance of core temperatures in the "normal range" [22].

Recommendations/Cold-Related Injuries

Cold-weather clothing protects against hypothermia and freezing injuries by reducing heat loss through the insulation provided by the clothing and the trapped air within and between clothing layers [151]. Typical cold-weather clothing when practicing outdoors consists of three layers; firstly, an inner layer (lightweight polyester or polypropylene), which is in direct contact with the skin and does not readily absorb moisture, but wicks moisture to the outer layers where it can evaporate; secondly, a middle layer (polyester fleece or wool), providing the primary insulation; thirdly, an outer layer, designed to allow moisture transfer to the air, while repelling wind and rain [22]. Hats and knit caps can be used as well to prevent heat loss from the head [152]. Practically, socks should not fit tight and constrict blood flow and shoes can be up to one size larger. Additionally, avoiding being "overdressed", reducing the duration of a training session/competition or even canceling it, and offering warm facilities for warm-up (*i.e.*, of sufficient duration to stimulate core temperature) or recovery routines would help mitigating cold-related injury risks. The largest occurrence of hypothermia is often when practitioners do not expect it. Finally, hypothermia is best prevented by careful monitoring of ambient temperature, wind, solar load, rain, immersion depth, and altitude when engaging in outdoor activities [153].

2.6. Altitude

In mountainous environments, barometric atmospheric pressure declines with altitude ascent above sea level. Because barometric atmospheric pressure is a function of the surface temperature [154], global warming likely increases barometric pressure at every mountain summit, thereby reducing hypoxia severity and eventually ameliorate exercise capacity (yet expected changes would not be perceptible). However, the physical and physiological effects that accompany a decline in barometric pressure can have a dramatic negative influence on prolonged-duration exercise performance (e.g., running, cross-country skiing) [155], as arterial oxygen pressure is impaired [156]. Meanwhile, air density is modified by pressure changes, which would affect the motion of the human body and/or projectiles (balls) through the air upon altitude ascent [157]. Thus, improved explosive performance (jumping, sprint running and skating) may be produced given that more energy would be available for acceleration [156].

Exercise capacity in oxygen-deprived environments not only depends on the absolute terrestrial altitude, but also on the altitude difference with the normal height of residence, as well as other environmental conditions (e.g., heat, cold; see above sections). Except for mountaineering activities, most of training/competition altitude venues are ranging between low- (500–2000 m) and moderate-

(2000–3000 m) elevations [158]. Reduced oxygen availability is the starting point of a cascade of events that may eventually lead to high-altitude illnesses, the most common being acute mountain sickness (AMS). In more severe circumstances (generally occurring at altitude > 2000 m [159]) high altitude pulmonary edema (HAPE) and high altitude cerebral edema (HACE) may also occur (see [14] for details on medical care). The prevalence of such maladaptation to hypoxic stress is higher in mountain sport participants (e.g., alpinists) [91]. Nevertheless, practitioners with sickle cell trait who are heterozygous for the hemoglobin S gene and at risk for splenic infarctions even at moderate altitudes [160,161] can also face such problem, in addition to their increased risk for sudden death from exertional heat illness and rhabdomyolysis. Outside individual susceptibility [162], other factors may also increase the risk of developing high-altitude illness when exercising outdoors; those are altitude severity, rate of ascent, time of exposure, sleeping altitude, previous history of altitude illness, permanent residence at low altitude, and level of exertion while at altitude [162–164].

Recommendations/Altitude

While professional athletes use a broad range of natural/simulated altitude exposure interventions to acclimatize (*i.e.*, 3–5 days, 1–2 weeks and >2 weeks for low, moderate and high altitude performance, respectively) [165,166], most recreational winter sport participants do not have time and budget to elaborate scientifically-sounded altitude acclimatization regimens in line with their characteristics and needs. However, altitude acclimatization does not necessarily need to be rigidly planned. This implies that even informal trips to the mountains for hiking or camping during the weeks or months preceding an expedition or a competition likely may reduce the prevalence and severity of AMS symptoms [162] and enhance performance during subsequent altitude sojourns. While the scientific ground is not solid yet, it seems that acclimatization using hypobaric hypoxia could be more efficient than normobaric hypoxia [167]. Being exposed to altitudes similar to those of the upcoming sporting events during the prior weeks or months, individuals are in a better position to judge whether or not they are susceptible to face AMS. They will also be able to modify the aforementioned risk factors in order to determine what strategies work best for them to improve exercise tolerance. Generally, it is recommended to stage ascent up to 2000 m and thereafter to spend one day of acclimatization for each 300–500 m above 2000 m. Once at altitude, it is also recommended to increase water intake up to 3–5 L day^{-1} to counteract water loss when breathing cold dry air (called "insensible water loss" which can reach 1–2 L day^{-1}), urine output, sweat loss during thermal regulation [168]. Finally, acetazolamide or glucocorticosteroid drugs (both listed as prohibited substances by the World Anti-Doping Agency) could be prescribed in non-competitive individuals to prevent or attenuate AMS symptoms.

2.7. Snow and Avalanche

Over the past 30 years, global-warming has resulted in an elevation of the heights (~100–300 m) at which the ground is permanently frozen in the Mount Everest region [169]. Additionally, because of the snow cover decline, the snow season has been shortened by ~3 weeks in reference to the early 1970s in the Northern Hemisphere [170]. However, it is not the quantity but quality of snow that is crucial for safety while skiing or practicing other emerging snow-related activities (e.g., snowshoeing). A warmer, moister atmosphere increases the risk to produce heavier or wetter snow, which also rises the density of the snowpack [170]. Altogether, at altitudes where most of ski resorts are installed, this may increase risks for avalanches, unstable seracs as well as rock falls (as a result of the permafrost alteration). The increasing incidence of avalanches fatalities (*i.e.*, 150 deaths/year in Europe and North America) [171] comes together with the wider practice of winter sports, with backcountry/out-of-bounds skiers accounting for almost half of avalanche fatalities [172].

The avalanche fatalities literature describes asphyxia as the main cause of death, as a result of airway obstruction, mechanical chest compression, and rebreathing expired air conducting to hypercapnia and hypoxia [173]. Reportedly, the incidence of lethal and nonlethal mechanical trauma also ranges from 5% to 32% [173]. In victims buried in snow avalanches, the presence of an "air pocket, defined as any space surrounding the mouth and the nose, no matter how small, with a patent airway", is necessary for prolonged survival from burial [174]. In this case, while initial survival is due to an effective thermoregulation, acute hypothermia takes approximately 30 min to develop [175].

Recommendations/Snow and Avalanche

In response to the increased participation and emerging out-of-bounds-related activities, many efforts have been invested in avalanche education and awareness. However, adherence to prevention and safety practices is still low, with discrepant behaviors between sports. To convey avalanche hazard, specific information bulletin are available from internet and/or most of ski resorts meteorological offices. Checking such information, including eventual discussing avalanche hazard to ski patrol, is an integral part of preventive routine practices (*i.e.*, strategies reducing the chance to be involved in an avalanche) for individuals leaving the ski area boundaries [172]. Similarly, carrying safety gears (*i.e.*, beacon, shovel and probe) and being properly trained to use them are also strategies increasing dramatically chances to survive an avalanche [176]. In addition to increase (e.g., S1 + DVA transceiver, Ortovox Sportartikel GmbH, Taufkirchen, Germany) or extend (e.g., AvaLung™; Black Diamond Equipment Ltd., Salt Lake City, UT, USA) survival in the case of burial, newly developed avalanche airbags (e.g., Halo 28 Jetforce avalanche airbag pack; Black Diamond Equipment Ltd., Salt Lake City, UT, USA) also prevent critical burial [176,177].

2.8. Exercise-Induced Asthma and Bronchial Hyper-Responsiveness

Development of outdoor practice may increase exposure to inhaled irritants (air pollution) and resilient airborne allergens in the spring and summer [178]. One of the most widespread types of allergy relates to the presence of allergenic pollens in the air. Along with climate changes, the total amount of pollens measured in the ambient air has grown in recent years, probably because temperature and CO_2 concentrations follow a similar trend. Evidence suggests that air pollutants and anthropogenic aerosols may alter the impact of allergenic pollens by changing the amount and features of the allergens, thereby increasing human susceptibility to them [179]. In addition, practicing outdoor activities in cold ambient conditions [178] elevates the incidence of respiratory complications such as exercise-induced asthma (EIA) and bronchial hyper-responsiveness (BHR) [180]. This is generally accompanied by an increased number of granulocytes and macrophages in the lower airways [181], susceptible to increase asthma, seasonal allergy and rhinitis.

Prevalence of EIA and BHR is high in endurance sports—cross-country skiing [182,183] and biathlon and Nordic combined [183] but also cycling [184], long-distance running [178,185] and swimming [186]—as well as in explosive-based sports—figure skating [187,188], speed skating [183] and ice hockey [189] or track-and-field [185,190]. For winter sports, it is worth mentioning that cold inhaled air is recognized as the main factor responsible for airways obstruction [191]. While mechanisms of EIA and BHR are still debated [192,193], the association between the increased ventilation rate during exercise and the fluxes of heat and water developed within the airways seems prominent [194].

Recommendations/EIA and BHR

Similar prevention approaches than for air pollution could be adopted: allergic practitioners will benefit from considering pollen distribution forecasting to effectively plan their outdoor activities. However, to date, there is no dose-response threshold that has been firmly established for pollen sensitivity, where severity of symptoms also varies considerably between individuals. For example, while symptoms would occur with counts of 15 to 75 grain·m^{-3} per 24 h in highly sensitive individuals, levels up to 10 times greater may be required less-sensitive individuals [195,196]. In-depth clinical examination of "at risk" outdoor sports participants, with the addition of preventive medication (e.g., non-sedating antihistamines, intranasal corticosteroid spray) or immunotherapy programs is recommended [195]; *i.e.*, especially before peak airborne allergen ripening and release in the atmosphere. To efficiently prevent EIA and BHR, outdoor exercises should be avoided during the full pollen season. When training in cold conditions, protection equipment (e.g., heat and water exchanger Lungplus, Hörby, Sweden) could also be used to convert cold incoming ambient air into a warmer and more humid breathed air.

In summary, main risks, increasing risk factors and countermeasures for different weather-related conditions in outdoor sports participants are displayed in Table 1.

Table 1. Main risks, increasing risk factors and countermeasures for different weather-related conditions in outdoor sports participants.

Environmental Challenge	Main Risks	Increasing Risk Factors	Safety Measures
Heat	Minor symptoms: - Dehydration state, increasing core temperature. Major symptoms: - From moderate-to-severe heat illnesses.	- Caucasian, male, age >40 yr, - Obesity (body mass index >30 kg·m^{-2}), - Previous history of exertional heat-related injury, - Sweat gland dysfunction, - Viral illness, diarrhea, sickle cell trait, sunburn, - High humidity, - Non-heat acclimatization, - Sleep deprivation, - Low fitness levels, - Excessive heat exposure (warm-up).	- Weather forecasting, - Heat acclimatization, - Endurance training, - Pre-cooling, - Remove extra clothing, - Practice in cooler periods, with shorter exercise time and longer/more frequent recovery periods (shaded areas), - Hydration/salt balance strategies; start exercise euhydrated and with unlimited fluid access.
UVR	- UVR-related skin damage, - Melanoma and non-melanoma skin cancers.	- Accumulation of chlorofluorocarbons and other industrial chemicals in the atmosphere, - Reflective environments (snow, water), - Heat and/or exercise-induced sweat production.	- Solar UV Index forecasting, - Wear protective clothing, - Apply sunscreen protection factor 15+, - Avoid peak UV exposure hours and use shaded areas.
Lightning	- Dermatologic manifestations, - Musculoskeletal, cardiopulmonary and neurologic disorders - Post-traumatic headache, sleep disorders, irritability, psychomotor impairment and sympathetic nervous system dysfunction.	- Thunderstorms.	- Weather forecasting, - Identify safe location before practice.

Table 1. *Cont.*

Environmental Challenge	Main Risks	Increasing Risk Factors	Safety Measures
Air pollution	Minor symptoms : - Cough, throat irritation, chest discomfort, skin or eyes irritations. Major symptoms: - Deteriorated lung function, increased levels of inflammatory markers and altered immune function in the pulmonary system, myocardial infarction, stroke, atherosclerosis, bronchitis, asthma, cardiovascular and cerebrovascular diseases and adverse effect on cognition.	- Hotter ambient temperatures, - Accumulation of greenhouse gas CO_2, - Urban environment.	In addition to heat countermeasures: - Air quality indices forecasting, - Practice activities away from congested traffic and preferably in the morning. - Wear a mask.
Cold	- Hypothermia, frostbite and nonfreezing injuries, - Cold-induced asthma and acute cardiovascular events such as myocardial infarction, - Cognitive alteration, loss of dexterity, - Post-hypothermic hallucinations.	- Afro-American, female, age >60 yr, - Health status, anthropometry, fatigue, - Hypoxia, rain, wind, wet clothing, - Fitness level.	- Weather forecasting, - Cold-weather clothing protects, - Reduce the duration of practice, - Offer warm facilities for warm-up or recovery routines.
Altitude	- Acute mountain sickness (AMS), - High altitude pulmonary edema (HAPE) and high altitude cerebral edema (HACE).	- Individual susceptibility, - Previous history of altitude illness, - Sickle cell trait, - Permanent residence at low altitude, - Altitude severity, rate of ascent, time of exposure, sleeping quality, - Level of exertion while at altitude.	- Stage ascent up to 2000 m with one day of acclimatization spend for each 300-500 m above 2000 m - Increase hydration.
Snow and avalanche	- Asphyxia (airway obstruction), mechanical chest compression, and rebreathing expired air conducting to hypercapnia and hypoxia.	- Warmer, moister atmosphere, - Snowpack quality and density.	- Check specific information bulletin. - Carry safety gears.
Exercise-induced asthma and bronchial hyper-responsiveness *	- Exercise-induced asthma and bronchial hyper-responsiveness, - Allergies.	- Cold inhaled air, - Air pollution.	In addition to heat or cold and air pollution countermeasures: - Pollen distribution forecasting, - Avoid the full pollen season (for allergic individuals).

* Weather-related complications which may appear in addition to heat or cold and air pollution conditions.

3. Integration of the Human-Environment Interaction

3.1. From Direct Weather Indices to Thermal Stress Modeling

Among the basic weather elements (*i.e.*, air temperature, mean radiant temperature, absolute humidity and air movement), the most commonly used is air temperature. However, considering air temperature alone is not an accurate approach to evaluate the thermal stress level. In this view, various thermal indexes have been developed over time [19,28], most of them being two-parameter indices, to apprise stressful situations (see [18,197–199] for comprehensive reviews of these simple indices). For instance, the WBGT (ISO 7243, ISO/DIS 7933 1984 [200], originally developed by the US Navy [201]), weighted from dry-bulb temperature, natural wet-bulb temperature and black-globe temperature for outdoor condition or wet-bulb and black-globe temperatures for indoor conditions (with approximation formula being mostly preferred [202]) probably represent the most widely used and recommended index of heat stress. Similarly, Wind-Chill Temperature (ISO 11079 [203], determined from air temperature and wind speed at 10 m above ground level) is a reference to assess cold stress. These indices have been adopted in several world's leading sports medicine organizations position stands and guidelines on heat [12], cold [22] and altitude [10] challenges for high-level and recreational athletes. Whilst these consensus statements are fully available, the key is how well sporting organizations implement these recommendations received from leading experts. Very recently, criticisms surrounded the 2014 Australian Open Tennis Championships (*i.e.*, with some matches played at ~44 °C) since players were apparently not made fully aware of the tournament's extreme heat policy (*i.e.*, decision to suspend play with ambient temperatures > 40 °C and WBGT > 32.5°C, yet at the referee's discretion). Other findings arising from the Fédération Internationale de Volleyball's heat stress surveillance system indicate that available guidelines (e.g., ACSM [12]) are too conservative to guide informed decisions regarding whether or not it is safe to let a professional beach volley tournament continue when facing elevated heat [204]. While Budds [20] concluded that the WBGT can "only provide a general guide to the likelihood of adverse effects of heat", Brotherhood [21] demonstrated that, regardless of the environmental conditions, the internal metabolic rate is the main driver determining exercise-induced heat strain. Because available indices are neglecting significant fluxes or variables (e.g., cloud cover which influences the intensity of solar radiation, and wind speed [20]), they can never fulfill the essential requirement that for each index value there must always be a corresponding and unique thermo-physiological state (strain), regardless of the combination of the meteorological input values (stress) [7].

When exercising outdoor, thermal stress cannot be adequately represented with two-parameter indices, essentially because they lead to misrepresentations of the thermal environment. They cannot be implemented to approximate safety thresholds, be transferred to other locations. Considering the large spatial and temporal variations of microclimate conditions [205] it is, therefore, likely that alternative thermo-physiological modeling would have more merit [18,206,207]. In this view, assessment procedures combining the four basic weather variables including the short- and long-wave radiation fluxes of the atmosphere [208], with two additional behavioral variables, *i.e.*, the metabolic rate and clothing (insulation and moisture permeability characteristics) [209], namely heat budget models (e.g., Predicted Mean Vote (PMV [197]); Predicted Heat Strain (PHS, ISO 7933 [210]; Klima-Michel-Model

(KMM [211]) were developed to better define the human thermal comfort and derived thermal stress [197]. Although heat budget models are not considered as "Gold-standards", neither by researchers nor by end-users [7], it is worth mentioning that only thermal climate models that incorporate all parameters of the human heat budget can be used universally across all climate zones, regions and seasons [212].

3.2. The Concept of Universal Thermal Climate Index (UTCI)

Thanks to a multi-disciplinary cooperation (thermo-physiology, occupational medicine, biophysics, meteorology, bio-meteorological and environmental sciences) which allowed resolving limitations with respect to occupational settings imposed by the assumed activity level and clothing behavior, the UTCI [213] has been introduced. It corresponds to an equivalent temperature defined as a reference condition for subsequent comparison with all climatic conditions. The published literature on its development include a clothing model [214,215], a multi-node physiological model [216] (for better fitting under all metabolic rates, including very high activity levels), a single-sector thermo-physiology, consisting of a sweating heated cylinder "Torso" [217], followed by a validation and time efficient operational procedure, a regression approach based computerization [218], and assessment in real setting [219]. In particular, the UTCI meets the following requirements: (i) Thermo-physiologically responsive to all modes of heat exchange between the body and its environment; (ii) Applicable for whole-body but also for local skin cooling (frostbite) (see [220]); (iii) Valid in all climates, seasons, and time and spatial scales; and (iv) Effective for a wide range of exercise intensities [214].

As a result, the operational UTCI procedure, classified into ten categories of thermal stress ranging from "extreme cold stress" to "extreme heat stress" [221], appears useful and promising to assess the outdoor sport participants' physiological responses to humidity and radiative loads in hot environments, as well as to wind in the cold. UTCI procedure is in good agreement with the assessment of other standards (heat budget, two-node and multi-node thermo-physiological models) concerned with the thermal environment [222]. Bearing in mind that objectives and underlying assumptions may differ when comparing ergonomics standards, the utility of the UTCI procedure for cold exposure quantification remains to be confirmed [220]. To date, local cooling of exposed skin including frostbite risk (wind chill effects), should be best regarded as a transient, rather than a steady-state phenomenon [223–225]. It is, therefore, anticipated that the UTCI will significantly enhance application to human health and well-being in the field of public weather services, with also promising issues in outdoor sports practice. However, the expansion of the UTCI approach still requires considerable future research effort via systematic simulations using varying metabolic rate, clothing characteristics and exposure time to different thermal stress.

4. Future Perspectives and Conclusions

Over the last 150 years, thermal physiologists and bio-meteorologists have attempted to propose an index that would accurately define thermal stress across a range of environmental situations. Meanwhile, global warming, as well as the large spatial and temporal variation of microclimatic conditions [205] exert serious challenges for outdoor sports participants. While national public weather services programs recently integrate specific information to improve individual understanding of relevant environmental issue, this also complicates the definition of appropriate sport-specific guidelines to best protect practitioners' health.

Despite the obvious observation that a model can only be as accurate as its inputs, additional environmental parameters (e.g., sunlight, precipitation, air quality, UVR) that are known to significantly impact thermal stress levels, would need to be included when developing future models. With recent technological developments, measurement and inclusion of several environmental-related factors (*i.e.*, air pollutants, pollens) that were not possible even few years ago, we could improve the well-being of practitioners [226]. As an example, the Air Quality Index and Global Solar UV Index [227] are relatively simple measures to indicate potential airways and skin damages. Along with other weather forecast data, integration of these indexes may serve as a vehicle to raise public awareness about the necessity to adopt appropriate protective measures. While research efforts are being addressed to assess thermal comfort during different sport activities to improve the UTCI modeling, further investigation combining UTCI with Air Quality Index and Global Solar UV Index are warranted to better consider an overall environmental stress.

As mentioned earlier in the "*environmental-related risk factors*" section, tolerance to thermal extremes not only depends on morphological and physiological characteristics (*i.e.*, age, fitness, gender, acclimatization, morphology, and fat thickness being the most influencing factors) but also on psychological attributes since perception of exercise difficulty (mental awareness, perceptual strain) in challenging conditions is also highly individual. Overall, increasing thermal stress decreases self-motivation of sport practitioners [17], while subjective responses and fatigue patterns are affected by the surrounding microclimate [21,228]. Available human comfort models generally do not consider individual variations [229], while the environmentally-related perceptual research is still in its infancy [18].

To conclude, this review paper first offers an integrated view of the main environmentally-related risk factors and highlights the growing influence that they have on outdoor sports as a result of global warming (Table 1). We have also re-introduced the basis of the bio-meteorological approach and its merits for improving outdoor sport practice. Gaining knowledge about thermal physiology is imperative to improve our understanding of thermoregulatory mechanisms behind safer and more efficient outdoor sport participation. However, sport scientists and exercise physiologists are usually not well-acquainted with human comfort models and bio-meteorological knowledge. While this participates to limit potential transfers to outdoor sport applications, many omitted factors (e.g., precipitation, cloud cover) also question the ecological validity of laboratory-based studies. Incorporating perceptual responses and newly available meteorological variables (e.g., atmospheric pressure, precipitation and cloud cover, air quality, UVR), affecting substantially outdoor thermal stress, would considerably improve outdoor sport-specific modeling. Finally, integration of the interdisciplinary field of human bio-meteorology within the areas of sport sciences and exercise physiology is opening doors for promising research opportunities to improve the relevance of the available outdoor recreational and competitive sport guidelines.

Author Contributions

Franck Brocherie, Olivier Girard and Grégoire P. Millet conceived and designed the review; Franck Brocherie drafted the manuscript; Olivier Girard and Grégoire P. Millet revised it critically for important intellectual content; all authors approved the final manuscript for publication.

Conflicts of Interest

The authors declare no conflict of interest.

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