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Nixon, Ashley; Laouadi, Abdelaziz

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Effects of humidity on the health of occupants of dwelling units: A literature review

Authors: Ashley Nixon & Abdelaziz Laouadi

National Research Council Canada
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Acronyms

CBT – Core Body Temperature: the internal temperature of the human body, which is typically maintained around 37 °C.

HI – Heat Index: heat stress index accounting for the effects of air temperature and humidity.

H – Humidex: heat stress index accounting for the effects of temperature and humidity.

T_{wb} - Wet-Bulb Temperature: air temperature with 100% relative humidity.

RH – Relative Humidity: the percentage of moisture in the air at a given temperature.

EEG – Electroencephalogram: a device that measures electrical activity in the brain.

NREM - Non-rapid eye movement: the portion of the sleep stages that does not include rapid eye movement (i.e., Stage 1, Stage 2, Stage 3).

SOL – Sleep Onset Latency: the amount of time it takes to transition from wake to sleep.

SWS – Slow Wave Sleep: the deepest phase of NREM sleep, also described as deep sleep.

SE – Sleep Efficiency: sleep quality percentage calculated from the ratio of total sleep time to the total time spent in bed.

TST – Total Sleep Time: the total amount of time spent asleep in a sleep period.

WASO – Wake After Sleep Onset: the total amount of time spent awake after sleep onset.

N1 – Sleep Stage 1: the first stage of NREM sleep, characterized by light sleep.

N2 – Sleep Stage 2: the second stage of NREM sleep.

N3 – Sleep Stage 3: the third stage of NREM sleep, also called SWS.

REM – Rapid Eye Movement: the sleep stage characterized by rapid eye movements and increased brain activity.

SBS – Sick Building Syndrome: a condition where building occupants experience acute health/comfort effects linked to time spent in a building.

Executive Summary

Context

The proposed research work sought to address indoor overheating in the 2025 edition of the National Building Code (NBC). The initial phase of the task aimed to address overheating by establishing an acceptable (evidence-based) upper limit value for indoor air temperature in dwelling units. The standing committee on housing and small buildings (SC-HSB) accepted the proposed requirement for an acceptable upper limit indoor air temperature of 26 °C. However, the committee agreed that the proposed change did not adequately address the overheating issue and that further research is needed to understand the interacting effects of indoor humidity and temperature on overheating risk in dwelling units.

Study Objective

Through multiple meetings with the Overheating Task Group, the research objective evolved to focus on the exploration of the health effects of indoor humidity in dwelling units at non-extreme indoor temperatures (around the proposed value of 26 °C). The objective of this literature review was to better understand the possible effects of indoor humidity at non-extreme warm temperatures around 26 °C on the health of occupants of dwelling units to provide evidence-based technical support for a proposed change to address overheating in the National Building Code of Canada (2025 edition).

Method

The literature was reviewed using a search strategy in the Scopus database and publications recommended through informal conversations with experts in the field of human adaptation and physiology. Certain reviews were also screened for relevant articles. Inclusion criteria were applied to the potential 3000+ articles. This comprised of having documented indoor humidity measurements, health outcome(s), and having new empirical data. Studies only looking at extreme temperatures above 30 °C were excluded. Health outcomes were divided into three categories; symptoms, morbidity, and mortality.

Results

The literature search returned 13 studies evaluating the effects of indoor humidity and temperature on human health. Nine studies focused on sleep (as one of heat-related health outcomes), two studies examined symptoms such as sick building syndrome (a condition where building occupants experience acute health/comfort effects linked to time spent in a building) and heat-related symptoms, and two studies characterized morbidity through distress calls for respiratory distress and diabetic crises. As expected, no studies with mortality outcomes met the inclusion criteria. Most studies found an effect of humidity on health (11/13) at varying degrees of temperature; however, the array of possible humidity thresholds cause the question of an indoor upper-limit of humidity to remain unanswered when looking at non-extreme temperatures. The heterogeneity in the results (i.e., wide range in temperature/humidity levels having negative health effects) may stem from methodological limitations or from the variability in study design and outcome measures. Overall, results suggest that:

- sleep disturbances may occur as humidity and temperature increase, even below 26°C
- respiratory distress may increase with rising humidity, especially over 26°C

Conclusion

Based on this review, the possibility of negative effects of humidity on health at varying temperatures (> 20 °C) is conceivable. With global warming leading to an increase in environmental water evaporation, resulting in higher humidity across the globe, considerations for the effects of humidity on health may become increasingly relevant. With sleep seemingly being a more vulnerable state for high temperature and humidity, implications

as to which indoor space should be thermally controlled and/or during which time period, may be important. It would also be important for ongoing and future research to generate additional data to evaluate the impact of indoor environmental conditions and other confounding parameters on critical heat related health problems. These critical health problems include but are not limited to cardiovascular disease, asthma, diabetes, respiratory diseases, and mental health issues. This review was unable to determine whether indoor humidity has an effect on building occupant health at non-extreme temperatures (< 30 °C). The available scientific evidence supports the proposed requirement for an acceptable upper limit indoor air temperature to sufficiently protect Canadian occupants in dwelling units against overheating risk without explicitly considering the interacting effects of indoor humidity and temperature.

1 Introduction

Following the initial task by Codes Canada to address overheating in dwelling units by establishing an acceptable (evidence-based) upper limit of indoor air temperature that would mitigate the adverse effects on the health of heat-vulnerable occupants, the effect of humidity on health was put into question. Initial work on the health effects of temperature and humidity suggested a wet-bulb temperature limit of 35 °C (Twb; temperature air with 100% relative humidity, equivalent to 45 °C at 50% RH),[1] whereas, more recent work suggests that this upper limit should be lower (i.e., Twb of 30 °C, which is equivalent to 40 °C at 50% RH).[2-4] Mora,[5] reported the deadly upper limit for outdoor relative humidity in combination with outdoor temperature was a daily mean outdoor temperature of around 30 °C and 100% relative humidity. As air temperature increases, lower levels of relative humidity are needed to surpass this survivability threshold. Although this threshold is informative, it leaves several open questions such as;

- What are the indoor environmental conditions during extreme outdoor temperature events, given that most people remain indoors during these events and outdoor conditions differ from indoor conditions?[6]
- Does humidity also have negative effects on health at non-extreme temperatures (i.e., 26 °C) considering that the limiting effects of humidity on health seem to be relevant to sweating, which occurs at higher temperatures?
- Are there sub-populations (e.g., older adults, children, medical conditions, limited mobility) that may be more vulnerable to the proposed environmental condition (i.e., 26 °C at varying humidity levels)?

The following report summarizes the current, yet limited, literature on the topic.

Background

1.1 Effects of temperature on health

Several extreme heat events have been associated with high fatality rates,[7, 8] which is also true in the Canadian context.[9] A vast body of scientific research has explored the interplay between temperature and heat-related health consequences.[10, 11] See the report by Laouadi et al.[12] for an in-depth report on the literature pertaining to heat-related health consequences in the context of climate change and extreme heat events on indoor overheating risk.

As a summary, the human body thermoregulates in order to maintain a core body temperature (CBT) around 37 °C in order to adapt to both behavioural and environmental factors.[13] In addition to hormone levels, the body uses two main cooling systems, the first being through increasing peripheral skin blood flow when body temperature slightly increases and the second being sweat release. Sweat release is more efficient and is triggered when the first mechanism is insufficient.[14, 15] Although the exact mechanism that determines the temperature threshold which triggers the physiological cooling or warming processes remains unclear, the threshold is known to vary daily (in addition to monthly for women), and to be influenced by food intake, exercise, infection, anesthetic and other drugs (e.g., sedatives, nicotine, alcohol), acclimatization (i.e., physiological), and adaptation (i.e., behavioural and perceptual).[13, 16]

Heat related illnesses range from mild discomfort/symptoms to death in some instances. Heat-related mortality results mainly from dehydration, electrolyte deficiencies, and thermoregulation failures leading to heat stroke.[17] When determining the survivability temperature limit, initial work suggested that a wet-bulb temperature of 35 °C (T_{wb}; air temperature with 100% relative humidity, equivalent to 45 °C at 50% RH) was the upper limit, where constant exposure would not allow the body to cool itself leading to overheating, or hyperthermia.[1] Recent work has suggested that this upper limit may be lower with a suggested upper limit of a T_{wb} of 30 °C (equivalent to

40 °C at 50% RH).[2-4] These studies made the suggestion based on observations from young, healthy adults performing tasks at modest metabolic rates. This indicates the upper limit of T_{wb} could be even lower for vulnerable populations. One study looking at maximum T_{wb} values during the deadly 2003 European and 2010 Russian heat waves found that no data point exceeded a T_{wb} of 28 °C, suggesting an even lower upper limit for human health.[18]

1.1.1 Occupants vulnerable to heat

Sub-groups in the population are known to be more vulnerable to the effects of heat. Taken together these sub-populations cover a vast majority of the Canadian population, with individual susceptibility varying from time to time depending on one's age, health status, and current medications.

The way in which the body cools itself can create strain on some body systems (e.g., cardiovascular, respiratory, renal), especially in extreme conditions as the body attempts to maintain balance or compensate for the heat loss and gain.[19-22] Knowing that this additional strain is placed on these physiological systems, it is no surprise that individuals having disorders associated with these systems are at a greater disadvantage in extreme thermal conditions. Other medical disorders such as diabetes, multiple sclerosis, and spinal cord injuries are known to hinder thermoregulation mechanisms, making these individuals more vulnerable to high levels of heat, especially over sustained periods of time.[20, 23-25] Other factors that may lead the thermoregulation mechanism to be more susceptible are age and medication.

Across the lifespan, the thermoregulation system evolves. Infants generally have an underdeveloped thermoregulation system whereas older adults have an age-weakened thermoregulation system, making both these age groups vulnerable to overheating.[26-29]

Some medications are also known to interfere with the thermoregulation process. These include anticholinergic, antidepressants, anticonvulsants, psychotropics, benzodiazepines, and opioids.[29-31] Certain mental health disorders, such as schizophrenia have also been identified as potential mortality risk factors in extreme heat conditions.[32]

1.1.2 Sleep, circadian rhythms, and thermoregulation

Several studies have reported the association between high temperature and sleep disturbances.[33] One study in the United States of America (USA) reported an increase in hours of sleep when the number of days above 27 °C was reduced.[34] Another study done in an older sample in the Netherlands found that increasing indoor temperature by only 1 °C, when between 20.8 to 29.3 °C, raised the risk of sleep disturbances.[35] This study also highlights that the relationship between heat-related health problems in older adults was stronger with indoor temperature compared to outdoor values, emphasizing the importance of measuring indoor conditions.

Thermoregulation is known to vary across the day (i.e., follow a circadian rhythm), which implies that our thermoregulation capabilities may be more susceptible to adverse effects of heat and humidity at different times of the day if there is a greater regulation demand at the "wrong" time.[28] CBT decreases in the evening and starts increasing in the morning.[28] Mechanisms for heat dissipation (e.g., evaporative sweating and cutaneous vasodilation) have been shown to roughly follow CBT rhythms. Both sweating and vasodilation appear to be reduced when CBT is at its lowest (i.e., 3-4 am when CBT is typically at its nadir).[28]

If we turn to sleep architecture, during deep sleep (stage 3 sleep/ slow-wave sleep/ SWS), thermoregulation responsiveness is reduced. During rapid eye movement sleep (REM), which increases in proportion as the sleep period progresses, there is a greater reduction in thermoregulation responsiveness. High temperature and high humidity (which together add to the heat stress), are known to increase wakefulness and reduce SWS and REM sleep, thus, wakefulness appears to be the only state in which humans can suitably thermally regulate with high thermal environment conditions.[36] It can be speculated that this increase in wakefulness may be in part adaptive, allowing us to respond and to avoid serious adverse outcomes related to the inadequate environmental conditions.

Sleep being fundamental for proper brain functioning and numerous physiological processes that are important for maintaining good health it is not surprising that sleep disruption is associated with several short- and long-term adverse health effects, including mortality.[37] Poor sleep associated with poor environmental conditions (e.g., high temperature)[38] could exacerbate cardiovascular strain, considering the link between poor sleep and risk of cardiovascular diseases.[39] There is also increasing evidence that high temperatures are associated with an increased severity in sleep-disordered breathing.[40-42] Considering the high prevalence of sleep apnea in Canada, that most cases are unrecognized,[43, 44] and that there is an even greater prevalence in those with cardiovascular disease,[45] this may be a particularly large vulnerable sub-population. There is also the additional symptom of increased sweating associated with sleep apnea,[46] which may be relevant when discussing indoor humidity, and potentially the efficacy of CPAP (continuous positive airway pressure) machines.

An investigation led by CBC News in 2023,[47] measured summer indoor temperature and humidity across 5 Canadian cities in dwelling units that had minimal cooling. They found that indoor temperature was warmer than outdoor temperature measures and that heat index measures were above 28 °C across the 24hrs period. On average, temperature peaked around 7pm indoors and more than half of the data points remained above 26 °C just after midnight. In most cities, the relative humidity just after midnight was also above 50%. This highlights the fact that even though outdoor temperature may drop during the evening, this may take longer indoors, which has implications for sleep onset and sleep quality in general,

1.2 Effects of humidity on health

As mentioned above, the body uses two main cooling mechanisms to cool itself in order to maintain a CBT of approximately 37 °C. At low temperatures, where body cooling can be achieved by increased blood flow to the skin and slight sweating, the effects of humidity might not be noticeable from the psychological point of view (i.e., no significant effect on thermal perception). In contrast, at high temperatures and humidity (or high relative humidity) sweating may not be as efficient to cool the body since sweat evaporation decreases. In other words, in the context of high humidity, sweat evaporates from the skin at a slower rate which leads to sweat dripping off the body and the latter to feel warmer for longer periods of time and compensate by further increasing the sweat rate for longer, resulting in higher CBT. This also has implications for dehydration, since long exposure with inadequate water and electrolyte replacement (i.e., dehydration) will also lead to a reduced sweating rate in addition to worsened cardiovascular strain in heat.[48] High humidity can therefore lead to a double effect (i.e., body overheating and dehydration).[49]

Although beyond the scope of this review, it is important to keep in mind that high indoor relative humidity levels are also associated with other indirect negative health outcomes. High indoor relative humidity (> 55 RH%) is known to increase indoor pollutants such as fungus, allergenic mites, and off-gassing of certain products (e.g., formaldehyde), which all negatively affect health.[50-53]

1.3 Objectives

The objective of this review was to scan the literature to gain a better understanding of the possible effects of indoor humidity at non-extreme heat temperatures (< 30 °C) on noncommunicable health outcomes. This is being done to provide technical support for a proposed change to the National Building Code of Canada to address overheating in dwelling units by having indoor temperature set to no more than 26 °C during summer months.

2 Methodology

Using a narrative review approach, this report gathered relevant studies through a search strategy applied in the Scopus literature database and publication recommendations from researchers and experts in the field.

Studies were included based on the following criteria:

- Indoor humidity measurements are reported
- A health-related outcome is measured
- New empirical data is reported

Studies that exclusively looked at indoor temperatures above 30 °C were not included.

Health was divided into three categories; symptoms, morbidity, and mortality.

- **Symptoms** (including, but not limited to): fatigue, dizziness, nausea, fainting, heat cramp, heat syncope, heat exhaustion, heat stroke, body dehydration (thirst), sleep deprivation, etc. Medical conditions that are exacerbated by heat include cardiovascular diseases, respiratory diseases, diabetes, renal failure, etc.
- **Morbidity** indicators include hospital emergency visits, hospitalisation, hospital admission, emergency calls, medical services, ambulance call-outs, and outpatient visits.
- **Mortality** indicators include cause-specific or all-cause (non-accidental) excess deaths above locally-determined average death values.

2.1 Scopus literature database

With the help of the NRC's Intelligence and Analytics team, several iterations of a search strategy were generated. It slowly became apparent that using this approach would not efficiently capture all studies since humidity is often a secondary measure. This implies that humidity is often not mentioned in the title or abstract, which are the components to which a search strategy is applied.

On March 26th 2024, the below search strategy was applied to the Scopus database which returned over 3000 studies to be screened for inclusion. Due to the time restriction of this report, keywords that may be more relevant of environments below 30 °C were further applied to narrow the sample to n = 1459.

(TITLE (heat OR temperature) AND TITLE-ABS-KEY (((wet PRE/1 bulb) OR humidity) AND (health* OR hospital* OR illness OR sick* OR symptom* OR medical OR disease? OR cardio* OR heart OR respir* OR ((thermal OR heat) W/1 (strain OR comfort OR stress)) OR well-being OR wellbeing OR morbidity OR mortality OR death OR fatal* OR lethal OR distress))) AND NOT (nano* OR animal OR virus OR viral OR gene OR genetic OR chicken OR turkey OR poultry OR horse OR pig OR swine OR sheep OR ovine OR cattle OR cow OR bovine OR agricultur*)*
(Additional keywords - dehydration, vulnerable, indoor, sleep, distress)

Through the various iterations of the search strategy, a total of 2 articles[54, 55] were included from this approach.

2.2 References from experts

To supplement the review, experts in the field of human adaptation and physiology were informally approached to gather more insights on the topic and for potential references.[56, 57] A total of 4 articles[58-61] were included through this approach. Recommended review references were used in the introduction of this report. Another article[62] was added from non-structured literature searching.

2.3 Review references

The systematic review by Chevance et al.[63] was recommended by an expert in the field. References were screened and yielded 4 included articles.[64-67]

The studies looking at both temperature and humidity in the review by Lan et al.[33] were also included. Out of the possible 4 articles,[64, 68-70] 2 were added, 1 was already included in our database, and 1 was added to the discussion since it was slightly out of scope.

3 Summary of results

Table 1. Full summary of reviewed studies

Category	Reference	Study Type	Temperature (°C)	Humidity	Population	Age (average years)	Location	Köppen Class.	Time of year	Applicable conclusions	(-) No effect found (>26<) Effect found in ranges below or above 26 °C (**) Effect found at 26 °C
Symptoms	55	Field	~10 °C to 36 °C (Summer) see article fig. 1	~8mb to 33mb (Summer - vapor pressure) see article fig. 1	Apartment residents	Median: 28.5 (2-90)	New York City, USA	Cfa	Nov - Mar, May - Sep	**Heat-related symptoms** associated with perceived temperature, but not with measured indoor temperature or humidity.	-
Symptoms	54	Lab	26 °C, 30 °C, 37 °C	50%, 70% RH	College students	~ 22.5	Changsha, China	Cfa	-	Between 26 °C to 30 °C, increasing RH from 50% to 70% results in no difference in **SBS** symptoms.	>26
Symptoms - Sleep	66	Field	24.1 °C to 30.2 °C	50% to 83% RH	Young adults	25.5 ± 5	Shanghai, China	Cfa	Summer	**Sleep** - SWS and SE are not associated with RH. (24.1 °C to 30.2 °C/ 50% to 83% RH)	-
Symptoms - Sleep	**64**	**Field**	**Spring - 22.5 °C Summer - 27.8 °C Fall - 18.4 °C Winter - 10.3 °C**	**Spring - 64.8% RH Summer - 72.6% RH Fall - 69.8% RH Winter - 59.4% RH**	**Older males**	**64 ± 1**	**Tsukuba, Japan**	**Cfa**	**4 Seasons**	**Sleep – (Across seasons) increased RH is associated with waking up earlier, less TST, more WASO, less SE. (Comparing summer to other seasons) increase in wake time and reduced SE.**	**>26<**
Symptoms - Sleep	**67**	**Field**	**Averaged bedroom: 15.4 °C (fall), 9.5 °C (winter), 27.7 °C (summer)**	**Averaged bedroom: 69.2% (fall), 59.9% (winter), 74.0% RH (summer)**	**Healthy older adults**	**65.8 ± 2.6**	**Tsukuba, Japan**	**Cfa**	**Fall / Winter / Summer**	**Sleep is significantly worse in the summer (27.7 °C/ 74% RH) compared to other seasons (<15.4 °C/ 69.2% RH).**	**>26**
Symptoms - Sleep	**59***	**Field**	**14 °C to 32.2 °C**	**16% to 79% RH**	**Community dwelling older adults**	**79 ± 7.2**	**Boston, USA**	**Dfa**	**Oct 2021 - Feb 2023**	**The optimal sleep condition was found to be between 20 °C and 25 °C/ 50% RH. When temperature increased from 25 °C to 30 °C SE was negatively affected (not considering humidity). (Data was averaged across seasons)**	**>26**
Symptoms - Sleep	60	Lab	17 °C, 20 °C, 23 °C	40%, 55%, 70% RH	Healthy male university students	22.8 (21-24)	Shanghai, China	Cfa	Dec - Jan	Objective **sleep** (SOL, SWS, SE, TST) was negatively affected at 23 °C (both 55% and 70% RH) compared to lower environmental conditions.	<26

Category	Reference	Study Type	Temperature (°C)	Humidity	Population	Age (average years)	Location	Köppen Class.	Time of year	Applicable conclusions	(-) No effect found (>26<) Effect found in ranges below or above 26 °C (**) Effect found at 26 °C
Symptoms - Sleep	**58***	**Field**	**18 °C to 22 °C, 28 °C to 30 °C, 30°C to 33 °C**	**heat index - can't separate**	**Older adults**	**72.8 ± 7.0 (60-95)**	**Canada - QC**	**Dfb**	**Jun - Nov**	**The probability of trouble sleeping started increasing quicker after 20 °C/HI (over the summer and fall months).**	**<26**
Symptoms - Sleep	**65**	**Field**	**26 °C to 32 °C**	**36% to 88% RH**	**Community dwelling older adults**	**>65**	**Shanghai, China**	**Cfa**	**Jul - Aug**	**As RH increased light sleep stages (i.e., N1, N2) decreased.**	**>26**
Symptoms - Sleep	69	Lab	26 °C, 32 °C	50%, 80% RH	Young, healthy males	25 ± 3.8	Japan	-	Aug - Sep	Objective **sleep** (more wake, poor SE, less N1 and N2) worst in the T/ RH conditions of 32 °C/ 80% versus 26 °C / 50%. Not all sleep variables were significantly different (N3, REM, SOL).	>26
Symptoms - Sleep	68	Lab	29 °C, 35 °C	50%, 75% RH	Young, healthy males	22.7 ± 1.6	Kanto, Japan	Cfa	Aug - Sep	No differences in objective **sleep** at 29 °C (both 50% and 75% RH). Effects on sleep were found at higher temperatures.	>26
Morbidity	62	Field	13.5 °C to 33.5 °C (daytime) 12.8 °C to 29.3 °C (night)	4.7g/kg to 17.9 g/kg	New York residents	Patient (52) Control (35.5)	New York City, USA	Cfa	Jul - Aug	**Respiratory** calls increased (NS) when HI rose above 26 °C.	**
Morbidity	61	Field	Range missing	Range missing	Atlanta residents	Medians: Diabetes cases: 58 (3-96) Respiratory Cases: 57 (2-97) Controls: 51 (0-100)	Atlanta, USA	Cfa	May - Sep	Emergency calls for **diabetes** increased when the HI went from 30 °C to 31 °C. **Respiratory** calls increased when HI went from 34 °C to 35 °C.	>26

Notes. Conclusions/results beyond the scope of this report are not reported in this table. Relative Humidity (RH); Humidex (H); Heat Index (HI); Sleep Onset Latency (SOL); Wake After Sleep Onset (WASO); Total Sleep Time (TST); Sleep Efficiency (SE); Slow Wave Sleep (SWS); Stage 1 Sleep (N1); Stage 2 Sleep (N2); Stage 3 Sleep (N3); Rapid Eye Movement (REM); Sick Building Syndrome (SBS); Non-Significant (NS). *Indicates studies done in a similar climate to that of Canada. **Bolded** studies are those done in vulnerable populations. Temperature and humidity represent indoor measures. The summary of each included study can be found in Appendix A. The map of Canada with the Köppen climate classification can be found in Appendix B.

4 Critical review

This review searched the scientific literature for studies that quantified health outcomes (i.e., symptoms, morbidity, mortality) in relation to different humidity conditions, in mild temperatures (< 30 °C). Of the included studies (n = 13; Figure 3), eleven studies found an effect of humidity. That being said, the high degree of heterogeneity in humidity levels across the studies causes the question of an indoor upper-limit of humidity at non-extreme temperatures to remain unanswered.

Only one study demonstrated 26 °C as a potential heat index (HI) threshold, which was associated with a non-significant (p = 0.053) increase in respiratory distress calls.[62] Three studies found an effect of humidity and temperature on health below 26 °C,[58, 60] of these, one also found an effect on health above 26 °C,[64] and seven studies found an effect of humidity and temperature only occurring above 26 °C.[54, 59, 61, 65, 67-69] Most studies focused on the effects of humidity and temperature on sleep (n = 9), two studies touched on other symptoms such SBS and heat-related symptoms, and two studies touched on morbidity through distress calls for respiratory distress and diabetic crises. No studies with mortality outcomes met inclusion criteria. The fact that no studies were found pertaining to mortality is similar to the outcome of the WHO Housing and Health Guidelines systematic review that also did not find any studies on indoor temperature (not accounting for humidity) and mortality.[6 - Chap 5] This echoes the difficulty in studying mortality and dwelling conditions, as well as one of the reasons epidemiological studies have been developed based on national mortality and outdoor temperature databases to address overheating policy issues. Composite biometeorological indices, humidity as a confounder, humidity as an effect modifier, and limitations of epidemiological and weather data have been identified as factors explaining why epidemiological studies on humidity and heat-related health outcomes have not reflected physiological mechanisms.[29]

4.1 Health symptoms associated with indoor RH

Two studies focused on other health symptoms, which were sick building syndrome (SBS; e.g., skin/eye/noise dryness, fatigue, concentration, dizziness) and heat-related symptoms (e.g., dry skin, clammy skin, confusion, hallucinations). Both studies did not find an effect of humidity occurring at 26 °C. The study by Zuo et al.[54] looking at SBS symptoms found that increasing humidity from 50% to 70% only became an issue at 37 °C (i.e., increasing humidity from 50% to 70% at 26 °C and 30 °C saw no differences in SBS symptoms). This study was, however, done in young and healthy adults over a short exposure time (190 minutes). The second study looking at heat-related symptoms[55] found that they were associated with perceived temperature and not measured temperature or humidity, reducing its utility for specifying a code limit.

4.1.1 Sleep implications

Based on the assumption that humidity would have health impacts in relation to sweating efficiency, which typically occurs at higher temperatures, it was not expected that two studies[58, 60] would find negative effects on sleep occurring below 26 °C. That being said, their study design (i.e., no constant temperature and varying humidity levels) makes it unclear that the negative effects are due to temperature or humidity. The study by Cao et al.[60] found a negative effect on sleep occurring at 23 °C and 70% RH compared to 20 °C and 55% RH. This study was conducted in a laboratory with young adults during the winter months of a warm and humid climate. All participants had a comparable bed microclimate and daily behaviors. In contrast, the study by Teyton et al.[58] found self-reported sleep problems increasing at a humidex (H) of 20 °C. This study was conducted with older Canadian adults during summer months and the bedding system, as well as, daily behaviour was not controlled for.

Of the other included studies that measured sleep outcomes, one study found that increased relative humidity had associated negative effects on sleep occurring both below and above 26 °C.[64] One study found no relationship with RH,[66] and five found negative effects of humidity occurring above 26 °C on sleep.[59, 65, 67-69] See table 1 for details. Although all these studies were measuring sleep, they were doing so with different technologies and characterizing sleep in different ways. Some used wearable devices, such as actigraphy, which provides researchers with a sense of sleeping patterns over longer periods of time in a home setting.[59, 64-67] These devices typically quantify sleep based on patterns of body movement, light levels, and body temperature and estimate sleep periods and other "high" level sleep metrics (e.g., wake after sleep onset (WASO), sleep onset an offset time, SE). In contrast, laboratory grade devices, such as polysomnography, directly measure sleep (e.g., % of time spent in each sleep stage, WASO, sleep onset and offset time, SE, etc.), but usually over a shorter period of time (e.g., 1-2 nights) and in a non-naturalistic environment.[60, 68, 69] One study only relied on self-reported sleep related symptoms.[58] These different approaches result in studies and sleep metrics being slightly less comparable.

One review on humidity and sleep outlined several studies that demonstrated the association between high humid heat and sleep disruptions.[71] Different mechanisms explaining how humid heat may negatively affect sleep are also proposed, but require further research. Namely, sleep may be affected via the homeostatic pathway, where humid heat may interfere with adenosine accumulation in the basal forebrain.[71] There may also be disruptions occurring in the thermoregulatory feedback loop to the central nervous system which may disrupt sleep onset and circadian thermoregulation.[72] A particular note should be made about the relationship between sleep disturbances and health symptoms, morbidity, and mortality (e.g., hypertension, diabetes, cardiovascular disease, suicide).[73-76] Although humidity at lower temperatures may not have direct or clear effects on morbidity or mortality, it is conceivable to see how chronic sleep disturbance, in part due to high humidity levels, could lead to increased risks of negative health symptoms, morbidity, and mortality, especially in vulnerable populations such as older adults.[77] With a review on high temperature/humidity demonstrating negative effects on sleep and based on the current review's included studies at low temperatures and humidity, implications with regards to which room to cool arise.

4.2 Morbidity

Two studies in this review reported on morbidity. One study found that an indoor HI of 26 °C and above saw an increase in emergency respiratory calls.[62] This study also reported the average daytime indoor temperature to range from 13.5 to 33.5 °C and 12.8 to 29.3 °C during the night. Indoor humidity ranged from 4.7 to 17.9 g/kg. In contrast, another study found that these types of calls, along with emergency calls related to diabetes, increased at a higher HI (i.e., 30°C).[61] These conflicting results for respiratory related calls may be explained by the fact that temperature and humidity were reported as an index, which renders the results unclear as to whether the increase in distress is due to an increased humidity level, temperature, or both. Both studies recorded the indoor temperature and humidity levels when responding to the distress call, which provides the indoor conditions near in time to the event. That being said, the conditions that led to the distress call are typically those prior to the response to the call, and whether the participants were in a different environmental condition prior to the call is unclear.

4.3 Methodological factors

4.3.1 Humidity metrics

The heterogeneity found in the results of this report may stem from several methodological limitations. These align with a recently published commentary tackling the possible reasons as to why there is a disconnect between the epidemiological literature on humidity heat-related health outcomes and the physiological/health literature.[29] One of the proposed reasons was the use of a composite index (e.g., relative humidity, humidex, humidity index) over water vapor mass-based variables (e.g., absolute humidity). At 100% relative humidity (RH) the air is saturated and the wet bulb, dry bulb, and dew point temperatures are equivalent.[78] RH is a ratio of the actual amount of water vapor in the air to the maximum amount of water vapor that can exist in the air at a given temperature. This implies that changing the temperature will affect the relative humidity. Absolute humidity is not affected by temperature changes, except if the air is cooler then the dew point, which makes it a more accurate metric for reporting humidity.[78] In this report, 11/13 studies reported an index, such as RH, which means it was not possible to attribute changes solely to humidity or temperature, which renders the effects of humidity undistinguishable from temperature.

4.3.2 Environmental and seasonal variations

Other environmental parameters, such as types of heat (i.e., indirect or direct sun) or ventilation/air conditioning, may have also played a role in the effects.

The diversity in climate and the different time points of the year in which the studies of this review were conducted may also explain in part the heterogeneous results. In other words, acclimatization to a given climate is known to influence the absolute threshold temperature at which the body starts to thermoregulate.[16] Studies done at the start of a new season may see different results than at the end.[79] Studies completed across several seasons may also introduce additional variation. Cumulative effects of exposure (i.e., several hours or days) versus acute exposure should also be considered when interpreting results. In this review, 4/13 studies were field studies (generally longer exposure) and 9/13 were done in a laboratory (generally shorter exposure). Exceptionally, both morbidity studies[61, 62] were field studies but measured acute indoor conditions when responding to emergency calls.

4.3.3 Population diversity

Other possible explanations for the diversity in results can be attributed to the different populations studied (e.g., medical disorders, age, medication), or the lack of control or proper documentation of the sample diversity. In this review, 5/13 studies were done in older adults and the other studies were done in young adults (5/13) or residents in a given area (3/13).

Other factors that may introduce noise into the results may be the lack of control over the bed micro climate (e.g., warmer bedsheets), daily behaviour (e.g., level of exercise), and circadian timing (e.g., exposure to high humidity around the lowest CBT point (early morning) versus later in the afternoon at the highest CBT point).

4.4 Limitations

The chosen non-systematic approach to reviewing the literature might have led to some articles being missed, although this risk is present with any review approach. Typical search strategy approaches could not be effectively used for this report because humidity has often been a secondary measure in temperature studies, also reflecting the difficulty in studying humidity. As outlined across this report, many factors can cloud the interpretation of the effects of humidity on health (e.g., hydration, medication, health conditions, age, physical activity). The supplemental suggestions from the consulted experts may have also created bias in the dataset based on their field of expertise (i.e., over-representing certain fields). That being said, their field of expertise can be considered broad enough to reduce this limitation and the supplemental material represents only a small number of the included articles.

Another limitation stems from the large variability in the way in which humidity was reported across studies (e.g., HI, H, RH). Not only does this limit comparability across studies, the nature of an index also does not allow to separate the effects of humidity from temperature. Additionally, certain studies reported humidity and temperature as a range, and this, over long periods of time which hinders the ability to associate specific environmental conditions to health effects and determine a humidity threshold at 26 °C. This is additionally limited by the small number of summertime studies with room temperatures above or below 26 °C (for any humidity).

Considering that acclimatisation is an important factor and the that most included studies were done in climates that are not currently found in Canada, the generalizability of these studies to the Canadian context is limited.

That being said, changes in climate zones are projected to change in coming years[80], which means certain included studies in this report may become relevant.

Only five of the included studies investigated the health effects of vulnerable populations, however, this was limited to older adults. This leaves several open questions as to what the health effects of humidity are in other vulnerable populations such as young infants and persons with medical conditions that affect thermoregulation.

The number of studies pertaining to sleep were disproportionate to other health outcomes. The specific parameters of the research question (i.e., humidity measure indoors at non-extreme temperatures with a health outcome) lent itself easily to sleep research protocols which is likely why more studies of this type met inclusion. More studies on other health outcomes measured within this frame is needed to have a full picture of the effects on health.

This critical review describes several challenges in connecting heat related health problems with measured indoor temperature and humidity and other confounding parameters. It would be important for ongoing and future research to generate additional data to evaluate the impact of indoor environmental conditions on critical heat related health problem including but not limited to cardiovascular disease, asthma, diabetes, respiratory diseases, and mental health issues.

5 Conclusions

Based on this review, the possibility of negative effects of humidity on health at varying temperatures (> 20 °C) is conceivable. With global warming leading to an increase in environmental water evaporation, resulting in higher humidity across the globe, considerations for the effects of humidity on health may become increasingly relevant. With sleep seemingly being a more vulnerable state for high temperature and humidity, implications as to which indoor space should be thermally controlled and/or during which time period, may be important. It would also be important for ongoing and future research to generate additional data to evaluate the impact of indoor environmental conditions and other confounding parameters on critical heat related health problems. These critical health problems include but are not limited to cardiovascular disease, asthma, diabetes, respiratory diseases, and mental health issues. This review was unable to determine whether indoor humidity has an effect on building occupant health at non-extreme temperatures (< 30 °C). The available scientific evidence supports the proposed requirement for an acceptable upper limit indoor air temperature to sufficiently protect Canadian occupants in housing and small buildings against overheating risk without explicitly considering the interacting effects of indoor humidity and temperature.

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Appendix A - Literature review summaries

Symptoms

Quinn, A., & Shaman, J. (2017). **Health symptoms in relation to temperature, humidity, and self-reported perceptions of climate in New York City residential environments**. International journal of biometeorology, 61(7), 1209-1220. https://doi.org/10.1007/s00484-016-1299-4

- A total of 40 New York City homes were monitored for temperature and vapor pressure (VP) and residents were surveyed (i.e., sleep quality, perceived temperature and humidity, and heat/humidity symptoms) over summer and winter seasons. Compared to outdoor measures, indoor temperature and VP were on average higher in both seasons. Self-reported sleep problems were associated with prior day's measured temperature in the summer and perceived temperature (not humidity). Symptoms associated with heat illness were found to be associated with perceived and not measured temperature. As a result, authors warrant future research on the relationship between heat vulnerability and the perception of comfort indoors.
- To consider – the perception of humidity was found to be a confounded by temperature (and vice versa) in the summer season.

Zuo, C., Luo, L., & Liu, W. (2021). **Effects of increased humidity on physiological responses, thermal comfort, perceived air quality, and Sick Building Syndrome symptoms at elevated indoor temperatures for subjects in a hot-humid climate**. Indoor Air, 31(2), 524-540. https://doi.org/10.1111/ina.12739

- This laboratory study compared 6 conditions (three temperature levels (26, 30, and 37 °C) and two relative humidity levels (50% and 70%) in 24 college students in China. Physiological response, thermal comfort, perceived air quality, and Sick Building Syndrome (SBS) symptoms were evaluated. Results suggest that the increase from 50 to 70% was not associated with changes in the targeted symptoms/responses in temperatures between 26 and 30 °C.
- To consider – this study was done in a sample of individuals that were exposed to hot-humid environments for at least one year, suggesting a sample with strong heat tolerance. They are also young individuals and exposed to the environmental conditions for approximately 3hrs.

Symptoms – Sleep

Xu, X., Lian, Z., Shen, J., Lan, L., & Sun, Y. (2021l). **Environmental factors affecting sleep quality in summer: a field study in Shanghai, China**. Journal of thermal biology, 99, 102977. https://doi.org/10.1016/j.jtherbio.2021.102977

- This summer field study in 41 homes in China aimed to understand how bedroom environmental factors (i.e., air temperature, relative humidity, CO_2 concentration, and noise level) influence sleep quality. Temperature in bedrooms ranged from 24.1 to 30.2 °C (more than half of bedrooms were below 27 °C) and RH from 50 to 83% (the average RH being 77.5 and 80%). Using actigraphy, they found that slow wave sleep (SWS) and sleep efficiency (SE) were not associated with RH values, however, SWS was correlated with air temperature, where decreased air temperature is associated with greater sleep quality. The most comfortable air temperature and RH value was found to be 24.8 °C and 65% RH.
- To consider – this study used actigraphy to report on sleep stages and not polysomnography (PSG) which is the gold standard, especially when speaking about sleep stages. The study was also done in young adults and the effects of light were not accounted for, which is known to influence sleep quality.

Tsuzuki, K., Mori, I., Sakoi, T., & Kurokawa, Y. (2015). **Effects of seasonal illumination and thermal environments on sleep in elderly men**. Building and Environment, 88, 82-88. https://doi.org/10.1016/j.buildenv.2014.10.001

- Across 4 seasons (1 year), 8 older adults in Japan volunteered to monitor their indoor environment (e.g., humidity and temperature) and sleep. In the summer, the average bedroom temperature was 27.8 °C and 72.6% RH. Results indicate that increased bedroom humidity was correlated with waking up earlier, sleeping less, waking up more after sleep onset (WASO), and less sleep efficiency (SE). These correlations were also true with bedroom temperature. Across seasons, summer saw significantly worst quality of sleep.
- To consider – data was averaged by season in a small sample size of only males in a climate different to Canada.

Okamoto-Mizuno, K., & Tsuzuki, K. (2010). **Effects of season on sleep and skin temperature in the elderly.** International journal of biometeorology, 54(4), 401-409. https://doi.org/10.1007/s00484-009-0291-7

- A total of 19 healthy older-adults participated in this in-home 5-day field study in fall, winter, and summer (located in Japan). Sleep, skin temperature, and thermal/humidity/comfort sensation were measured, as well as the temperature and humidity in the bedroom. Overall, sleep was significantly worst in the summer (27.7 °C/74% RH) compared to fall (15.4 °C/69.2% RH) and winter (9.5 °C/59.9% RH). Peripheral skin temperature measurement was increased and more central skin temperature measures decreased in the summer compared to fall and winter. Summer was also felt as more humid, warmer, the thermal sensation of the body was generally felt as cooler, compared to fall and winter. Overall, these results suggest that sleep in the elderly is disturbed in the summer compared to other seasons.
- To consider – This sample was majorly elder men and the indoor humidity was very high compared to what is generally seen in Canada.

Baniassadi, A., Manor, B., Yu, W., Travison, T., & Lipsitz, L. (2023). **Nighttime ambient temperature and sleep in community-dwelling older adults**. Science of the total environment, 899, 165623. https://doi.org/10.1016/j.scitotenv.2023.165623

- This field study was conducted in Boston from October 2021-Feburary 2023 in community dwelling older adults (>65 years old). Temperature, humidity, and sleep was monitored in 50 homes for 12 months. When looking specifically to relative humidity (at 22 °C), sleep efficiency was the only predictable sleep metric, which followed an inverted-U. The optimal RH value was found to be 50%. With respect to temperature, when bedroom temperature increased from 25 to 30 °C, sleep efficiency decreased by 5-10% which authors point to being a threshold associated with impairments in cognitive performance, next-day activity and stress, postprandial glucose response to breakfast, anxiety, mood, and fatigue. This study suggests that optimal ambient temperature for sleep efficiency and restfulness is between 20 and 25 °C. They also report that humidity had a smaller effect on sleep efficiency compared to temperature.
- To consider – Data was averaged across seasons and collected in a sample with relatively high socioeconomic status/standard of living.

Cao, T., Lian, Z., Ma, S., & Bao, J. (2021). **Thermal comfort and sleep quality under temperature, relative humidity and illuminance in sleep environment.** Journal of Building Engineering, 43, 102575. https://doi.org/10.1016/j.jobe.2021.102575

- This 9-condition (17, 20, or 23 °C with 40, 55, or 70% RH) sleep study was run in China with 6 young healthy males, were all subjects slept in all 9 conditions. Subjective and objective sleep quality were measured in addition to environment perception questionnaires. Before sleep, but not after awakening, humid sensation and preference were significantly worst at 70% compared to 40% and 55% RH. When comparing the optimal sleep condition (20 °C/55% RH) to the upper limit conditions (23 °C with 55% and 70% RH), both subjective (calmness of sleep, ease of awakening, satisfaction with sleep) and objective (SOL, SWS, SE, TST) sleep measures are significantly worst compared to the optimal condition.
- To consider – This study was done in a small sample of all males. This study also compared lower temperatures then the scope of this project, however, it demonstrates that sleep is negatively affected at high humidity (55 and 70%) and lower temperatures (23 °C).

Teyton, A., Tremblay, M., Tardif, I., Lemieux, M. A., Nour, K., & Benmarhnia, T. (2022). **A Longitudinal Study on the Impact of Indoor Temperature on Heat-Related Symptoms in Older Adults Living in Non-Air-Conditioned Households.** Environmental health perspectives, 130(7), 77003. https://doi.org/10.1289/ehp10291

- This Canadian field study measured in-home environmental conditions (temperature/humidity) of 277 older adults living without air-conditioning over 5-6months (summer). Heat-related symptoms were collected in parallel. Data was grouped in three categories based on 3 consecutive days at these temperatures (T1: 18-22 °C/ T2: 28-30 °C/ T3: 30-33 °C). The temperature and humidity were averaged for the 24hrs prior to the symptom survey for analyses. In the published text, authors indicate that the humidex results are similar to that of temperature. The authors provided additional graphs specific to humidex, which support the conclusion that sleep troubles increased quicker when the daily average humidex reached 20 °C. This increase was not as pronounced for other heat-related symptoms.
- To consider – This study was conducted in homes without air-conditioning and participants were mainly female (80.1%). The effects of humidity alone are difficult to interpret due to the use of a humidex. The interpretation of the graph can also be made that the 50% probably occurs at around 45-50 °C humidex.

Yan, Y., Lan, L., Zhang, H., Sun, Y., Fan, X., Wyon, D. P., & Wargocki, P. (2022). **Association of bedroom environment with the sleep quality of elderly subjects in summer: A field measurement in Shanghai, China**. Building and Environment, 208, 108572. https://doi.org/10.1016/j.buildenv.2021.108572

- This field study aimed to evaluate the typical sleeping conditions and how this affects sleep quality in elderly occupants of Shanghai (China) during summer months. A total of 40 participants completed the study and temperature, relative humidity, and CO_2 were monitored for six consecutive days. Objective sleep measures were collected with actigraphy. Results suggest that as RH increased by 1%, light sleep decreased by 3.1 minutes. There was also a significant combined effect of temperature and RH on light sleep. Overall sleep quality was significant affected by temperature and RH within the ranges of this study (26-32 °C/ 36-88% RH). As an aside, CO_2 may have an aggravating effect on the interaction between temperature and RH on REM sleep.
- To consider – this study used actigraphy to report on sleep stages as opposed to PSG. More than half of the nights had a SE below 85% (which is indicative of poor sleep).

Tsuzuki, K., Okamoto-Mizuno, K., & Mizuno, K. (2004). **Effects of humid heat exposure on sleep, thermoregulation, melatonin, and microclimate**. Journal of Thermal Biology, 29(1), 31-36. https://doi.org/10.1016/j.jtherbio.2003.10.003

- This Japanese sleep laboratory study compared sleep, body temperature, melatonin, heart rate, and sweat lose in two environmental conditions (26 °C/50% RH and 32 °C/80% RH) across nine young healthy male participants. Heart rate, sweat losses, core and skin temperature (except chest skin temperature) were all higher in the 32/80 condition, versus 26/50. Although some sleep variables were worst in the 32/80 condition (e.g., more wake, less NREM1, less NREM2, poorer sleep efficiency), no significant differences were found for other sleep aspects (e.g., NREM3, REM, sleep onset latency) and melatonin secretion.
- To consider – This study was run at the end of summer (after a period of acclimatization to a hot and humid climate), in a small sample of young males. A difference between these conditions does not suggest that sleep in the 26/50 condition was not affected.

Okamoto-Mizuno, K., Mizuno, K., Michie, S., Maeda, A., & Iizuka, S. (1999). **Effects of humid heat exposure on human sleep stages and body temperature**. Sleep, 22(6), 767-773. https://doi.org/10.1093/sleep/22.6.767

- This laboratory study compared sleep EEG (e.g., SWS, REM, TST, SOL) and core body temperature across four conditions (29 °C/50% RH; 29 °C/75% RH; 35 °C/50% RH; 35 °C/75% RH) during sleep. A total of seven young males from Japan, not previously acclimatized to a hot climate, participated in five nights (the first being an adaptation night). No significant sleep differences were found across 29 °C at 50% or 75% RH. Differences were found at higher temperatures, but this is beyond the scope of this report.
- To consider – This study is looking at the effects of humidity at a slightly higher temperature (>26 °C) and was conducted on a small sample of all males.

Morbidity

Uejio, C. K., Tamerius, J. D., Vredenburg, J., Asaeda, G., Isaacs, D. A., Braun, J., Quinn, A., & Freese, J. P. (2016). **Summer indoor heat exposure and respiratory and cardiovascular distress calls in New York City, NY, U.S**. Indoor Air, 26(4), 594-604. https://doi.org/10.1111/ina.12227

- This study compared the indoor heat exposure of cases resulting from 911 calls for cardiovascular (n=291) or respiratory (n=338) to controls (n=471). Indoor temperature and humidity were collected passively by paramedics. Although not statistically significant, when the heat index rose above 26 °C, there was an increased proportion of respiratory distress calls, but not cardiovascular.
- To consider – Same concerns as Uejio et al 2022. Sampling of indoor conditions was also not limited to one space, and patients might have re-entered the dwelling for care after exposure to outdoor conditions.

Uejio, C. K., Joiner, A. P., Gonsoroski, E., Tamerius, J. D., Jung, J., Moran, T. P., & Yancey, A. H. (2022). **The association of indoor heat exposure with diabetes and respiratory 9-1-1 calls through emergency medical dispatch and services documentation**. Environmental research, 212(Pt B), 113271. https://doi.org/10.1016/j.envres.2022.113271

- This case-control study explored the effects of indoor heat (and humidity) on the odds of 911 calls in Atlanta (USA) for diabetic (n=90) or respiratory (n=126) emergencies compared to controls (n=698). A temperature and humidity sensor were attached to EMT's medical bag and recorded the indoor environment when responding to calls. The odds of a diabetes emergency call increased in odds when the heat index increased from 30 °C to 31 °C and from 34 °C to 35 °C for respiratory calls.

- To consider – the results combined temperature and humidity into a heat index which does not allow to separate the humidity effect. The heat index also only represented a few minutes during the call response, and not during the progression of the symptoms.

Mortality

Based on the included studies for this report, no studies directly touched on mortality outcomes with regards to indoor humidity levels at temperatures around 26 °C.

Appendix B - Köppen climate classification

The Köppen climate classification system was applied to the included studies considering the acclimatization aspect of the heat-humidity-health interaction. As can be seen, only two studies in this review fall within climates found in Canada. See Figure B1 [81].

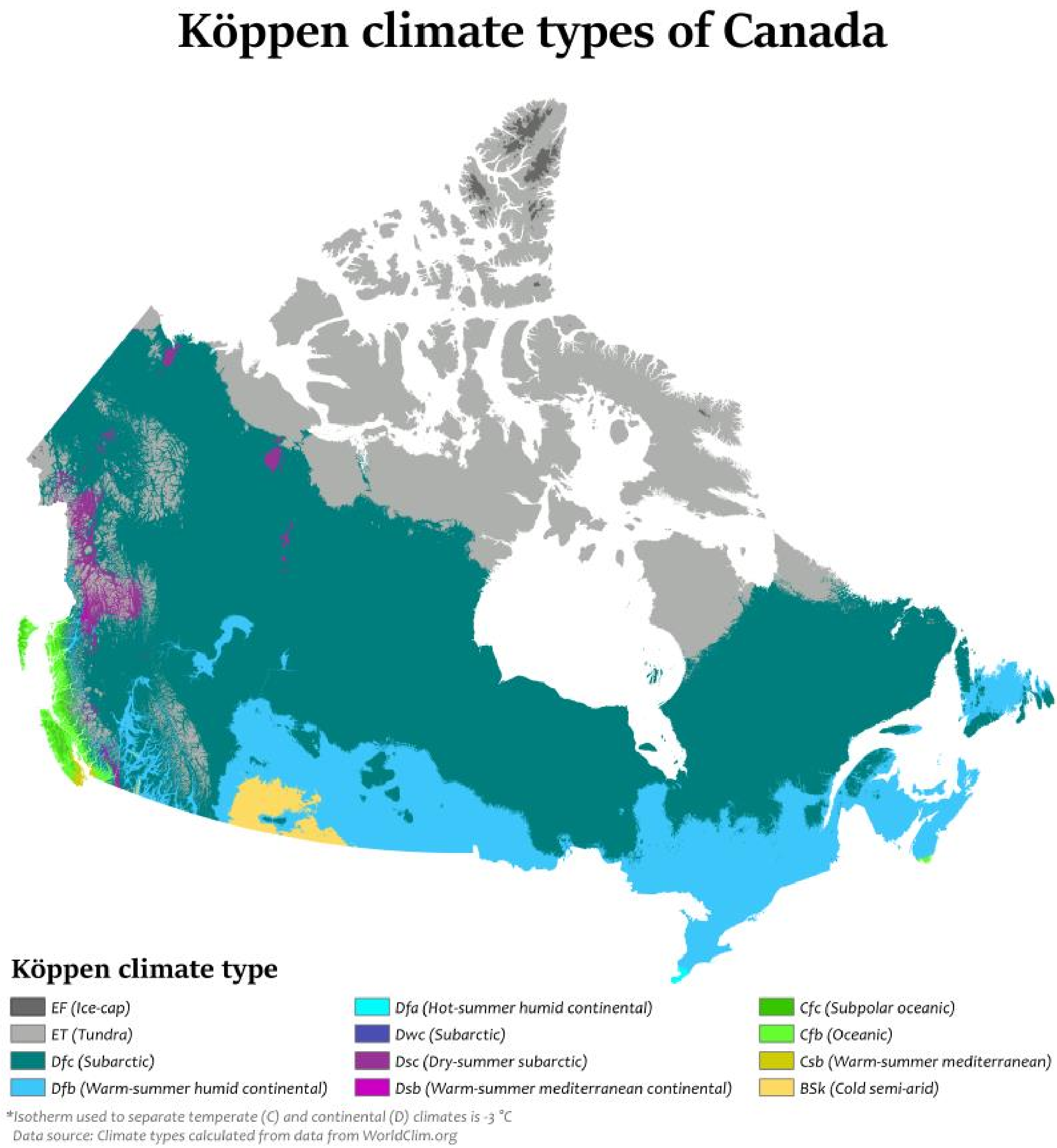

Figure B1. Köppen climate classification system types for Canada.