C25

# Building Durability in Extreme Cold Climates

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## ABSTRACT

*Building construction practices in the Arctic have largely been inadequate for energy efficiency and durability. Extreme cold temperatures and intense weather create challenging conditions for buildings. In addition, rapidly changing weather patterns in the Arctic are bringing warmer and wetter conditions to the area. Current modeling practices for building moisture and durability rely on typical 30-year data that is no longer representative of current conditions. Several hygrothermal models were developed for existing and energy retrofitted Arctic construction to evaluate the durability of buildings in an extreme and changing climate. Weather data from the most recent 10 years of observed weather in Utqiaġvik (Barrow), Alaska was used to develop new average and extreme weather scenarios. The results show that existing construction is moisture durable but energy inefficient and that energy retrofits will be hygrothermally complex and will require careful design to ensure moisture durability. This research highlights the data gaps in modelling efforts in extreme cold and changing climates.*

## INTRODUCTION

The extreme cold areas of the globe are seeing dramatic local climate changes due to global climate change. The annual temperature across the Arctic Coastal Plain of Alaska increased by 3.4°C (6.2°F) between 1970 and 2019; the annual precipitation increased by 12% in that same time (Grabinski and McFarland 2020). Figure 1 shows the dramatic changes in weather across Alaska and along the Arctic Ocean in particular. Climate change models predict that the Arctic could transition from snow-dominated to rain-dominated within the century (McCrystall et al. 2021). There is limited research on building moisture durability in extreme cold climates. For the purposes of this paper, an area with more than 9,300 heating degree C days ($HDD_{18C}$) (16,740 $HDD_{65F}$) is an "extreme cold climate." The Alaska Housing Finance Corporation calls this the Arctic Climate Zone (Wiltse and Madden 2018). In Alaska it covers areas along the Arctic Ocean coastal plain north of the Brooks Mountain Range. The Arctic climate zone also encompasses parts of northern Canada, Greenland, Iceland, Norway, Finland, Sweden, and Russia.

No literature was found on building durability in the Arctic climate zone; in fact, there are few articles that address building durability in climates with greater than 7,000 $HDD_{18C}$ (12,600 $HDD_{65F}$). Straube et al. (2016) included Yellowknife, Canada, which has 8,170 $HDD_{18C}$ (14,706 $HDD_{65F}$), in their analysis of high-R wall assemblies; they concluded that "sufficient exterior continuous insulation" by climate is important to moisture durability. Craven and Garber-Slaght (2014) evaluated common wall retrofit strategies for Fairbanks, Alaska, which has 7,515 $HDD_{18C}$ (13,527 $HDD_{65F}$) and found the most common retrofit of rigid foam on the outside of walls creates a double vapor barrier and creates moisture problems if not done with the proper ratio of exterior-to-interior R-value.

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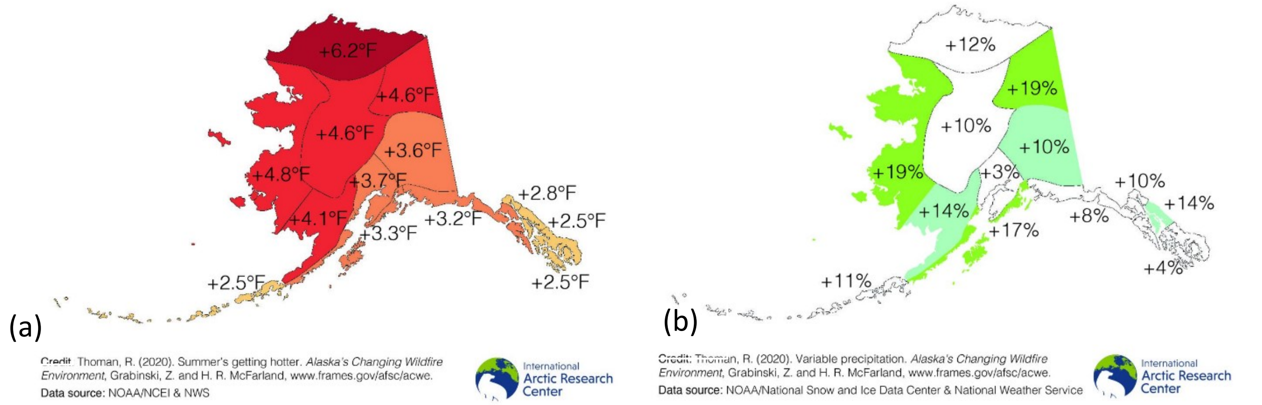


**Figure 1** Climate change trends from 1970 to 2019 across Alaska: (a) change in annual temperature and (b) change in annual precipitation. (Grabinski and McFarland 2020)

In 2008 Auld called for incorporating climate change into the design of Canadian infrastructure. Auld (2008) suggested a climate change adaptation factor be added to the standard safety factor for infrastructure engineering with a focus on extreme weather events. In 2010 Auld et al. provided further suggestions for specific Canadian building code changes to address climate change. Canada has been updating their national building code to account for climate change, with major changes to be implemented in 2025. However, the Arctic is already dealing with major climatic changes and building codes are not adequately addressing those changes.

Research into the effects of a rapidly warming Arctic beyond extreme weather events has been very limited. A warmer, wetter climate affects the moisture durability of buildings in varying ways. Warmer temperatures lower the freeze-thaw cycles of masonry, but more rain increases exterior wetting events (Lacasse, Gaur, and Moore 2020). Lacasse et al. conducted an assessment and literature review of what climate change will mean for different building compositions around the world. After an analysis of projected climate change in Canada, they concluded that buildings in Canada will be exposed during their lifetimes to drastically different climates than the typical historical climate data used in current codes (Lacasse, Gaur, and Moore 2020). In the less extreme climates of southern Canada, warmer winters lower the concern for freeze/thaw cycles in masonry walls (Sehizadeh and Ge 2016; Wells, Lacasse, and Sturgeon 2020). Junginerger et al. (2020) evaluated Canadian code compliant walls in Ottawa, Calgary, and Vancouver with climate change scenarios. In their analysis, wind driven rain is the defining characteristic for increased mold index across Canada. Defo and Lacasse (2021) found that modeled wood framed walls across Canada all had poorer moisture performance under the future weather scenarios when compared to baseline models. Nik et al. (2012) simulated attics in Sweden using different climate scenarios. They found that attic temperature and relative humidity will increase under climate change scenarios and may increase the risk of mold; they recommend mechanical ventilation as the best option to prevent mold in existing attics.

This paper provides a preliminary model of the durability of buildings in the rapidly changing Arctic and highlights the data needed to make those models more accurate.

## METHODOLOGY

Two typical above-grade wall assemblies in Utqiaġvik, Alaska, were evaluated using WUFI Pro 6.5 hygrothermal modeling software. WUFI Pro is a 1-D program that models heat and mass transfer in porous materials, requiring detailed hourly weather data for each location, including air temperature and humidity, global and diffuse solar radiation and cloud cover, precipitation, wind speed and direction. Using interior and exterior weather boundary conditions, it can model the heat and mass balance across a wall assembly. WUFI Pro has been validated in warm and moderately cold climates (Petersen and Harderup 2013; Künzel, Schmidt, and Holm 2002). The wall assemblies were evaluated using historic (1976-1990) typical year weather data (TMY3) as well as modern typical year, hot year, and cold year data for the most recent 10 years (2011 to 2020) of observed weather.

There are four Arctic weather data sets that are standard within WUFI Pro; none of this weather data is ideal for evaluating construction in the rapidly changing Arctic. Tromsø, Norway, is very temperate with a minimum temperature of -14°C (6.8°F). The data for Karasjok, Norway, is from 1976; the Kiruna, Sweden, data is TMY3 for 1995 to 2005 but is missing cloud index data; there is no information on how the data for Sodankyla, Finland, was developed. A WUFI weather file was developed for Utqiaġvik, Alaska, using 30-year typical meteorological year (TMY3) data. The TMY3 data for Utqiaġvik is from typical months between 1976 and 1990 and has no precipitation data. To complete the WUFI data file, precipitation data from 1999 (the earliest year hourly data could be found) was added to the TMY3 data. While this TMY3 data for Utqiaġvik is not ideal, it correlates well with the European Arctic historical data sets.

The modern weather datasets for a typical year, extremely cold, and extremely hot year were developed using hourly weather data from the years between 2011 to 2020. The three weather files were created by selecting representative typical, extremely cold, and extremely hot months from the 10-year dataset and concatenating the months to construct a full year of weather data, following the methodology described in Nik (2016). Since this work is focused on studying the impacts of climates with extreme and typical temperatures, the representative months are based on the outdoor dry bulb temperature. Future work involves creating a dataset for different precipitation scenarios including extremely wet, extremely dry, and typical precipitation years and studying the impact of these weather datasets on mold growth in the wall assembly. Table 1 summarizes the climate parameters for the generated modern and TMY3 weather files.

**Table 1. Comparison of weather parameters for different weather files**

| | Temperature °C (°F) | | | % Relative Humidity | | | Counterradation Sum kWh/m²year | Mean Cloud Index | Normal Rain Sum mm/year | Mean Wind Speed m/s (mph) |
|---|---|---|---|---|---|---|---|---|---|---|
| | Max. | Mean | Min. | Max. | Mean | Min. | | | | |
| **TMY3 (1976-2005)** | 16.1 (61) | -1.82 (29) | -41.7 (-43) | 100 | 84.19 | 45 | 2072.8 | 0.68 | 48 (1.9 inch/yr) | 5.44 (12.2) |
| **Typical Year (2011-20)** | 18.7 (66) | -9.42 (15) | -39.6 (-39) | 99 | 84.96 | 36 | 2162.3 | 0.7 | 106.9 (4.2 inch/yr) | 5.53 (12.4) |
| **Hot Year (2011-20)** | 19.4 (67) | -5.88 (21) | -39.6 (-39) | 100 | 85.5 | 52 | 2331.9 | 0.78 | 133.9 (5.3 inch/yr) | 6.04 (13.5) |
| **Cold Year (2011-20)** | 11.7 (53) | -13.6 (7.5) | -42.8 (-45) | 99 | 83.14 | 61 | 2109.1 | 0.81 | 71.6 (2.8 inch/yr) | 5.08 (11.4) |

## Hygrothermal Simulation

A typical residential building in Utqiaġvik, Alaska, was used as the basis of the model. The house has a 7.6m x 12.2m (25ft x 40ft) floor plan which aligns with the average home size in the North Slope Borough (Wiltse and Madden 2018). Typical, finished, residential-construction-height ceilings of 2.4m (8ft) were used to determine a conditioned volume of 227 $m^3$ (8,016$ft^3$).

The prevailing winds were generally from the south and the west but were not strongly in any one direction. However, because of the high latitude, the south face of the building will see more sun than the northern side. The shaded north side of the house will see much less drying by solar radiation than the south face. The north side of the building was modeled as it is expected to be the worst-case condition.

An estimated natural air exchange rate ("Energy Star Home Sealing Specification v1.0" 2001; Chan et al. 2003) of 0.3 changes per hour was determined from the North Slope Borough average pressure-induced envelope leakage rate of 4.5 ACH50 (Wiltse and Madden 2018) and an n-factor of 17 (Sherman, Turner, and Walker 2011). This estimated air leakage was used to inform the air tightness of the house and input into WUFI as a constant moisture source on the outer edge of the fiberglass using the WUFI air infiltration model IBP. Section 4-6 of ASHRAE 160 -Criteria for Moisture-Control Design Analysis in Buildings was used to determine the rain load on the wall (ASHRAE 2016).

A severely overcrowded typical home with 2 bedrooms and 7 occupants (Blake, Kellerson, and Simic 2007) was used for the analysis based on the 2018 Alaska Housing Assessment (Wiltse and Madden 2018). Using ASHRAE 160 residential design moisture generation rates, this equates to 0.54 kg/hr (1.19 lb/hr) of moisture. When combined with the natural air exchange rate of 0.3 $ACH_{nat}$, a typical interior temperature of 21°C, and the exterior temperature and RH, the interior relative humidity ranges from 45% in the winter to 70% in the summer. This is very high for an extreme cold climate; however, for a typical overcrowded home in Arctic Alaska, this high relative humidity is not unexpected (Singleton et al. 2017).

Two walls were evaluated: a residential wall assembly typical to the North Slope Borough (Figure 2a) and a typical energy retrofit wall (Figure 2b), based on IRC minimums for climate zone 8 ("2018 International Residential Code (IRC) | ICC Digital Codes" 2018). The homes are wood-framed (38mm x 140mm, nominal 2in x 6in) with fiberglass batt insulation filling the wall cavity. The exterior finish is painted T1-11 oriented strand board (OSB), which is an integrated sheathing and siding product that can be manufactured from OSB or plywood, with a weather resistive barrier comprised of a spun bonded polyolefin membrane. The IRC retrofit adds 1 inch of extruded polystyrene insulation and an air gap and new T1-11 siding.to the exterior of the wall The interior finish contains a class I vapor retarder with painted, interior gypsum wallboard. The wall assembly is comprised of separate components with different material properties that affect the movement of heat and moisture throughout the assembly. Table 2 details the components for the simulated walls.

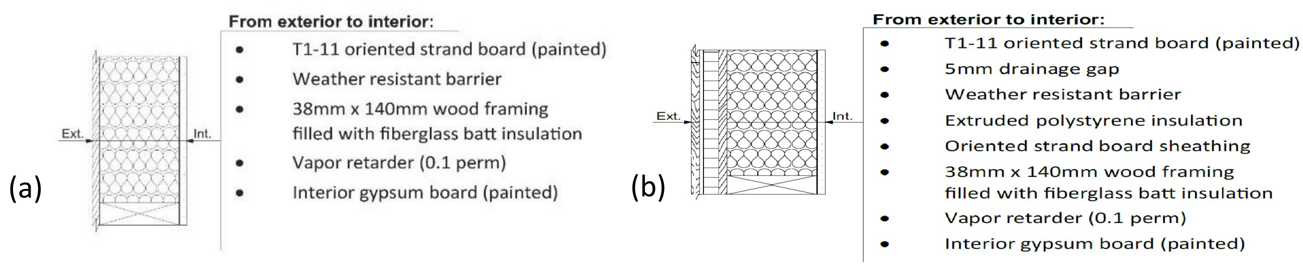


**Figure 2** Components of the evaluated wood-frame wall assemblies, (a) is typical to the North Slope Borough housing stock (nominal 2 in x 6 in frame cavity) and (b) is the IRC minimum retrofit wall (nominal 2 in x 6 in frame cavity).

**Table 2. Properties of simulated walls with the extra IRC components highlighted in green**

| Component | Layer Thickness mm(in) | Bulk density $kg/m^3(lb/ft^3)$ | Porosity $m^3/m^3$ | Spec. Heat Capacity J/kg K (Btu/lb R) | Thermal Conductivity W/m K (Btu/hr ft R) | Water Vapor Diffusion Resistance Factor[b] (perm) |
|---|---|---|---|---|---|---|
| **Exterior Oil Paint** | 1.0[a] (.04) | 130.0 (8.1) | 0.001 | 2,299.8 (1.78) | 2.30 (1.3) | 184.0 (17.8) |
| **T1-11 (Oriented Strand Board)** | 12.5 (.5) | 650.0 (40.6) | 0.950 | 1,879.9 (1.45) | 0.09 (0.05) | 812.6 (0.3) |
| **Rain Deposition Layer[c]** | 1.0[a] (.04) | 1,670.7 (104.3) | 0.196 | 841.6 (.65) | 0.4 (0.23) | 15.9 (207.7) |
| **Spun Bonded Polyolefin Membrane** | 1.0[a] (.04) | 65.7 (4.1) | 0.001 | 1,500.1 (1.16) | 2.25 (1.3) | 49.3 (66.3) |
| **Fiberglass** | 139.7 (5.5) | 30.4 (1.9) | 0.990 | 841.6 (.65) | 0.04 (0.23) | 1.3 (18.0) |
| **Class I Vapor Retarder** | 1.0[a] (.04) | 130.1 (8.1) | 0.001 | 2,299.8 (1.78) | 2.25 (1.3) | 32,800.2 (0.1) |
| **Interior Gypsum Board** | 12.5 (.5) | 624.7 (39) | 0.706 | 870.9 (.67) | 0.16 (0.09) | 7.0 (37.2) |
| **Air Layer** | 5.0 (.2) | 1.3 (.08) | 0.999 | 999.8 (.77) | 0.05 (0.029) | 0.8 (828.0) |
| **Extruded Polystyrene** | 25.4 (1) | 28.6 (1.8) | 0.990 | 1470.0 (1.14) | 0.03 (0.17) | 170.6 (0.8) |
| **Vapor Retarder (0.1 perm / 1.0 perm)[d]** | 1.0[a] (.04) | 130.1 (8.1) | 0.001 | 2,299.8 (1.78) | 2.25 (1.3) | 32,800.2 (0.1)/ 3,279.9 (1.0) |

[a] These layers are appreciably thinner than 1 mm but in order to insert them into WUFI their material properties are transferred to effective material properties for this thickness.

[b]Water vapor diffusion resistance factor is a unitless value representing a material's allowance for vapor transportation, independent of temperature and pressure, compared to diffusion in air.

[c] Rain deposition layer is a fictitious building component utilized to simulate a moisture reservoir in the wall assembly.

[d]The IRC model was run twice—once with a 0.1-perm vapor retarder, and one with a 1.0-perm vapor retarder, as both Class-I and Class-II vapor retarders are permitted by IRC- 2018 R702.7.

## RESULTS

There are two potential moisture sources within the typical modeled wall: rain and exfiltrating warm moist air. Both moisture sources tend to deposit the majority of their moisture at the OSB sheathing. When warm, moist air exfiltrates, it condenses on the first surface that is below dew point, which, in this case, is the sheathing. In extreme cold climates with overcrowded housing, the air leakage is the larger moisture source at the OSB (Figure 3). With the increase in rain in the past 10 years, rain leakage is becoming a bigger source of moisture at the sheathing, but the air leakage still predominates as a percentage of the total moisture deposition. However, the higher rain years (hot year and typical year) have higher levels of moisture in the wall indicating that rain leakage could have a higher impact on the interior of the wall.

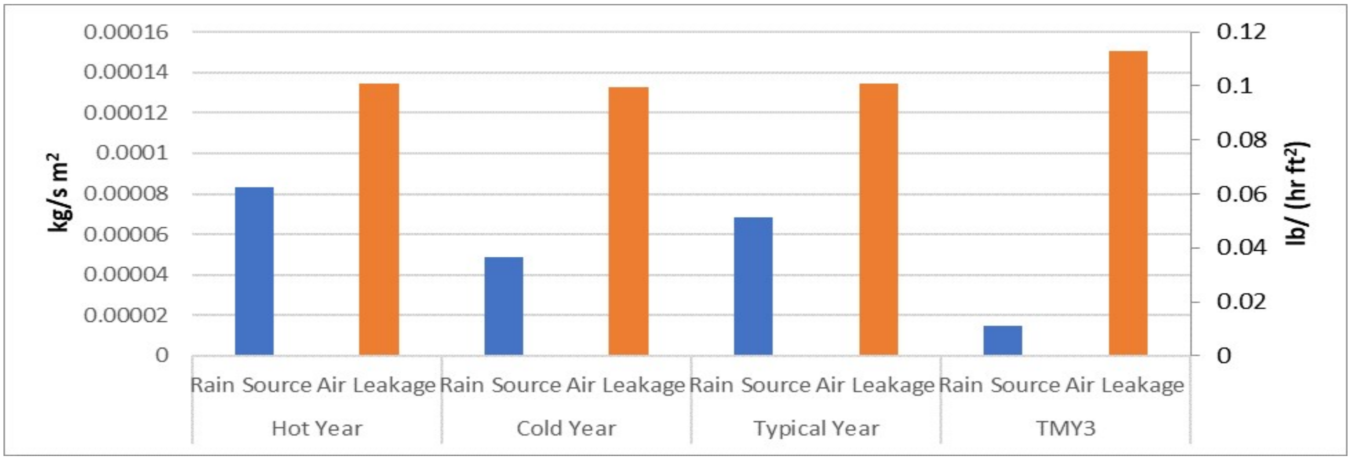


**Figure 3** Annual moisture deposition on the exterior sheathing for the typical residential wall in Arctic Alaska.

Instead of looking at moisture content of the material, the combination of temperature and relative humidity (from WUFI) over time was used in combination with material properties to evaluate mold risk. The WUFI Mould Index VTT 2.1.4 post processor (equations per (H. A. Viitanen et al., n.d.)) was used to evaluate mold risk across the wall components. The "mold index" ranges from 0 to 6. While there exist limitations of the mold index criteria (limited substrates tested, experiments conducted under laboratory conditions, etc.), the index is still considered the best fit for prediction of mold growth, especially for wooden materials, and is invoked by ASHRAE Standard 160-2016. The prescribed mold-index failure threshold is 3 (ASHRAE 2016), which corresponds to visual evidence of mold covering less than 10% of the substrate (or less than 50% as seen under a microscope) (H. Viitanen 2011). Additionally, if the mold index increases over time without reducing proportionally year-over-year, this is also considered a failure mode, as this would likely lead to the eventual buildup of visual mold levels.

The primary point of focus for mold concern was the interior side of the exterior sheathing (OSB) since this is the most common point of failure in cold climates. As typically appropriate for OSB, a sensitivity factor of "sensitive" was selected for the mold-index analysis, and decline (decay) coefficients of 0.25 and 0.1 were evaluated for two reasons: ASHRAE Standard 160-2016 notes that 0.25 may be more appropriate for materials that exhibit relatively high mold-growth rates (e.g., OSB), and the authors' observations from years of field work indicate that significant rates of decline occur in response to prolonged freezing temperatures outside the viable temperature range for mold growth.

The mold model (Figure 4) shows that this wall tends to perform well when the mold decline is considered significant (0.25), meaning that when conditions are not conducive to mold growth, mold declines on the material. When there is almost no decline (0.1), each scenario shows a slow but steady increase in mold index. None of the scenarios surpass the failing threshold of 3 in the 10 years modeled. However, the slowly increasing mold index every year indicates that all 4 scenarios with low decline rate will eventually surpass 3 and fail. This is not surprising, as mold is a common and recognized problem for residential buildings across Alaska (Nelson et al. 2021).

While the modern typical year scenario is the most concerning in terms of moisture content over time, the hot year poses the biggest threat in terms of simulated mold growth in the first few years—likely because warmer conditions mean more favorable conditions for mold growth throughout the year. Because mold does not grow under freezing conditions, warmer years with temperatures more frequently above freezing will permit conditions favorable to mold-growth for longer time periods. The hot year's fall temperatures do not decline as quickly as those of other years, which likely contributes to additional favorable conditions for mold between summer and winter. Over time, however, the modern typical year surpasses the mold index of the hot year, possibly because moisture content is highest in that wall, as discussed previously. This increase in moisture content means that surface relative humidity more frequently reaches critical relative humidity as the moisture content accumulates, causing more favorable conditions for mold growth. Figure 5 shows a comparison of a minimum IRC retrofit wall with a class 1 vs. a class 3 vapor retarder. Neither scenario performs well in the Arctic.

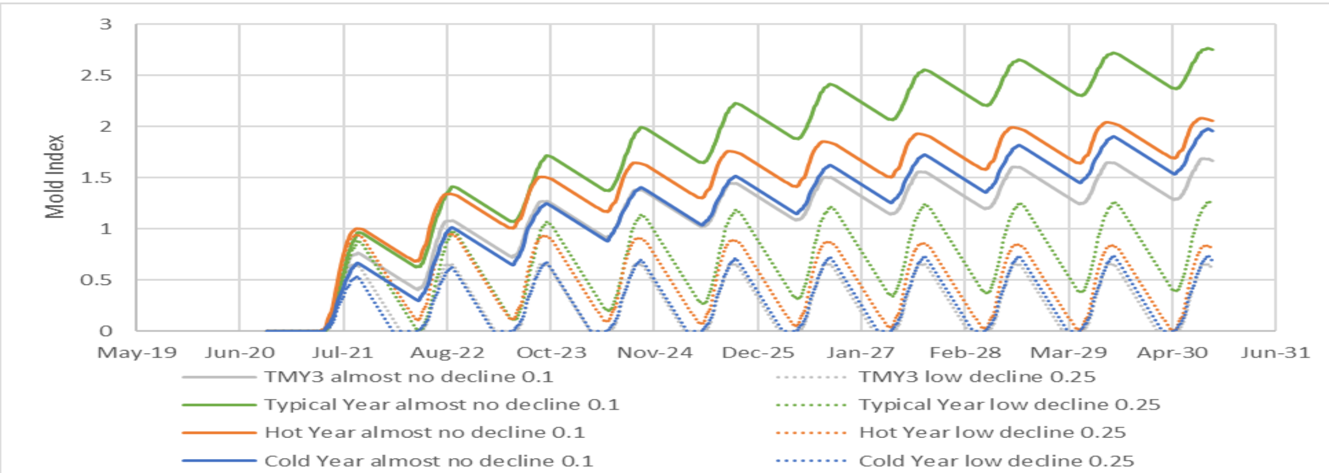


**Figure 4** Mold index (at the inner face of the exterior sheathing) for a wall representative of existing building stock across weather scenarios. The solid lines in Figure 4 show the data with almost no decline 0.1, which is the default for OSB in the mold model. The dotted lines are relative decline, 0.25.

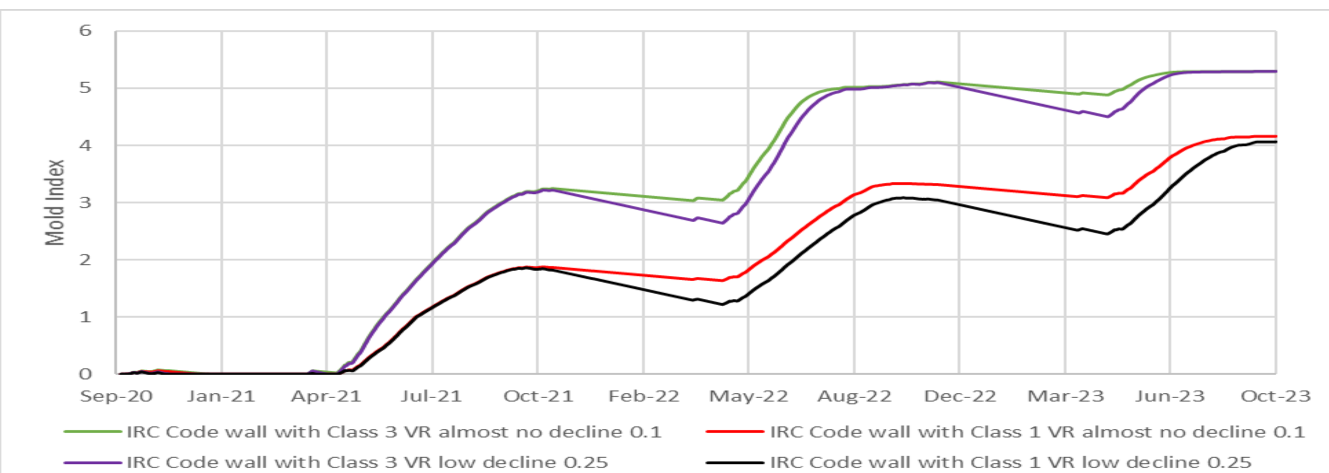


**Figure 5** Change in mold index over time for IRC-code-minimum retrofit scenarios. This data is for the interior layer of OSB that is directly beside the fiberglass.

## DISCUSSION

The development of the typical hot year data from modern observed weather was an attempt to look at the worst-case scenario of the changing Arctic climate. While the hot year weather might provide good insight into current and near future building durability in the Arctic, it is not necessarily a good proxy for climate change scenarios. It only considers the ambient air temperature when determining the typical month; all other weather variables are associated with the date and time of hotter temperature. Climate change scenarios predict a hotter and wetter climate in the Arctic (Lemmen and Bush 2019). Future weather data should consider higher precipitation, potentially less solar radiation, and more cloud cover. Global climate models may account for such changes on a global scale, but downscaling that data (similar to (Gaur, Lacasse, and Armstrong 2019; Nik 2016; 2017; Jiang et al. 2019)) for particular locations in the Arctic would aid in better models and planning for Arctic buildings. However, there does not seem to be one consistent method. Climate change scenario weather data is necessary for building durability analysis in the Arctic.

The decline value has a strong impact on mold growth and accumulation. Based on past observations in cold climates, researchers expect some level of decline in mold growth during the frozen winter (Craven and Garber-Slaght 2014). The decline factors are not well studied for typical climates, let alone extreme climates (H. A. Viitanen et al., n.d.).

Better understanding of interior conditions in Arctic buildings is also necessary to develop better building durability models. Residential construction is typically overcrowded, relatively airtight, and lacking in mechanical ventilation (Wiltse and Madden 2018); however, when these assumptions are used with ASHRAE 160 to determine interior conditions, the results are quite extreme. Additionally, commercial buildings in the Arctic tend to have exceedingly low interior relative humidity, but ASHRAE 160 does not account for interior humidity below 40%, potentially overestimating the interior moisture.

## CONCLUSION

A hygrothermal analysis of two wall types in the Arctic was developed using typical, hot, and cold year data developed from the most recent 10 years of weather data. The typical energy inefficient wall with no exterior insulation performed adequately due to the low exterior temperatures keeping the exterior sheathing below freezing and below mold growth initiation temperatures. The retrofit wall with the code minimum amount of exterior insulation performed poorly. Further research on many aspects of building durability in extreme cold climates is necessary to develop a better understanding of the current state of buildings and the potential performance of buildings with rapid climate change.

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## REFERENCES

"2018 International Residential Code (IRC) | ICC Digital Codes." 2018. Accessed December 6, 2021. https://codes.iccsafe.org/content/IRC2018.

ASHRAE. 2016. "Criteria for Moisture-Control Design Analysis in Buildings." ANSI/ASHRAE Standard 160-2016. ASHRAE.

Auld, Heather E. 2008. "Adaptation by Design: The Impact of Changing Climate on Infrastructure." *Journal of Public Works & Infrastructure* 1 (3): 276–88.

Auld, Heather, J. Waller, J. Klaassen, R. Morris, S. Fernandez, V. Cheng, and D. MacIver. 2010. "The Changing Climate and National Building Codes and Standards." In . https://ams.confex.com/ams/19Ag19BLT9Urban/techprogram/paper_174517.htm.

Blake, Kevin, Rebecca Kellerson, and Aleksandra Simic. 2007. "Measuring Overcrowding in Housing." U.S Department of Housing and Urban Development Office of Policy Development and Research.
Chan, Wanyu, Phillip Price, Michael Sohn, and Ashok Gadgil. 2003. "Analysis of U.S. Residential Air Leakage Database." *LBNL Report*, no. 53367 (July). https://www.osti.gov/servlets/purl/816784.
Craven, Colin, and Robbin Garber-Slaght. 2014. "Exterior Insulation Envelope Retrofits in Cold Climates: Implications for Moisture Control." *HVAC&R Research* 20 (4): 384–94. https://doi.org/10.1080/10789669.2014.887028.
Defo, Maurice, and Michael A. Lacasse. 2021. "Effects of Climate Change on the Moisture Performance of Tallwood Building Envelope." *Buildings* 11 (2): 35. https://doi.org/10.3390/buildings11020035.
"Energy Star Home Sealing Specification v1.0." 2001. ENERGY STAR. http://mathscinotes.com/wp-content/uploads/2016/10/ACH_Reference_ES_HS_Spec_v1_0b.pdf.
Gaur, Abhishek, Michael Lacasse, and Marianne Armstrong. 2019. "Climate Data to Undertake Hygrothermal and Whole Building Simulations Under Projected Climate Change Influences for 11 Canadian Cities." *Data* 4 (2): 72. https://doi.org/10.3390/data4020072.
Grabinski, Z, and H.R. McFarland. 2020. "Alaska's Changing Wildfire Environment [Outreach Booklet]." Alaska Fire Science Consortium. 2020.
Jiang, Aiyin, Xudong Liu, Emily Czarnecki, and Chengyi Zhang. 2019. "Hourly Weather Data Projection Due to Climate Change for Impact Assessment on Building and Infrastructure." *Sustainable Cities and Society* 50 (October): 101688. https://doi.org/10.1016/j.scs.2019.101688.
Junginger, Max, Maurice Defo, Travis Moore, Michael A. Lacasse, and Vanderley M. John. 2020. "Assessment of Moisture Performance of National Building Code Canada Compliant Wall Assemblies under Climate Change." *XV International Conference on Durability of Building Materials and Components (DBMC 2020)*, September. https://doi.org/10.23967/dbmc.2020.012.
Lacasse, Michael A., Abhishek Gaur, and Travis V. Moore. 2020. "Durability and Climate Change—Implications for Service Life Prediction and the Maintainability of Buildings." *Buildings* 10 (3): 53. https://doi.org/10.3390/buildings10030053.
Lemmen, D., and E. Bush, eds. 2019. *Canada's Changing Climate Report.* Enviroment and Climate Change Canada. http://publications.gc.ca/collections/collection_2019/eccc/En4-368-2019-eng.pdf.
McCrystall, Michelle R., Julienne Stroeve, Mark Serreze, Bruce C. Forbes, and James A. Screen. 2021. "New Climate Models Reveal Faster and Larger Increases in Arctic Precipitation than Previously Projected." *Nature Communications* 12 (1): 6765. https://doi.org/10.1038/s41467-021-27031-y.
Nelson, Abigail, Aaron J. Salkoski, Bailey Richards, Whitney Elliott, Christine Tan Cadogan, Matthew Hirschfeld, Gretchen Day, Peter Holck, Jonathon Peterson, and Rosalyn Singleton. 2021. "Environmental Health Consults in Children Hospitalized with Respiratory Infections." *Journal of Community Health* 46 (2): 324–33.
Nik, Vahid M. 2016. "Making Energy Simulation Easier for Future Climate – Synthesizing Typical and Extreme Weather Data Sets out of Regional Climate Models (RCMs)." *Applied Energy* 177 (September): 204–26. https://doi.org/10.1016/j.apenergy.2016.05.107.
———. 2017. "Application of Typical and Extreme Weather Data Sets in the Hygrothermal Simulation of Building Components for Future Climate – A Case Study for a Wooden Frame Wall." *Energy and Buildings* 154 (November): 30–45. https://doi.org/10.1016/j.enbuild.2017.08.042.
Nik, Vahid M., Angela Sasic Kalagasidis, and Erik Kjellström. 2012. "Assessment of Hygrothermal Performance and Mould Growth Risk in Ventilated Attics in Respect to Possible Climate Changes in Sweden." *Building and Environment*, Implications of a Changing Climate for Buildings, 55 (September): 96–109. https://doi.org/10.1016/j.buildenv.2012.01.024.
Sehizadeh, Ali, and Hua Ge. 2016. "Impact of Future Climates on the Durability of Typical Residential Wall Assemblies Retrofitted to the PassiveHaus for the Eastern Canada Region." *Building and Environment* 97 (February): 111–25. https://doi.org/10.1016/j.buildenv.2015.11.032.
Sherman, Max H., William J.N. Turner, and Iain S. Walker. 2011. "Infiltration as Ventilation: Weather-Induced Dilution." LBNL--5795E, 1173153. https://doi.org/10.2172/1173153.
Singleton, R., A. J. Salkoski, L. Bulkow, C. Fish, J. Dobson, L. Albertson, J. Skarada, et al. 2017. "Housing Characteristics and Indoor Air Quality in Households of Alaska Native Children with Chronic Lung Conditions." *Indoor Air* 27 (2): 478–86. https://doi.org/10.1111/ina.12315.
Straube, John, Trevor Trainor, Jonathan Smegal, and A. Parekh. 2016. "Measured and Predicted Moisture Performance of High-R Wall Assemblies in Cold Climates." In *Proceedings of Buildings XIII*.
Viitanen, H.A, T. Ojanen, M. Krus, V. Eitner, S. Bogl, and D Zirkelbach. n.d. *WUFI Mold Index VTT* (version 2.1.4). Fraunhofer Institute of Building Physic.

Viitanen, Hannu. 2011. "Moisture and Bio-Deterioration Risk of Building Materials and Structures." In *Mass Transfer - Advanced Aspects*, edited by Hironori Nakajima. InTech. https://doi.org/10.5772/21184.

Wells, John A., Michael A. Lacasse, and Gary Sturgeon. 2020. "Assessment of Moisture Response and Expected Durability of a Heritage Masonry Building Subjected to Projected Future Climate Loads of Ottawa, Canada." *XV International Conference on Durability of Building Materials and Components (DBMC 2020)*, September. https://doi.org/10.23967/dbmc.2020.212.

Wiltse, Nathan, and Dustin Madden. 2018. "2018 Alaska Housing Assessment." Fairbanks, Alaska: Cold Climate Housing Research Center. https://www.ahfc.us/pros/energy/alaska-housing-assessment/2018-housing-assessment.