NSER Alliance “Next Generation Wood Construction” HQP seminar

High Performance Climate Resilient Building Envelope

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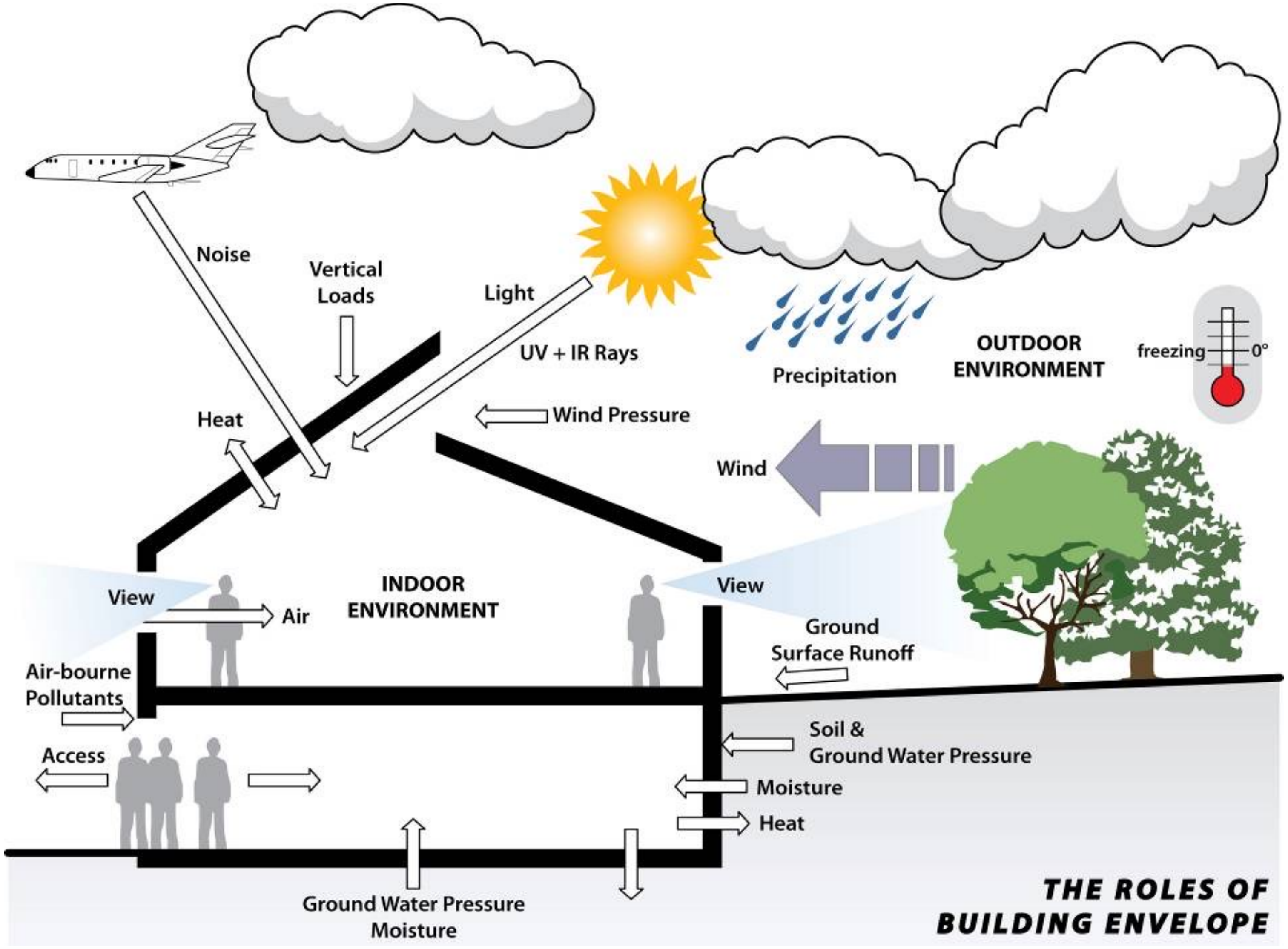
Integrated Approach for High Performance Building Envelope

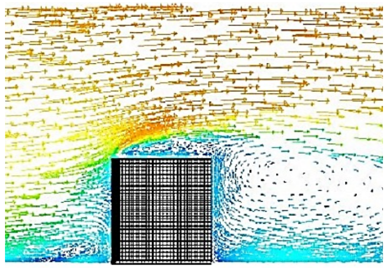


Simon&Hauglustaine, 2001

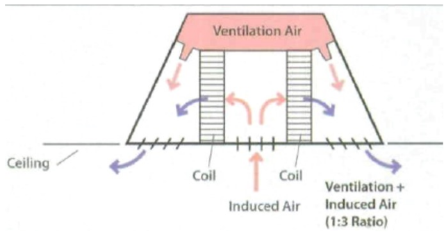
Building envelope:

- System of components and materials that make up the outer shell of a building
- Environmental separator: heat, air, moisture, noise, solar radiation, wind, precipitation, fire, smoke, etc.
- Function: control, support, finish, distribution of services
- Moderating indoor environment, energy generation, resiliency

Integrated Approach for High Performance Building Envelope



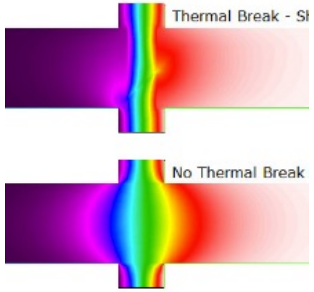
Interaction with HVAC systems
- Design & operation



Micro-climatic loads
- Wind
- Rain/precipitation
- Solar
- RH,T
- Long-wave radiation

Building Envelope
- Material
- Components
- Systems

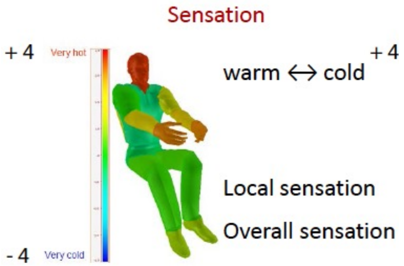
Indoor climatic loads (RH, T, Pressure)
- Occupant activities
- Operation of HVAC



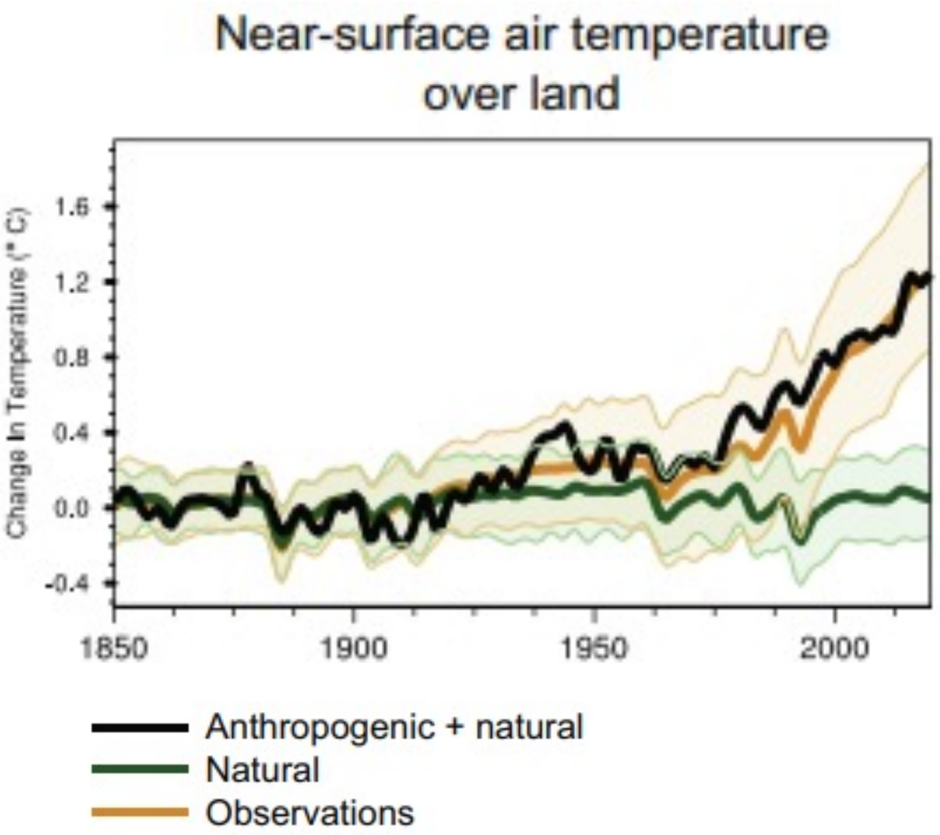
Energy Efficiency & Life cycle carbon
- Building form
- Insulation, air-tightness, thermal bridges, fenestrations;
- Passive solar design: WWR, shading, thermal mass, etc.
- Integration of solar technologies
- Low carbon materials
- Etc.

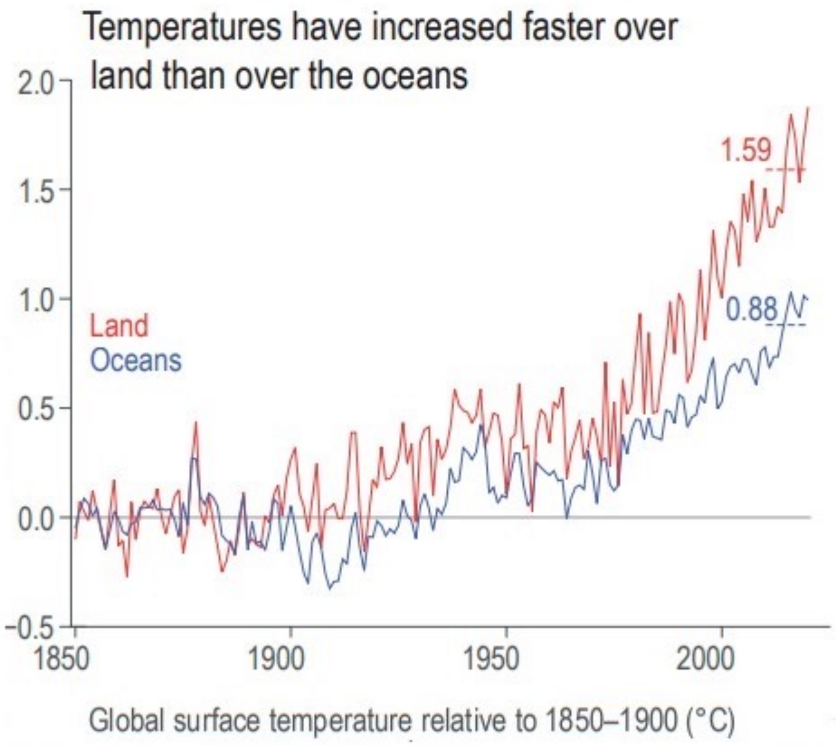
Durability
- Hygric properties
- HAM transports (rain penetration, air leakage & vapour diffusion)
- Component & system performance (HAM)
- Connection details/construction quality

IEQ
- Thermal comfort
- Visual comfort
- Acoustic comfort
- Indoor air quality



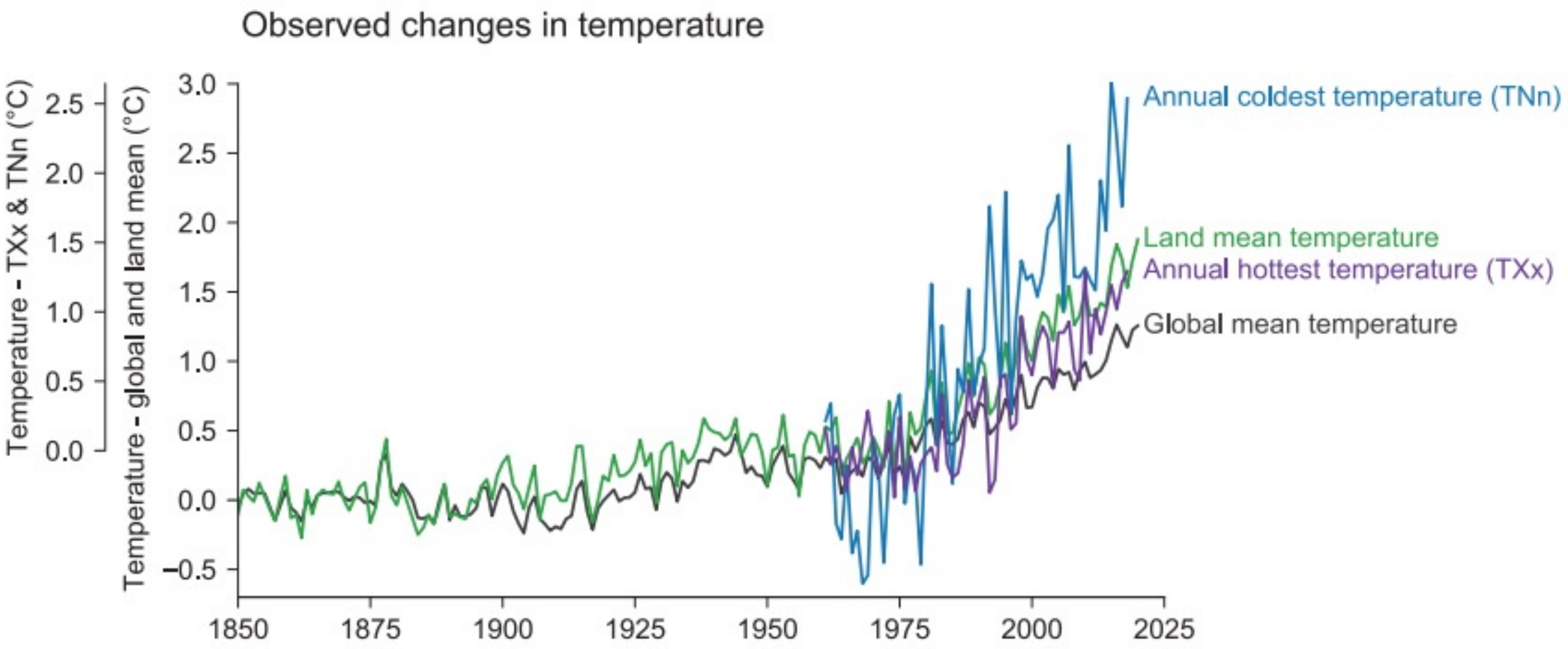
Climate change





- Consistent, systematic increase in global temperatures; Human-induced warming reached approximately 1^{o}C (likely between 0.8 and 1.2^{o}C) above pre-industrial levels in 2017, increasing at 0.2^{o}C (likely between 0.1 and 0.3^{o}C) per decade
- faster warming over land than over ocean

Climate change



- Extreme events more frequent than the mean climate
- WMO data showing that the past two decades have included **18** of the **20** warmest years since record-keeping began in 1850

Climate change

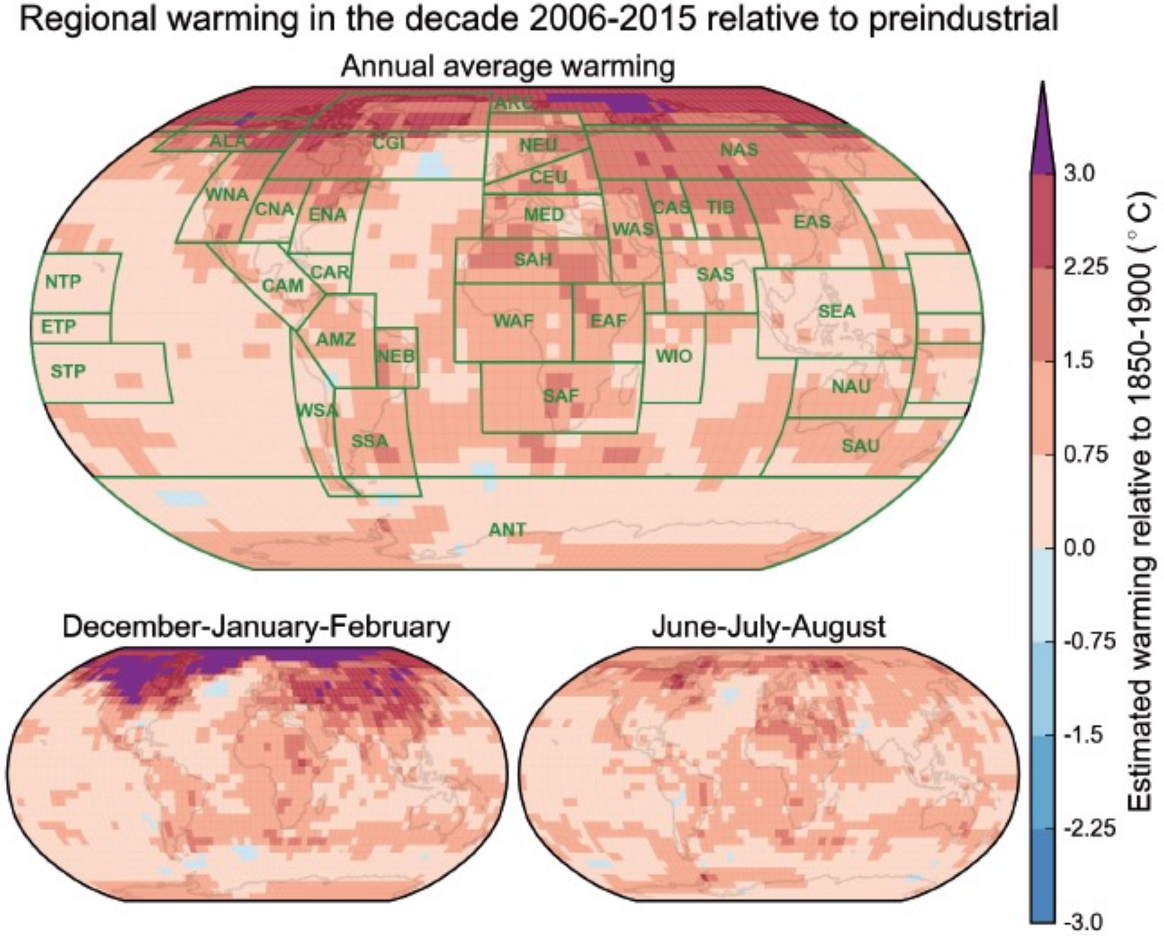


Figure 1.3 | Spatial and seasonal pattern of present-day warming: Regional warming for the 2006–2015 decade relative to 1850–1900 for the annual mean (top), the average of December, January, and February (bottom left) and for June, July, and August (bottom right). Warming is evaluated by regressing regional changes in the Cowtan and Way (2014) dataset onto the total (combined human and natural) externally forced warming (yellow line in Figure 1.2). See Supplementary Material 1.SM for further details and versions using alternative datasets. The definition of regions (green boxes and labels in top panel) is adopted from the AR5 (Christensen et al., 2013).

Source: IPCC, Global warming of 1.5^{o}C

- Regional variations: warming greater than the global average has already been experienced in many regions and seasons, with higher average warming over land than over the ocean; in northern hemisphere mid-latitude winter, etc.

Impact of Climate change on Canada

- Both past and future warming in Canada is, on average, about double the magnitude of global warming, triple in Arctic region
- Precipitation has increased in many parts of Canada, and a shift toward less snowfall and more rainfall.
- Extreme hot temperatures will become more frequent and more intense. This will increase the severity of heatwaves, and contribute to increased drought and wildfire risks.

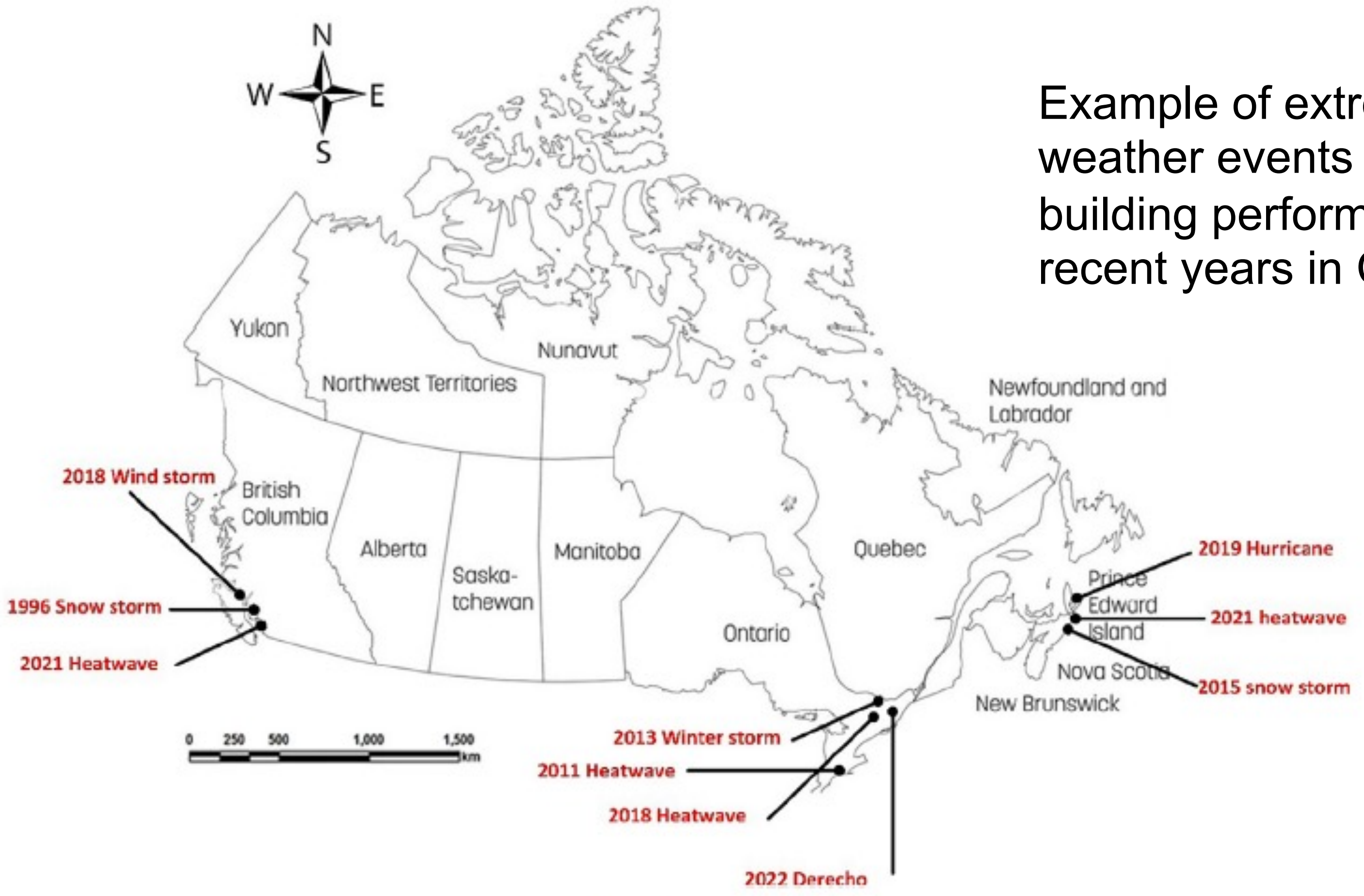


Fig. 1. Map of extreme events.

Example of extreme weather events affecting building performance in recent years in Canada

Milad Rostami, Santinah Green-Mignacca, Scott Bucking. 2-24. Weather data analysis and building performance assessment during extreme climate events: A Canadian AMY weather file data set. Data in Brief *52 (2024) 110036*

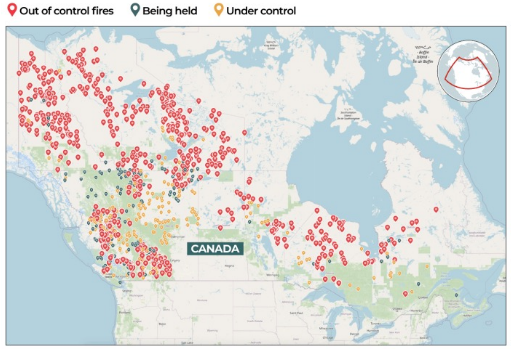
Impact of Climate Change on Canada

- **Heat waves** lasting three days or more have become more common over the last six decades in cold climate

- Montreal recorded the highest temperature (36.6°C, 97.9 °F) in history (147 years) on 2nd July 2018.
    - **66** heat-related death during heat wave period (June 30-July 8)
- BC 2021 June 25-July 2, **619** lives due to heat exposure

- **Wildfires**
  The annual number of large wildfires has increased by more than 75 percent.

With roughly **18.5 million hectares of Canadian land burned,** 2023 was the worst wildfire season ever recorded



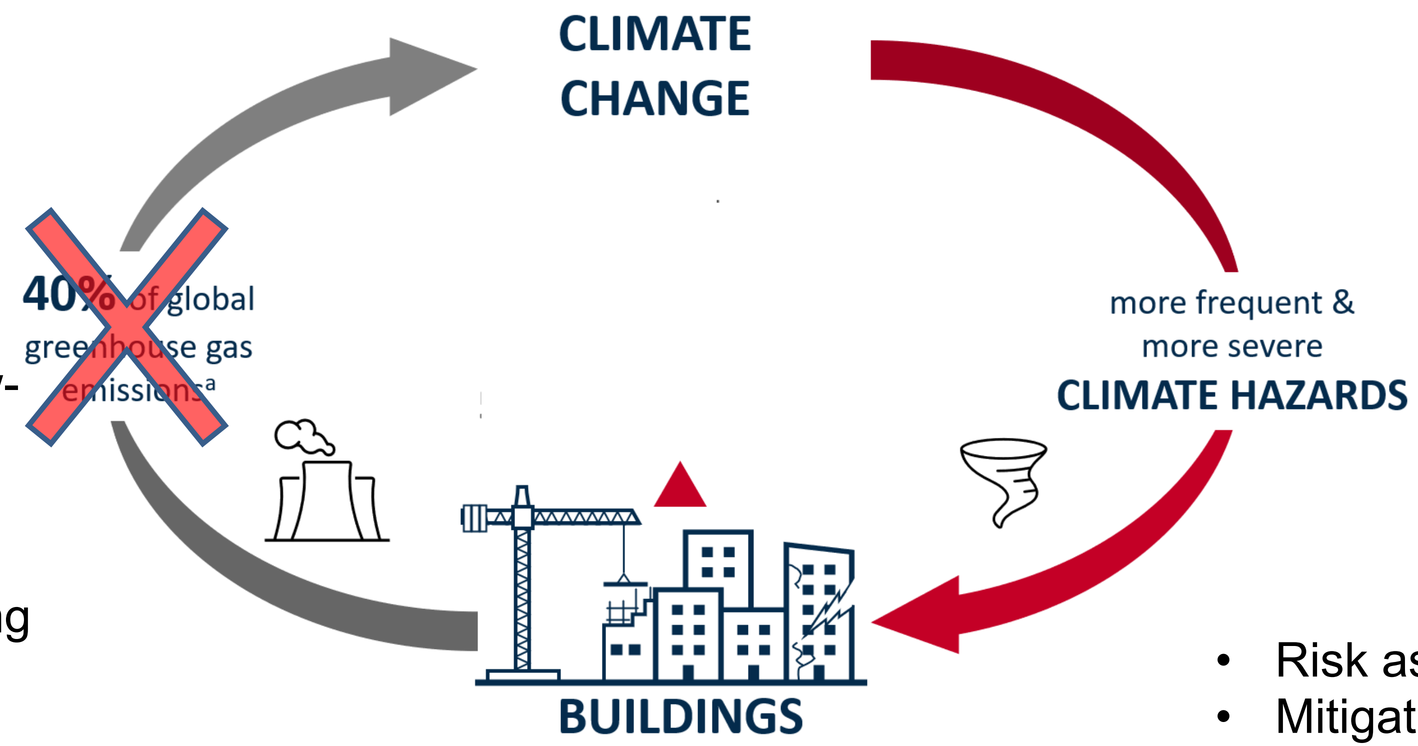
- **Rising seas and increased coastal flooding**
  Average global sea level has increased 8 inches since 1880
- Increased urban flooding risks due to more intense rainfall

- **Hurricanes & Tornados**
  Number of hurricanes that reach Categories 4 and 5 in strength has roughly doubled comparing with 1975
- 2019 PEI, Aug. 21, 90mm rain, 115km/h gust
- 2022 Ontario, Derecho, 190km/h, 4 tornados

- Ice storms & snow storms

Relationship between climate change and building performance

- Strategies to reduce carbon emission from buildings
  - Energy efficient low-carbon new construction
  - Deep energy retrofitting of existing buildings
  - Efficient operation
  - Renewable energy sources and building electrification



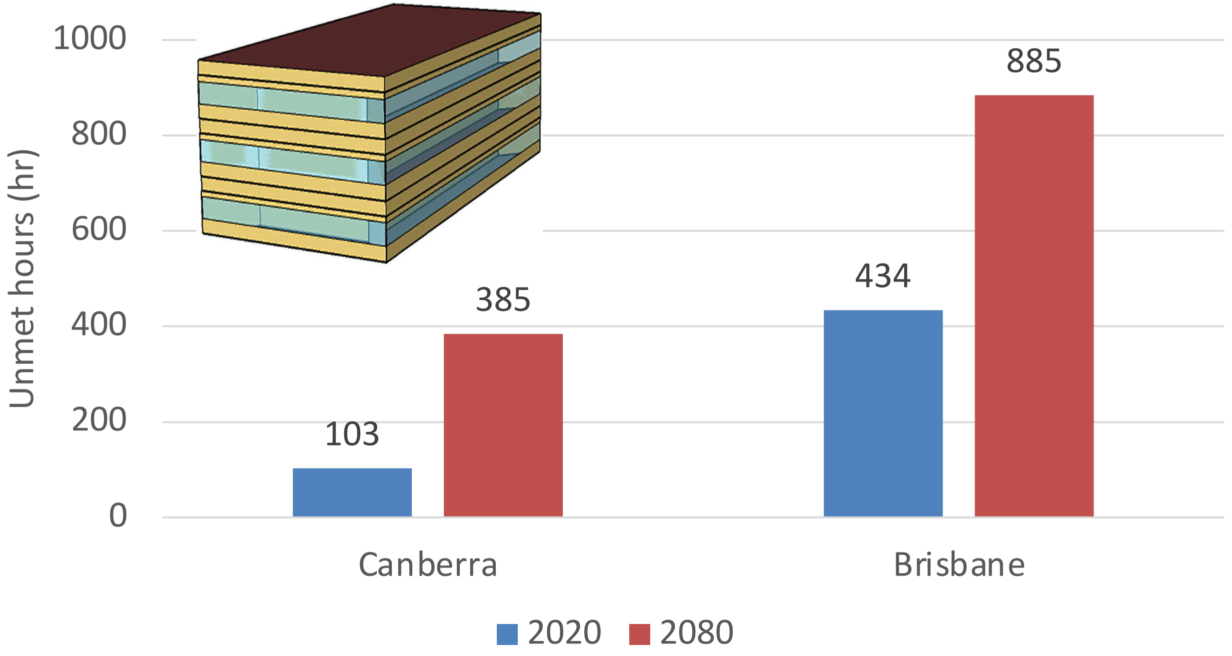
Building performance affected:

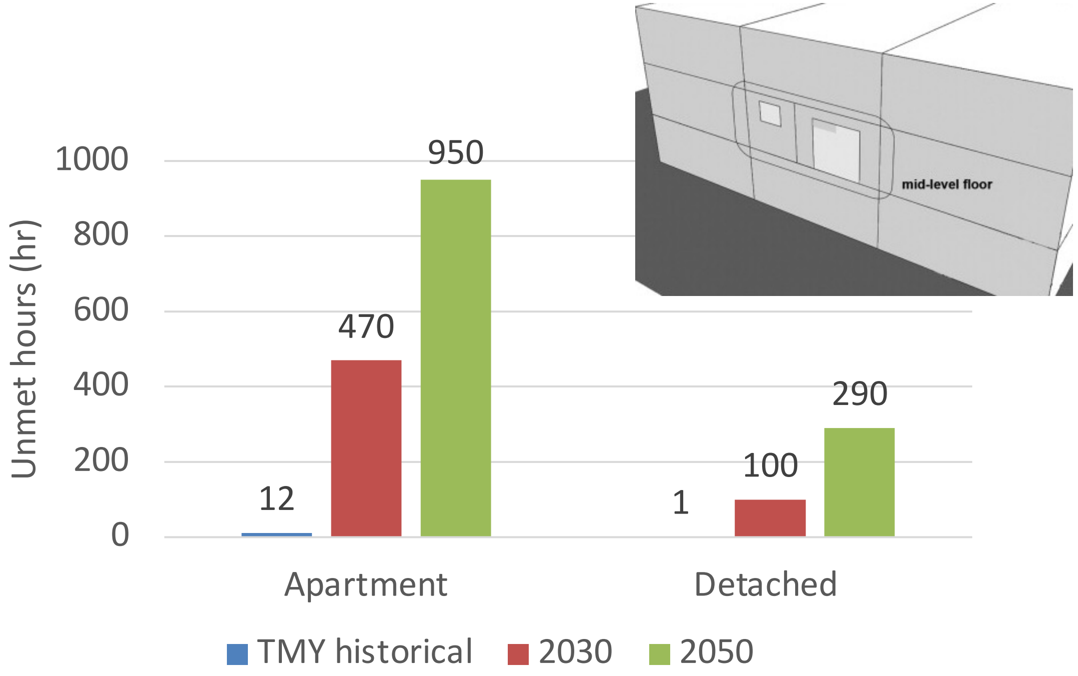
- Energy performance
- Thermal comfort and overheating
- Durability

- Risk assessment
- Mitigation and adaptation strategies

How does climate change affect building energy performance?

1) Effect on the adequacy of HVAC



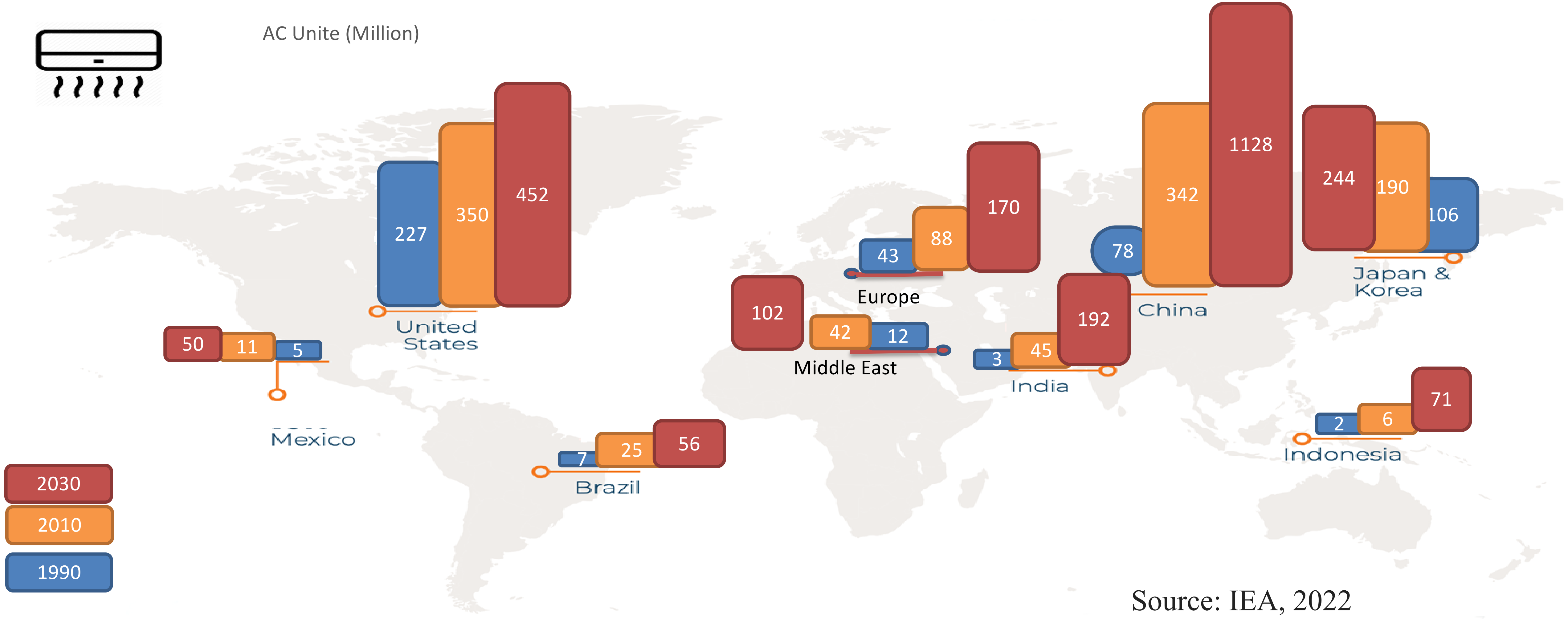


Office building in two cities in Australia (Bamdad, et al., 2021)

Residential buildings in London in UK (Gupta & Gregg, 2012)

How does climate change affect building energy performance?

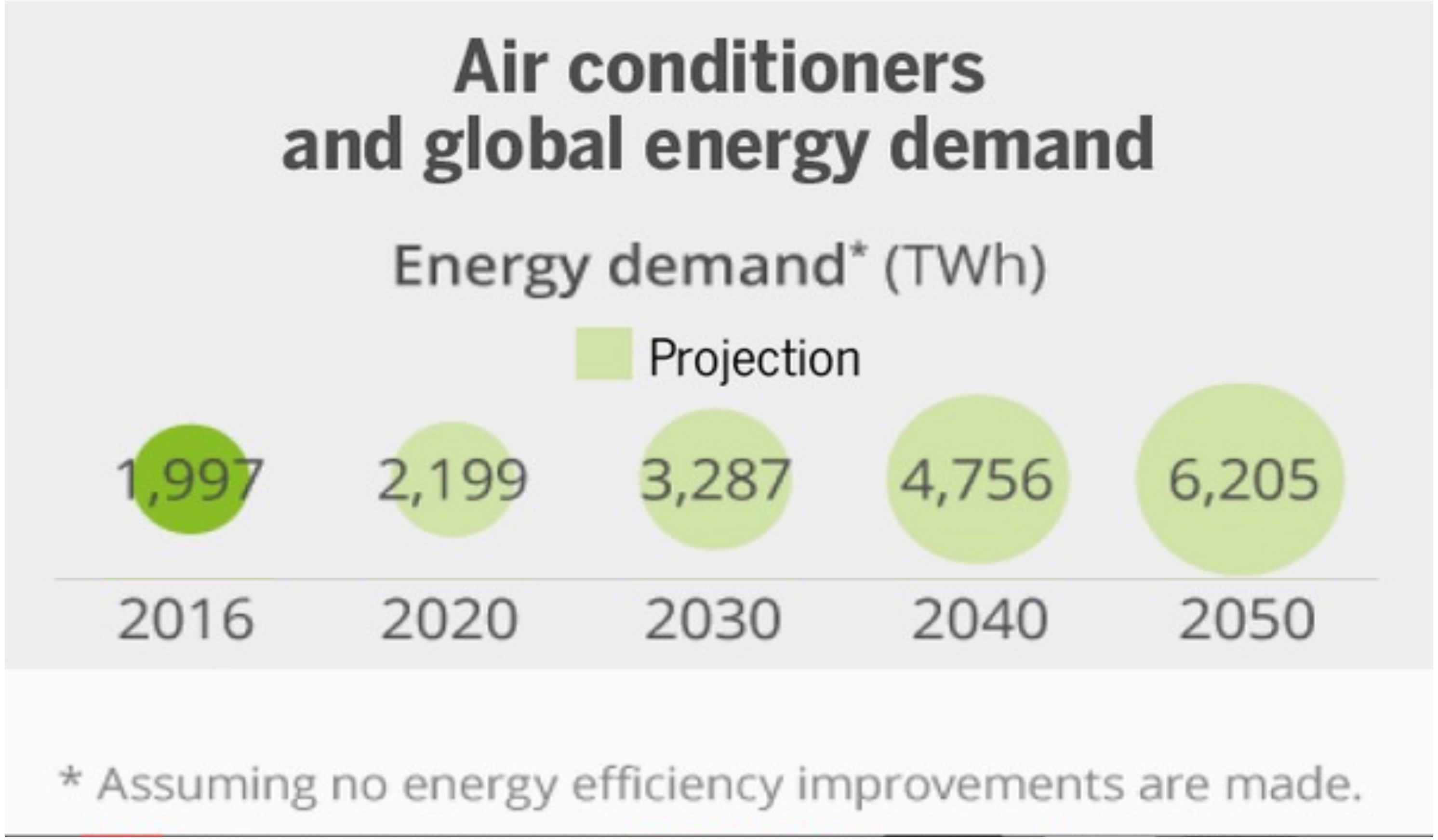
2) Increase the use of air conditioners and cooling energy demand in buildings



Source: IEA, 2022

How does climate change affect building energy performance?

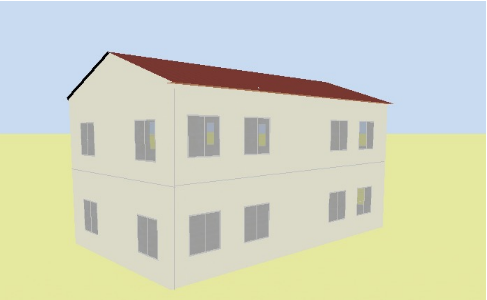
2) Increase the use of air conditioners and cooling energy demand in buildings

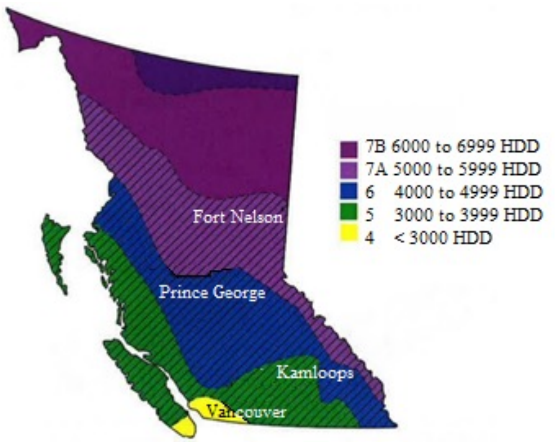


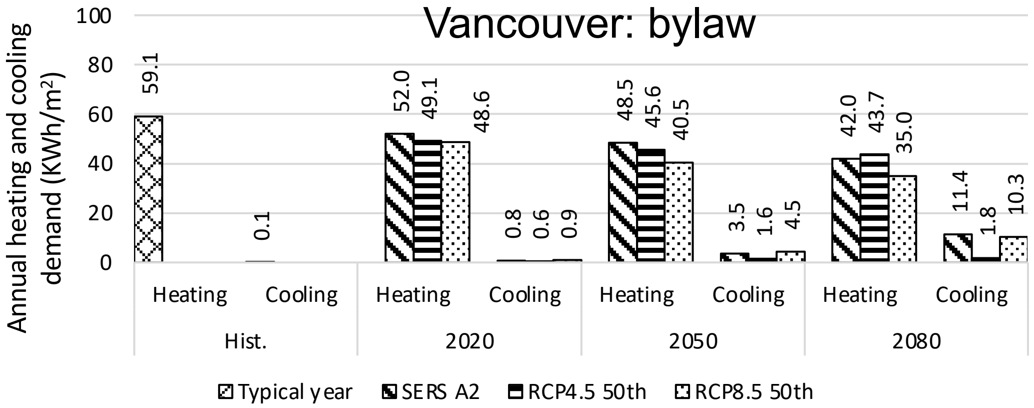
(IEA, 2022; and https://timesofindia.indiatimes.com/india/is-this-why-the-power-ministry-wants-to-set-ac-temperature-at-24c/articleshow/64748542.cms)

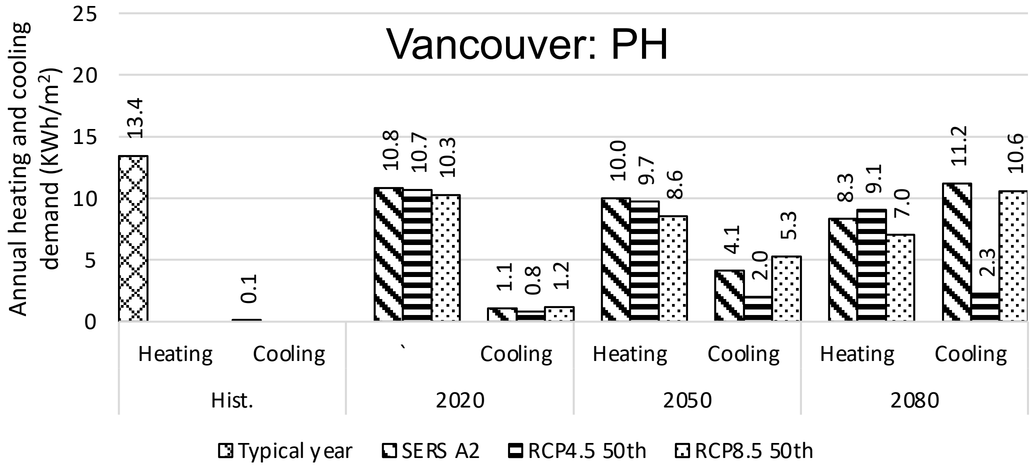
How does climate change affect building energy performance?

3) Reduce space heating energy demand for Canadian cold climate





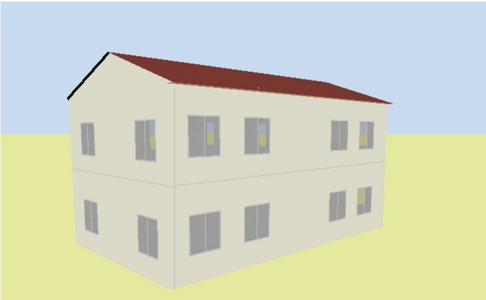


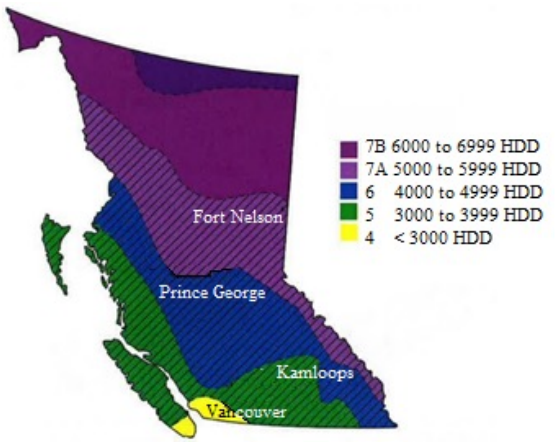


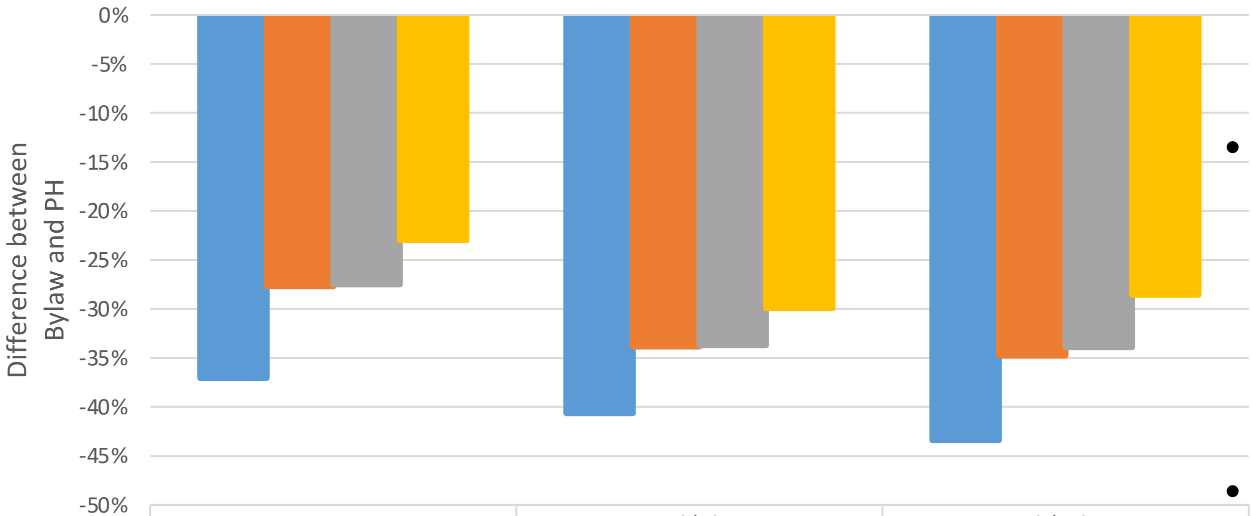
- Heating demand reduced while cooling demand increased, 25% of heating demand for bylaw construction
- More significant increase in cooling demand for PH under warming future climate compared to historical weather, greater than heating demand

How does climate change affect building energy performance?

3) Reduce space heating energy demand for Canadian cold climate







	House	Mid-rise	High-rise
Hist.	-37%	-41%	-43%
A2	-28%	-34%	-35%
4.5	-27%	-34%	-34%
8.5	-23%	-30%	-29%

Difference of life cycle energy consumption between the Bylaw and PH results under climate zone 4.

- Well-insulated buildings in cold climate such as PH significantly reduce the total energy consumption
- The energy saving is reduced from 37% to 23% under projected future climate

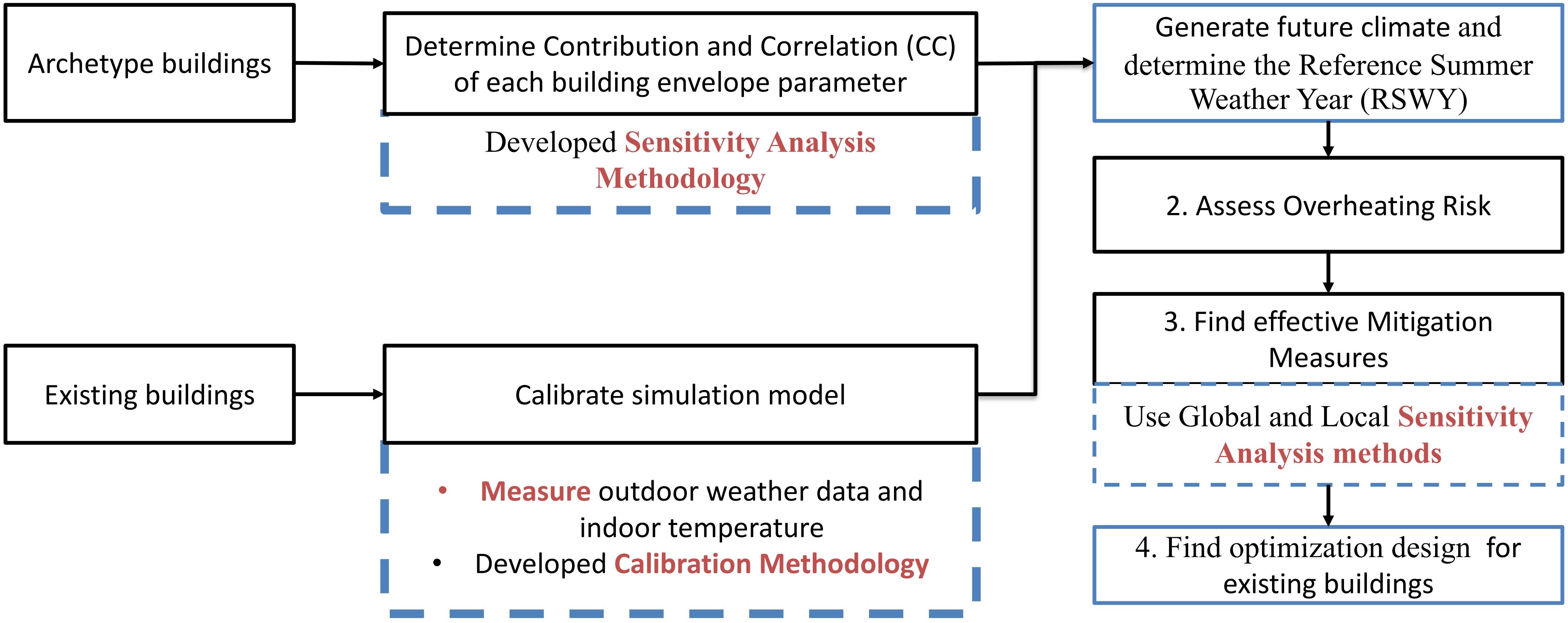
Impact of climate change on overheating in Canadian buildings

- Canadian buildings are designed primarily to withstand cold winters;
- More than 60% of Canadian buildings does not have mechanical cooling and rely on natural ventilation to cool buildings during the summer months;
- Canadian building codes and standards mandate high-energy efficient buildings (HEEB) to achieve net-zero energy buildings
- Some previous studies reported HEEB experience greater overheating risks, while others found contradictory conclusions

Research questions:

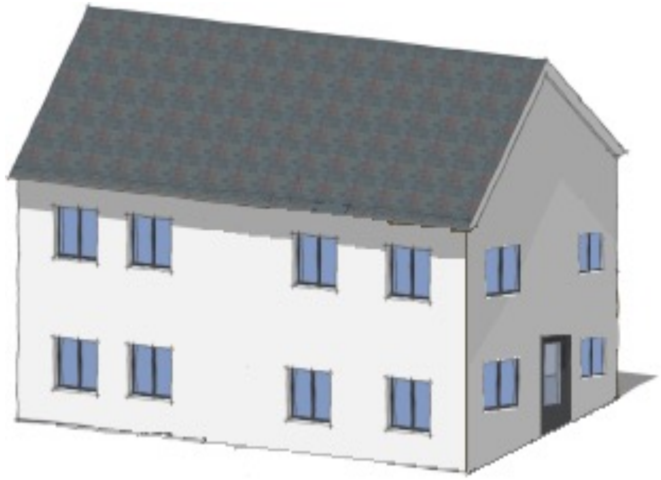
- Do HEEB increase overheating risk in summer in Canadian cold climates? What are the causes and mitigation solutions?
- How would existing buildings perform under current and future extreme heat events? How to mitigate overheating risks?

A framework to assess overheating risks and develop mitigation measures under projected future climates



Do high energy-efficient buildings increase overheating risk in cold climates?

Determine Contribution and Correlation (CC) of each building envelope parameter



Study building: single-family detached house

- 54% of residential buildings in Canada
- 17% of total energy use and
- 10% of Canada's greenhouse gas emissions

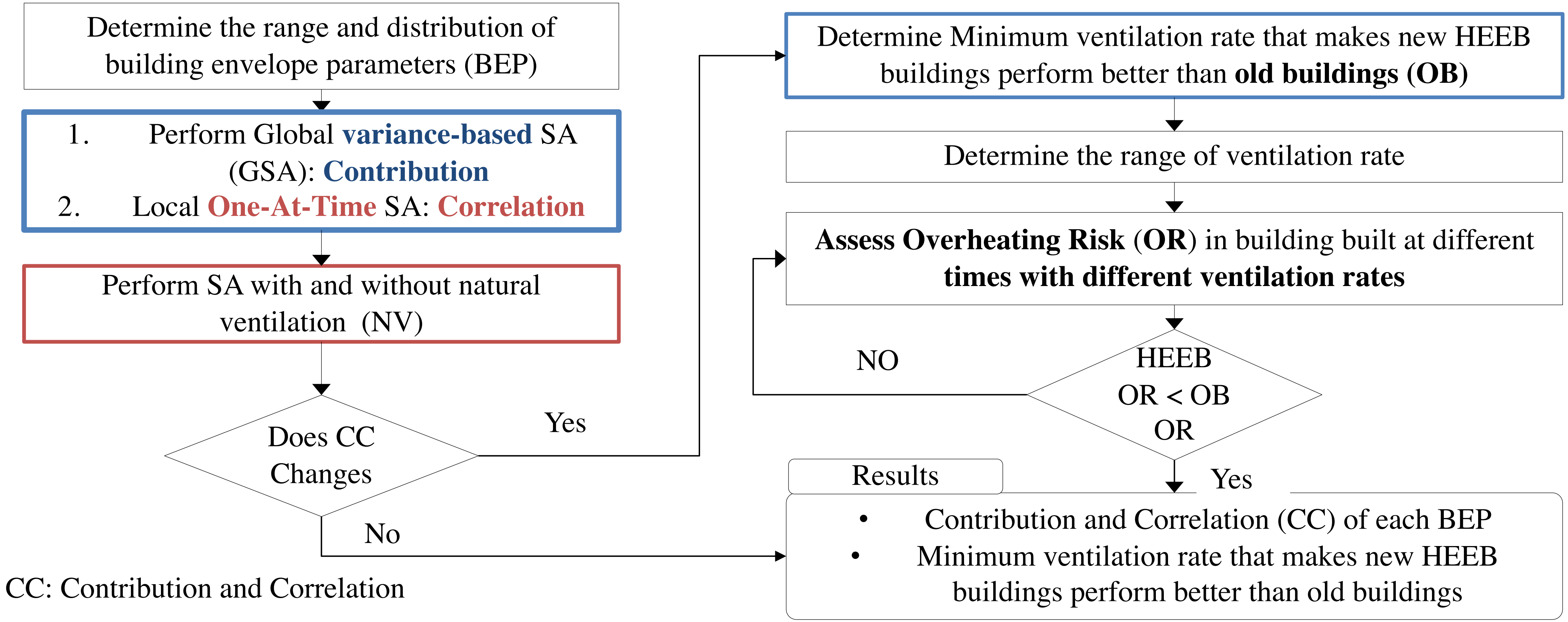
Range of building envelope parameters to cover old buildings and HEEB

Building Age	**Wall**	**Roof**	**Windows**		**Airtightness**
	U-value (W/m^2.K)		U-value (W/m^2.K)	SHGC	**ACH50**
Uniform distribution range	0.1-0.8	0.08-0.6	0.68-3.80	0.26-0.75	0.6-5.0

Do high energy-efficient buildings increase overheating risk in cold climates?

Determine Contribution and Correlation (CC) of each building envelope parameter

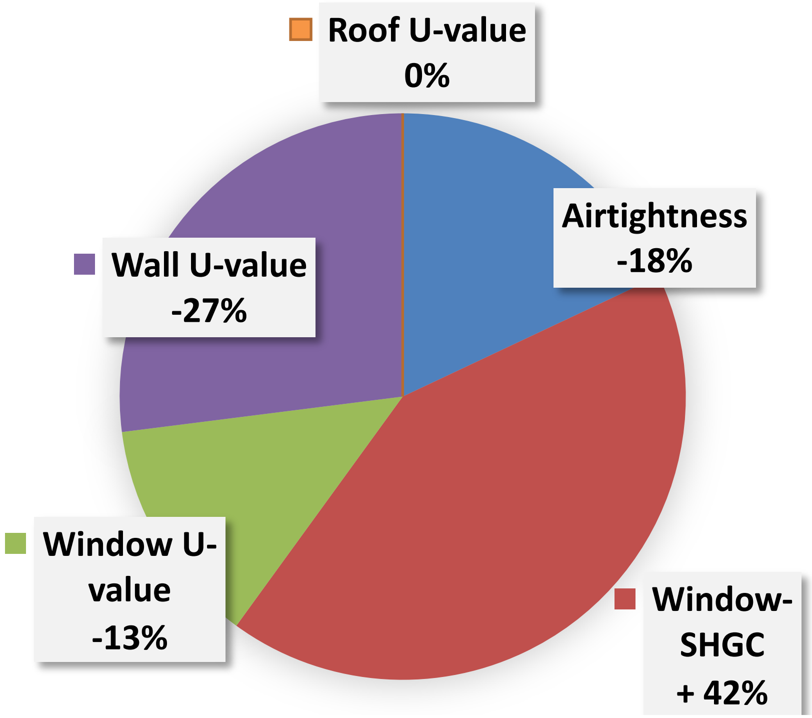
Existing studies: variation in ventilation rates; some with low ASHRAE 62.2 min. ventilation, natural ventilation not considered;



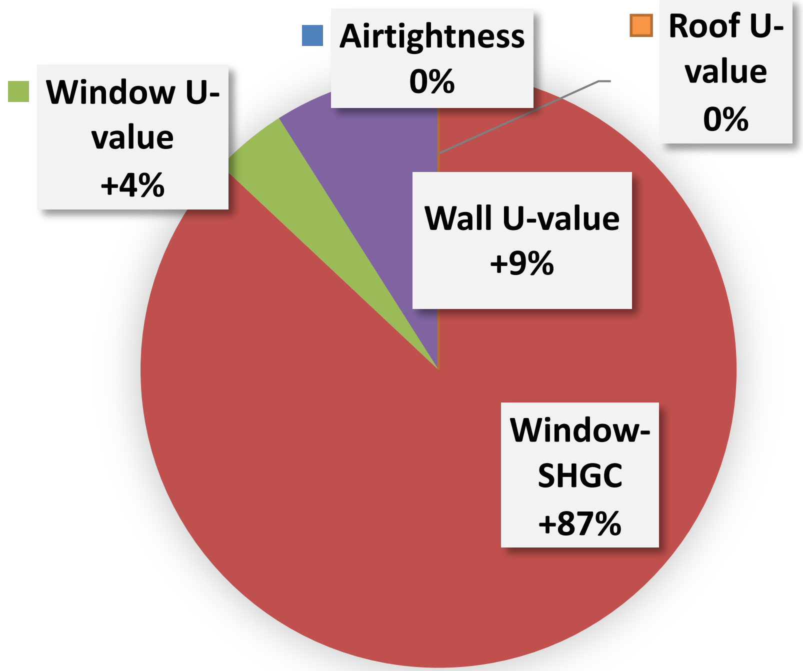
Baba, F. M., Ge, H., Wang, L. L., & Zmeureanu, R. (2022). **Do high energy-efficient buildings increase overheating risk in cold climates? Causes and mitigation measures required under recent and future climates.** *Building and Environment*

Do high energy-efficient buildings increase overheating risk in cold climates?

No Ventilation



With Natural Ventilation



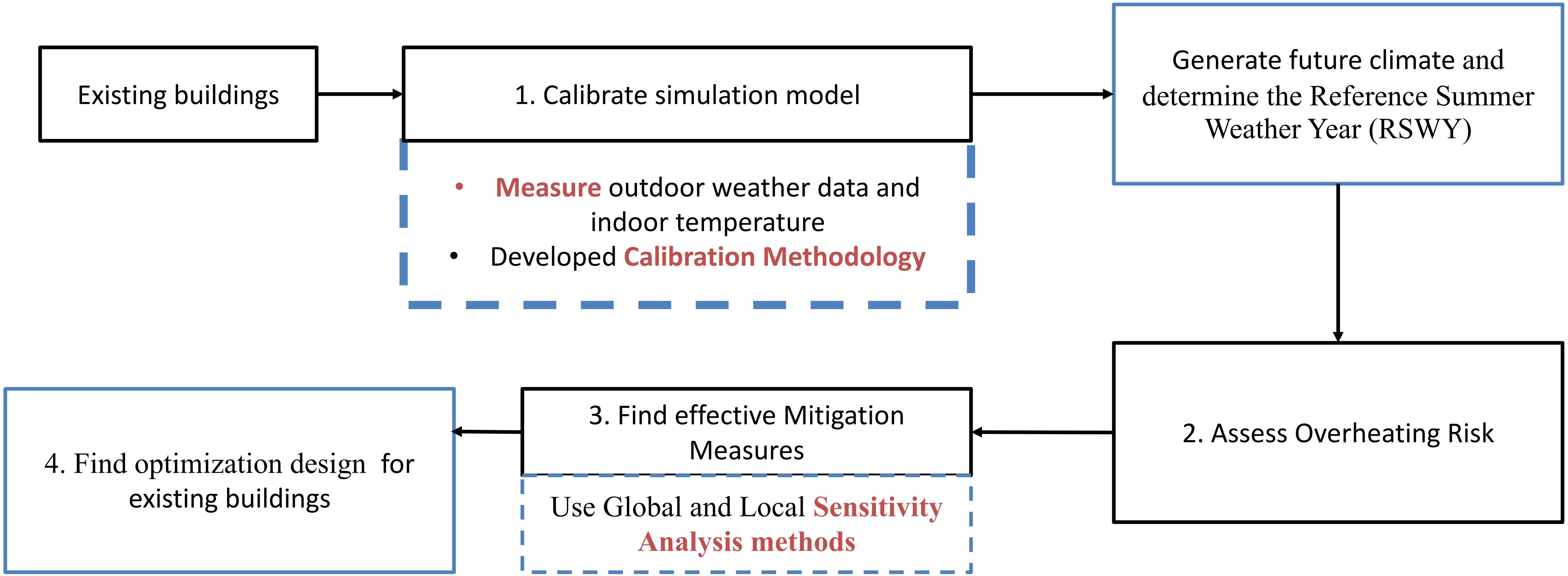
- Contribution and correlation of building envelope depends on the level of ventilation

Old buildings have overheating risk **lower** than HEEB (High Energy Efficient Buildings)

HEEB buildings have overheating risk **lower** than old buildings

Baba, F. M., Ge, H., Wang, L. L., & Zmeureanu, R. (2022). **Do high energy-efficient buildings increase overheating risk in cold climates? Causes and mitigation measures required under recent and future climates.** *Building and Environment*

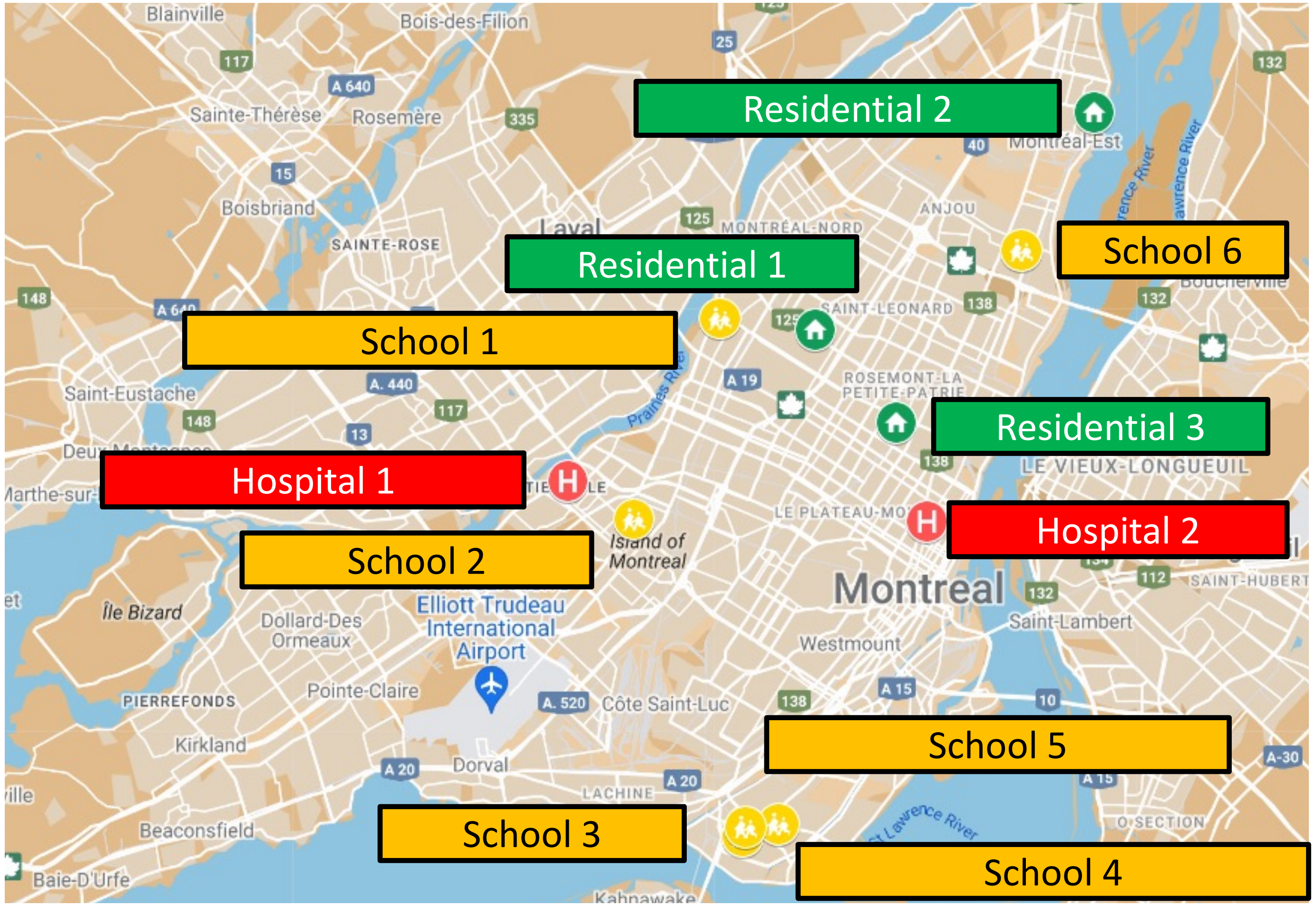
Assessment and mitigation of overheating risks in existing Canadian buildings under projected future climates



Baba, F. M., Ge, H., Zmeureanu, R., & Wang, L. L. (2022). **Calibration of building model based on indoor temperature for overheating assessment using genetic algorithm: Methodology, evaluation criteria, and case study.** *Building and Environment*, *207*.

Assessment and mitigation of overheating risks in existing Canadian buildings under projected future climates

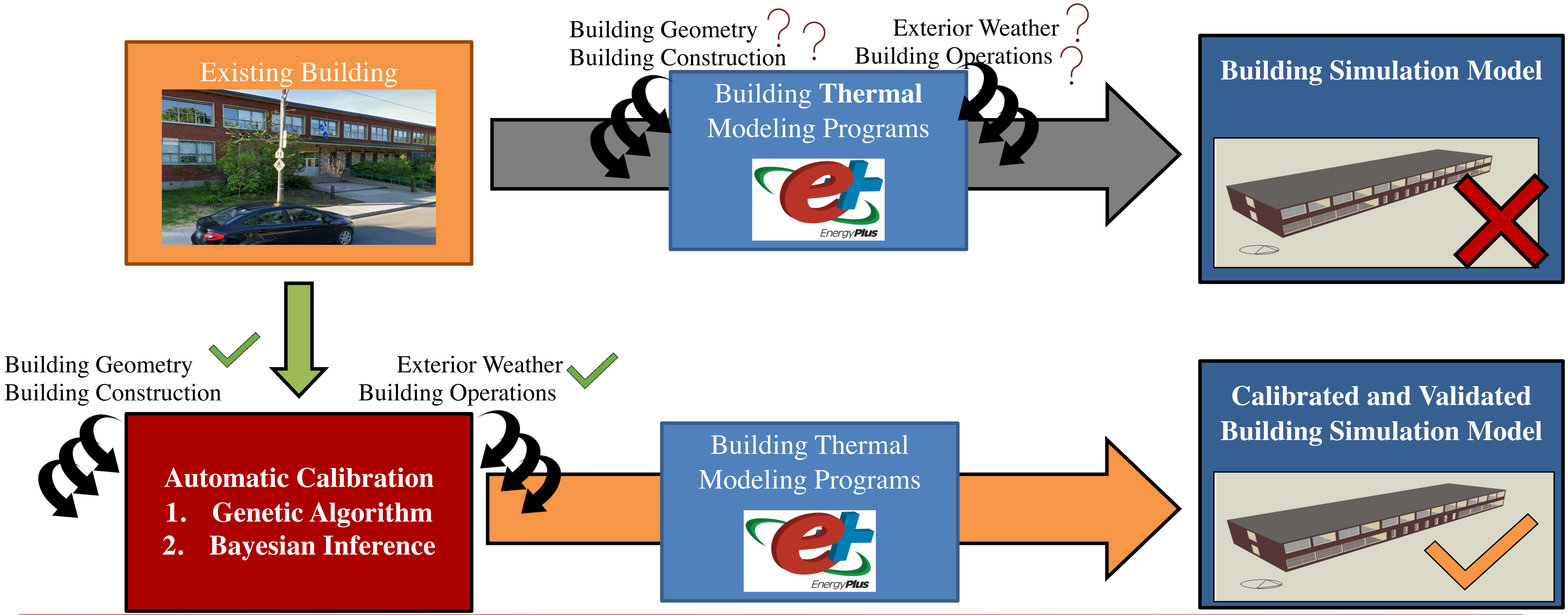
- Building selection and data collection in Montreal
  - 6 primary schools
  - 2 hospital buildings
  - 3 residential buildings



[NSERC Assessment and Mitigation of Summertime Overheating Conditions of Urban Agglomerations] led by Dr. Wang (PI), Dr. Ge and Dr. Zmeureanu collaborating with NRC, ECCC and Health Canada

Assessment and mitigation of overheating risks in existing Canadian buildings under projected future climates

Calibration BSM based on indoor hourly temperature

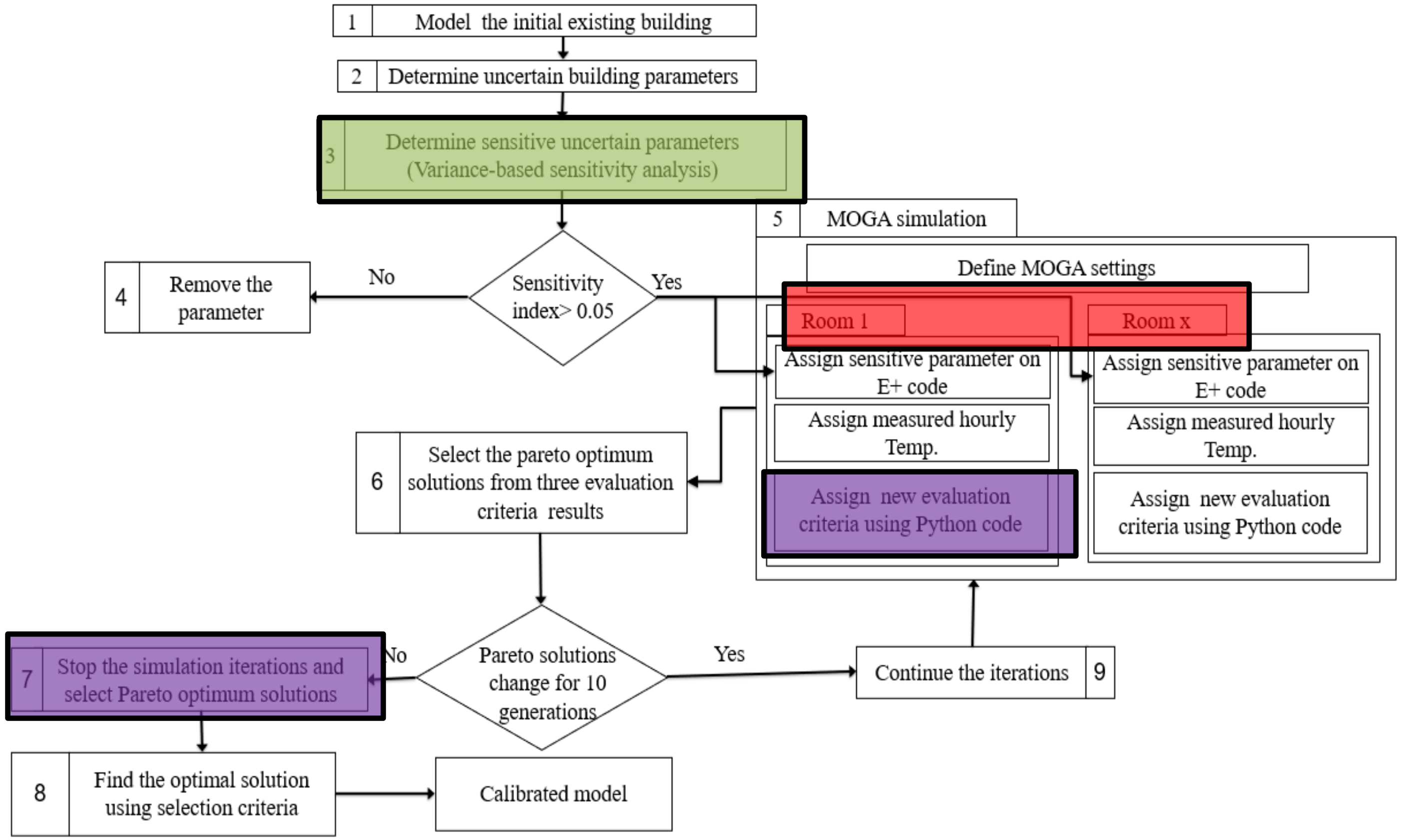


Automatic model calibration

All rooms can be calibrated simultaneously

Implement SA with GA

Develop a new evaluation and selected criteria



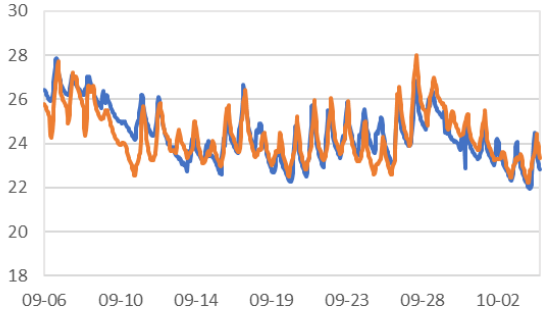
*Baba, F. M., Ge, H., Zmeureanu, R., & Wang, L. L. (2022). **Calibration of building model based on indoor temperature for overheating assessment using genetic algorithm: Methodology, evaluation criteria, and case study**. *Building and Environment*, *207*, 108518.

Automatic model calibration

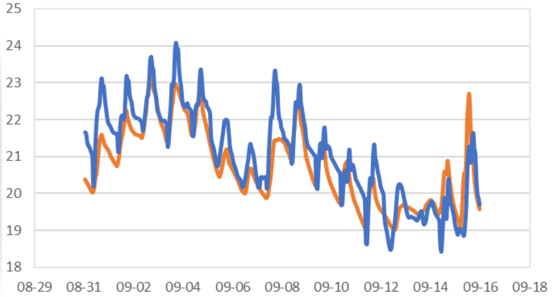
High accuracy were achieved as shown in these examples:

Measured temperature
Predicted temperature

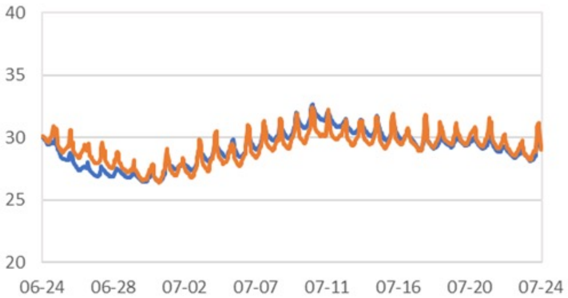
School 1



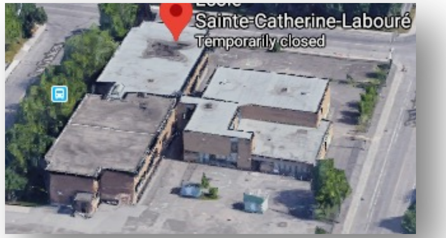
School 2

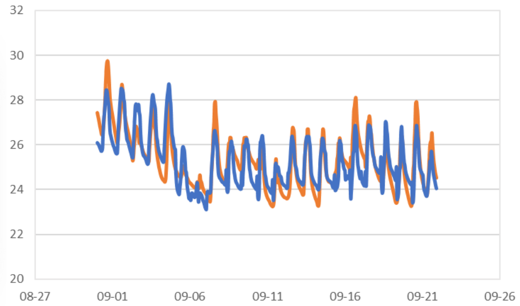


School 3

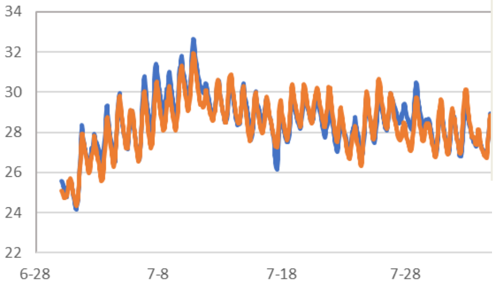


School 4



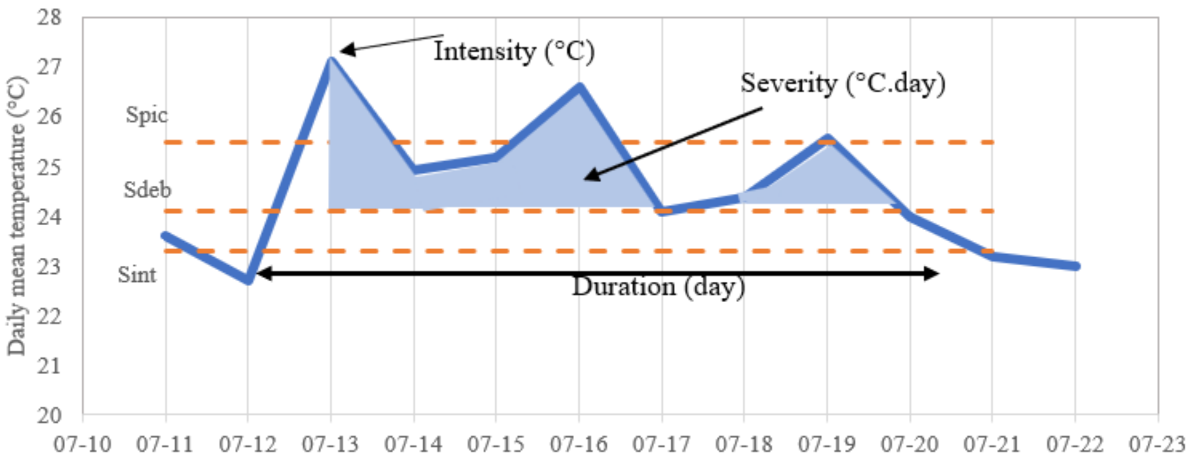


School 5

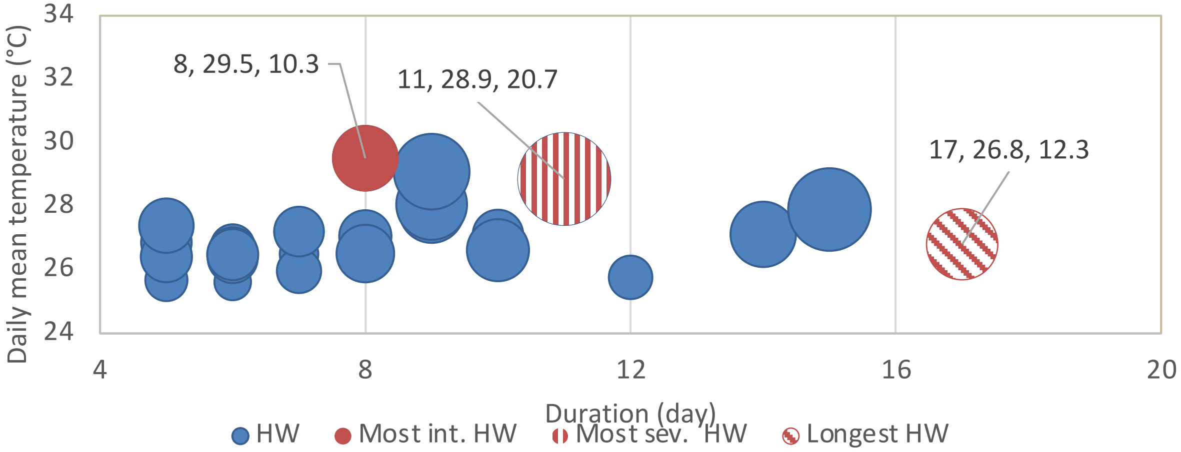


Baba, F. M., Cheong, K. C. T., Ge, H., Zmeureanu, R., Wang, L., & Qi, D. (2023). **Comparing overheating risk and mitigation strategies for two Canadian schools by using building simulation calibrated with measured data.** *Journal of Building Performance Simulation*, 1-19.

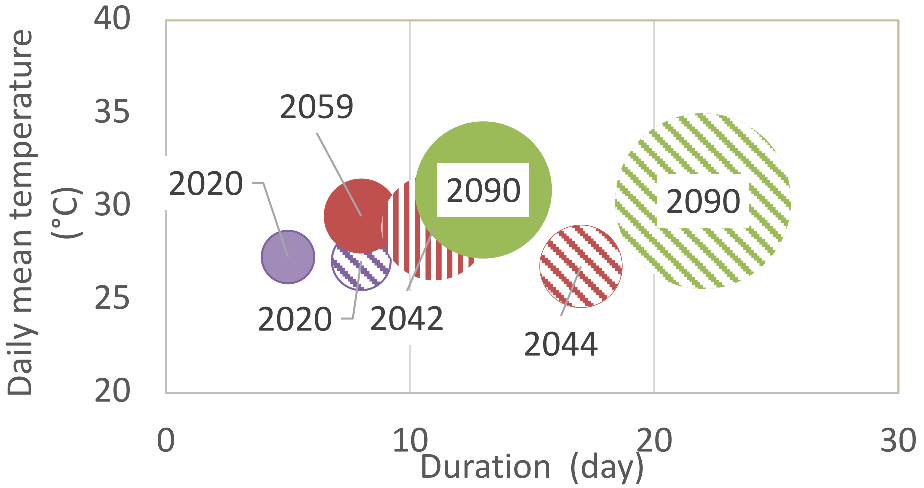
Detect the Extreme Year



- The "Heatwave Detection Operational" method is used to detect the extreme year.
- The year that has the most severe, intense, and/or longest heatwave is considered the extreme year



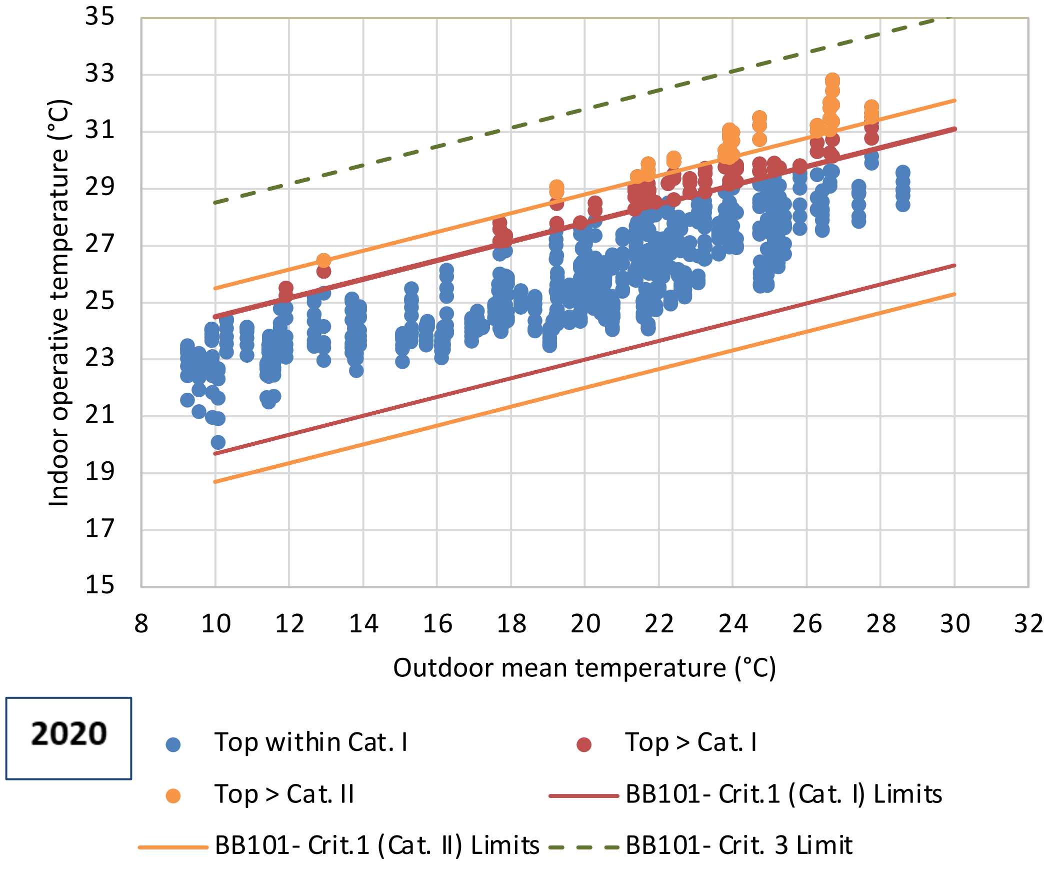
Heatwave events between 2041-2060



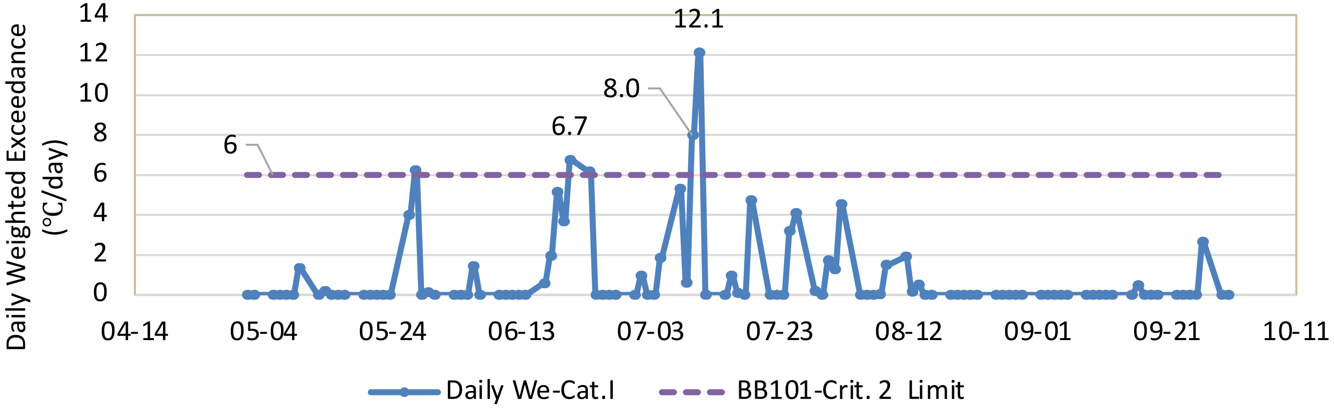
Baba, F. M., Ge, H., Wang, L. L., & Zmeureanu, R. (2023). **Assessing and mitigating overheating risk in existing Canadian school buildings under extreme current and future climates**. *Energy and Buildings*, *279*, 112710.

Overheating risk assessment

Overheating Risk in a School using BB 101 – EN 15251



Measurement period: 01 May 2020 - 31 September 2020				
Reference room	R 200	R 203	R 208	R 212
Number of overheating hours (T > Cat. 1) in the summer months. Acceptance limit is 40 hr	110	102	48	44
Number of days in the summer months that the Daily Weighted Exceedance (Cat.1) > 6 °C/day	3	3	0	0



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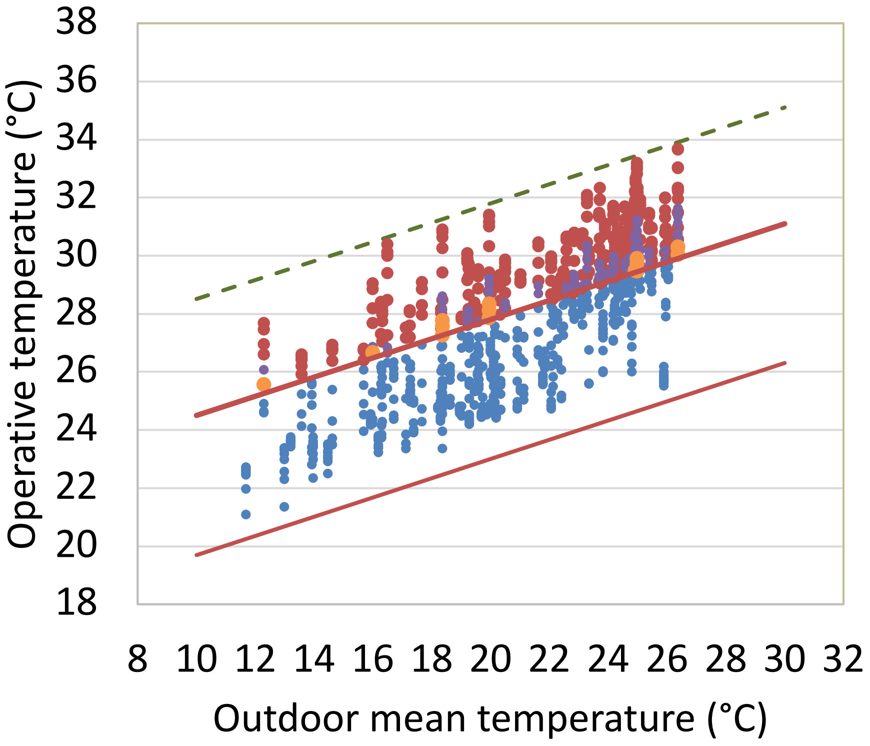
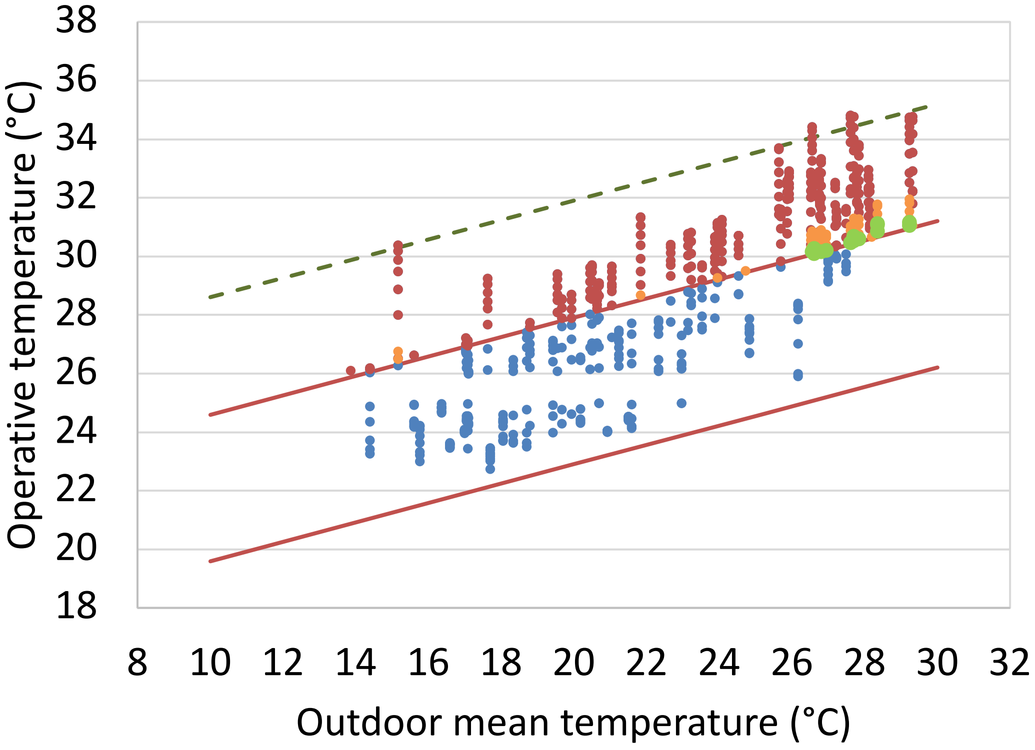
Overheating risk assessment with mitigation measures



(2044)



(2090)

- Top within Cat. I
- Top (No MM) > Cat. I
- Top (BR) > Cat. I
- Top (BR&NC) > Cat. I
- Top (BR&NC&CR) > Cat. I
- Criterion 1 (Cat. I) limits
- Criterion 3 (Cat. I) limits

BR: Exterior blind roll

NC: Night cooling

CR: Cool roof

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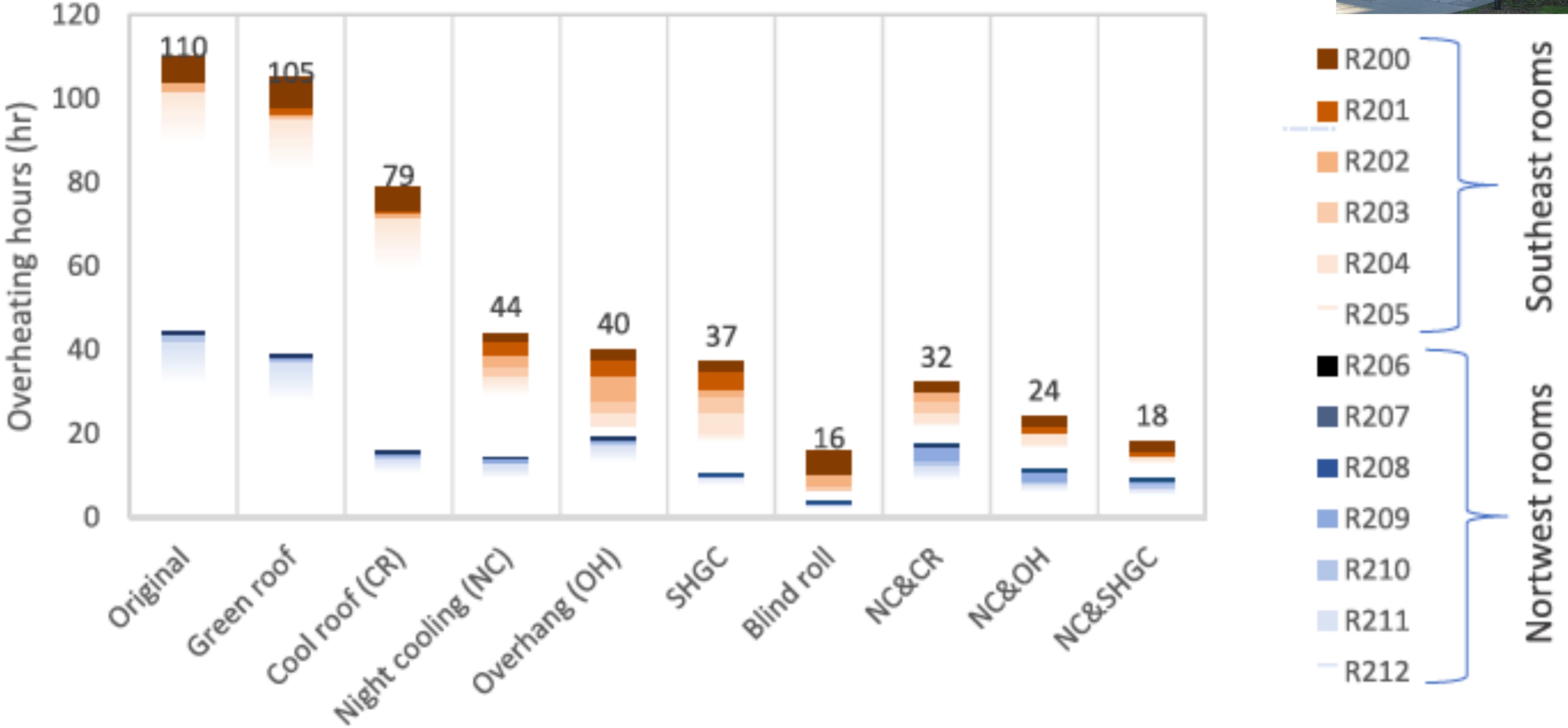
Overheating risk assessment with mitigation measures



(2090)

Baba, F. M., Ge, H., Wang, L. L., & Zmeureanu, R. (2023). **Assessing and mitigating overheating risk in existing Canadian school buildings under extreme current and future climates**. *Energy and Buildings*, *279*, 112710.

Durability: Assessing the hygrothermal performance of wood-frame walls under future climate

RESEARCH QUESTIONS:

- What is the moisture risks of wood-frame construction under future climate?
- Considering the uncertainty of future climates and the responses to the uncertain future climates, many simulations will be needed, what is the solution to this?
- How to select the representative moisture reference year to reduce the simulation load?

OBJECTIVES:

1. Develop a framework for the proper assessment of moisture risks of wood-frame construction under future climates
2. Evaluate reliability of existing climate-based indices (CBIs) in assessing moisture risks
3. Developing response-based indices (RBIs) for moisture assessment as it include the influence of wall instead of only climate data like in CBIs
4. Response-based Index (RBI) is influenced by weather parameters, by construction, and moisture loads.
    - Develop a model that could represent typical wood-frame constructions under typical moisture loads for similar climates.
5. Outcome: Evaluating the moisture risks of wood-frame construction under future climate using meta-model to reduce simulation efforts.

Climate data and uncertainty

- Different future climate scenario based on different levels of global warming levels
- F0 means historical period (1986-2016) and F7 means when global temperature increases by 3.5°C (2062-2092)
- Each scenario in between represents 0.5°C rise in global temperature as compared to F0

F0 F1 F2 F3 F4 F5 F6 F7

R1
R2
R3
|
R14
R15

Different runs due to different initial conditions used in climate model

- Temperature
- RH
- Cloud

|
etc.

In this study, we use:

1. F0 and F7 to compare historical and the pessimistic scenario
2. Median run based on Moisture index

Methodology

Approach to reduce simulation load:

Response-based Index (RBI) based prediction model to rank years for Moisture Reference Year selection; predict wall performance using meta-model

Anticipated outcome:

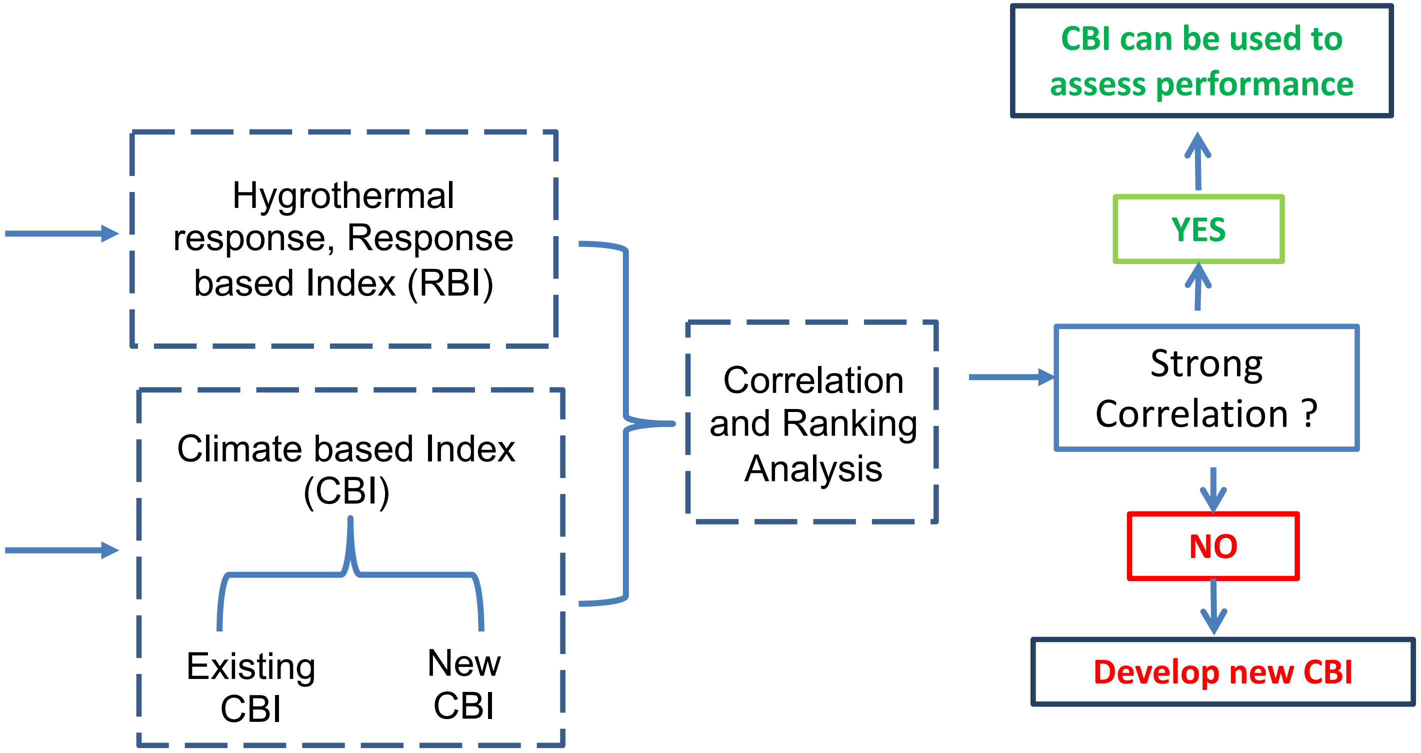
- CBI gives an estimated wall performance
- CBI rank the years in a manner similar to RBI to construct MRY
- Chosen cities, walls and climate run works for all other possible scenarios

City:
Out of the many Canadian cities, 4 was selected as representative

Climate period:
Among different scenarios of climate change, historical and future projected with rise of 3.5°C global temperature [RCP 8.5]

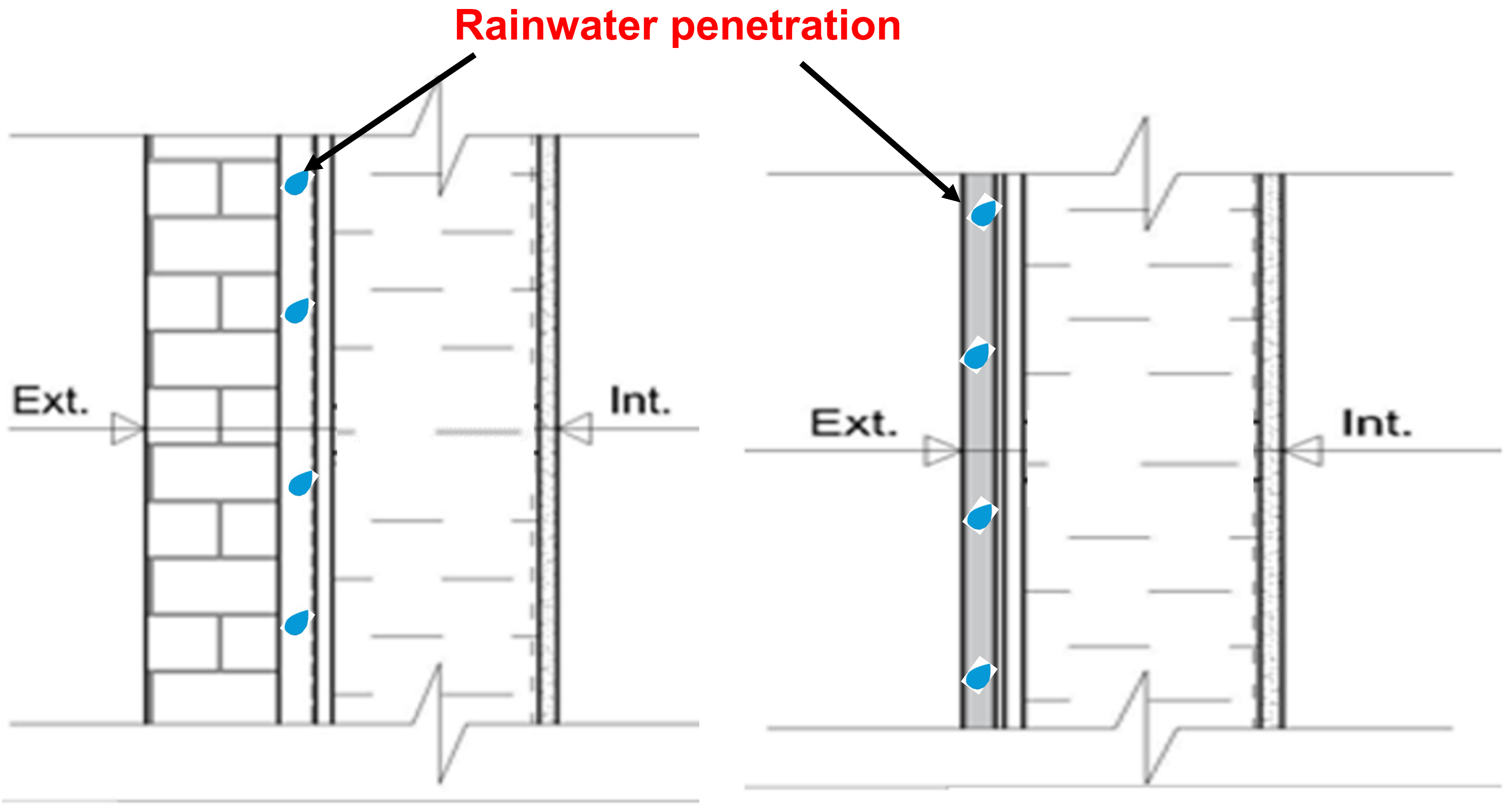
Climate uncertainty:
15 different **RUNS** are available, one run was selected

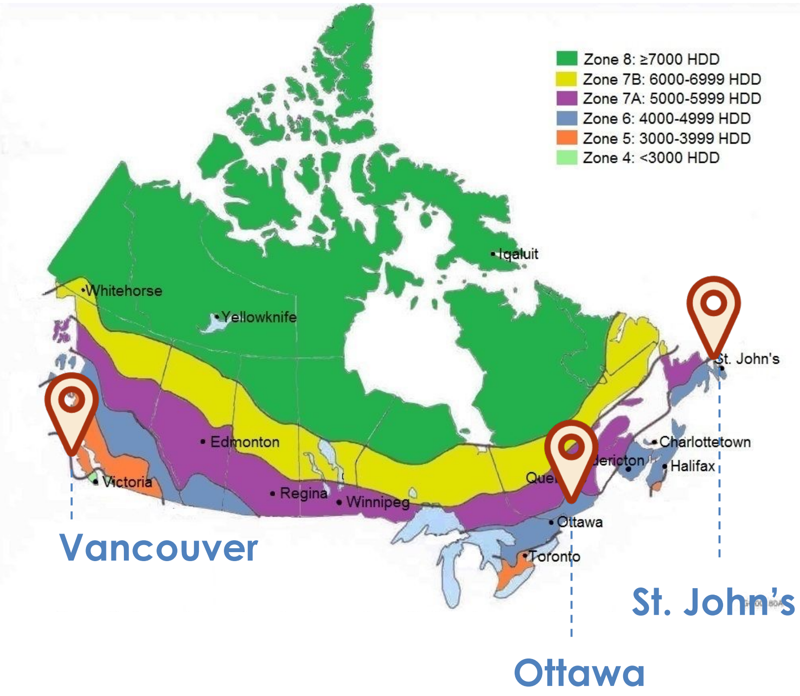
Wall assembly:
Brick veneer and stucco cladding wood frame wall was used for the analysis



Wall assemblies and cities

Brick veneer cladding wall Stucco cladding wall





Methodology for developing Partial Least Square (PLS)regression model

PLS analysis

Training set

Parameters

Group of Cities	Ottawa, Vancouver and St. John’s
Climate	Historical and Future (Median run based on MI)
Wall orientation	6 wall orientations (Cardinal and orientation with least and highest WDR)
Climate years	16 years per wall orientation per climate period

Climate variables

- Yearly avg, max and min of 5 variables (Temperature, RH, Wind speed, WDR and normal solar radiation)
- Selecting most influential variables
- Kept only yearly average variables

Test set

Cities	Ottawa, Vancouver and St. John’s
Climate	Historical and Future
Wall orientation	Any random wall orientation

Regressor

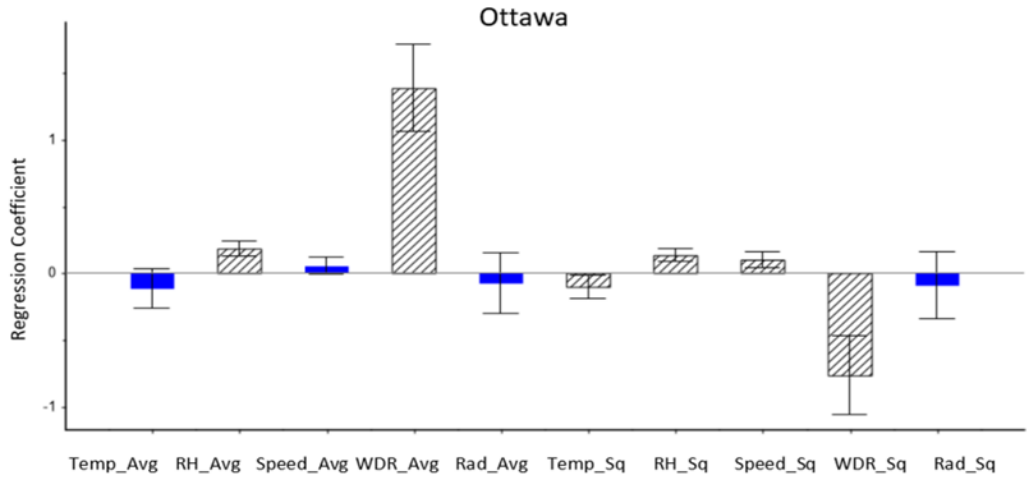
Response variable

Maximum Mould Index

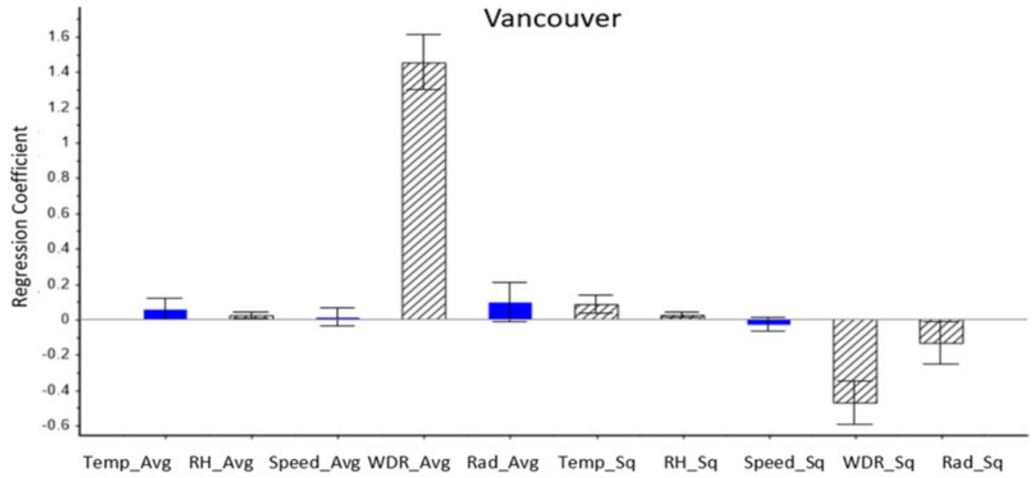
PLS regression equation

Predicted response

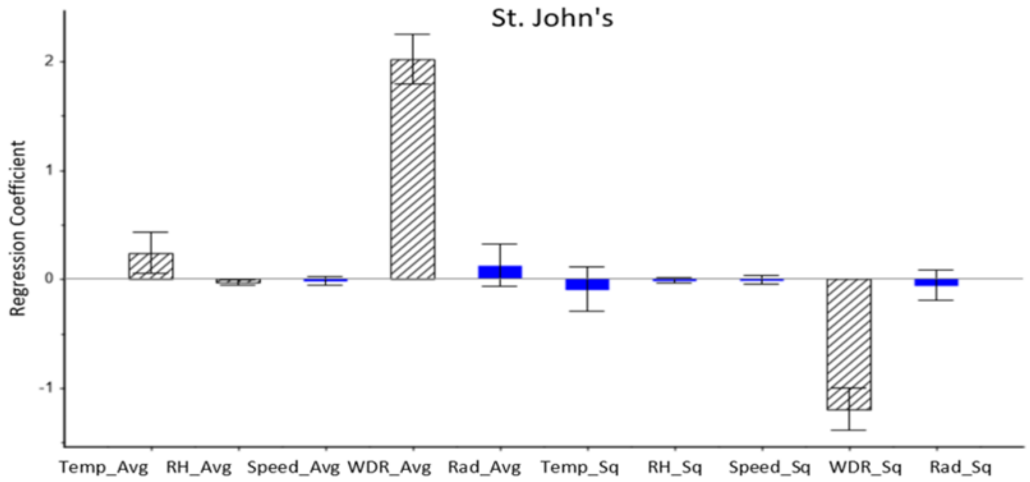
PLS models for different cities



$$\mathbf{Mould} = -13.77726 - 0.0421 * \mathrm{T_{avg}} + 13.8374 * \mathrm{RH_{avg}} + 1.7442 * \mathrm{Speed_{avg}} + 101.3418 * \mathrm{WDR_{avg}} - 0.0038 * \mathrm{Rad_{avg}}$$



$$Mould = -3.6923 + 0.1118 * T_{avg} + 3.7850 * RH_{avg} + 0.3543 * Speed_{avg} + 48.5317 * WDR_{avg} + 0.0088 * Rad_{avg}$$

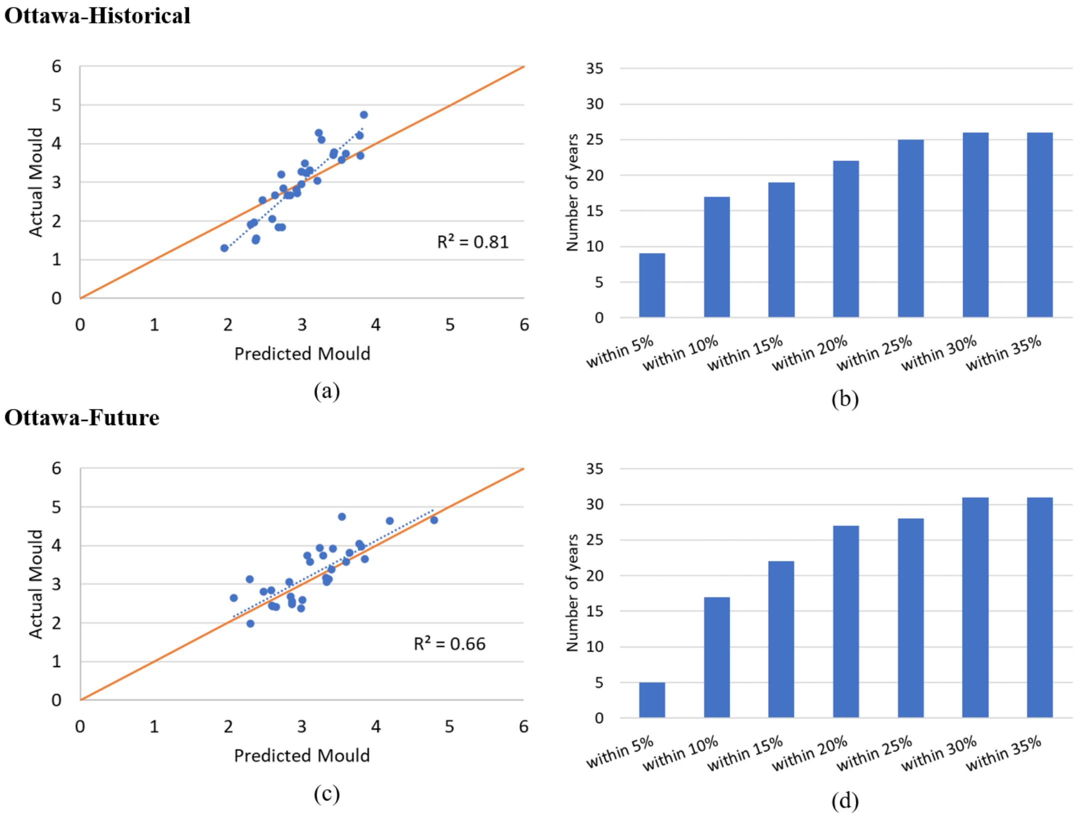


$$Mould = 5.71795 + 0.0619 * T_{avg} - 4.7976 * RH_{avg} + 83.1395 * WDR_{avg} - 586.4042 * WDR_{avg}^2$$

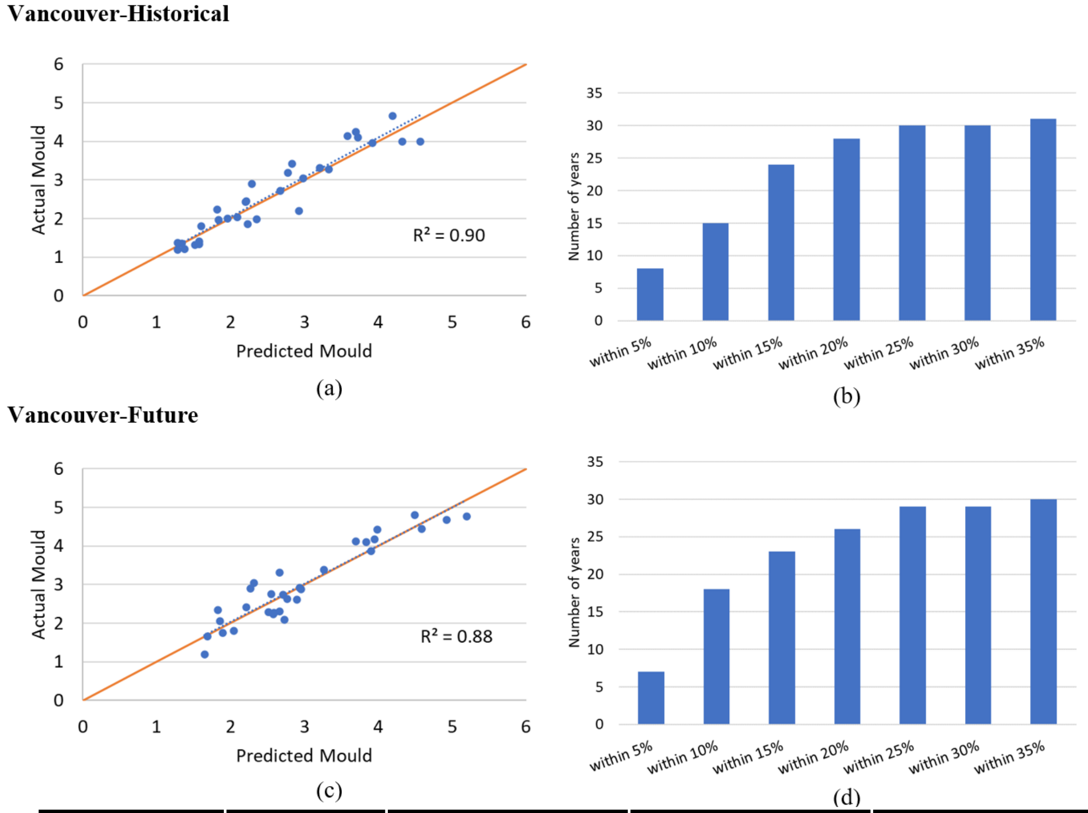
C. Aggarwal, H. Ge, M. Defo, M.A. Lacasse, Hygrothermal performance assessment of wood frame walls under historical and future climates using partial least squares regression, Build. Environ. 223 (May) (2022), 109501, https://doi.org/10.1016/j.buildenv.2022.109501.

Performance of PLS model

Ottawa



Vancouver



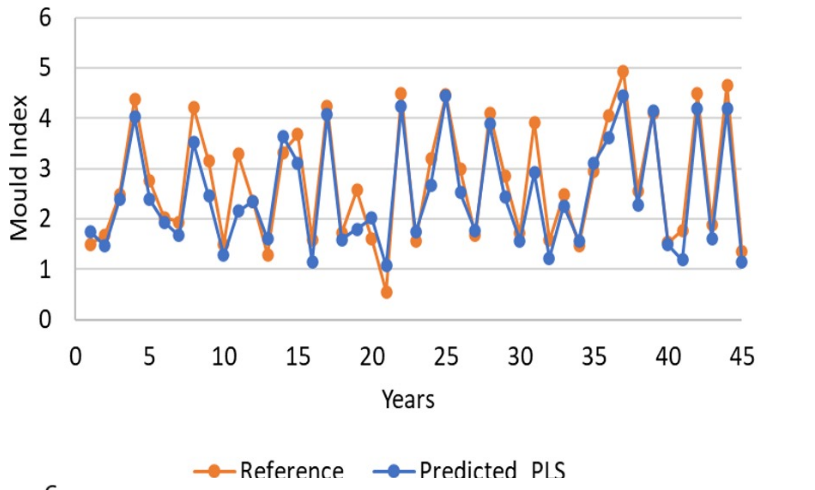
Case	R^2	RMSE (31)	Matches (3)	Matches (5)
Ott-His	0.81	0.50	2	2
Ott-Fut	0.66	0.44	2	4

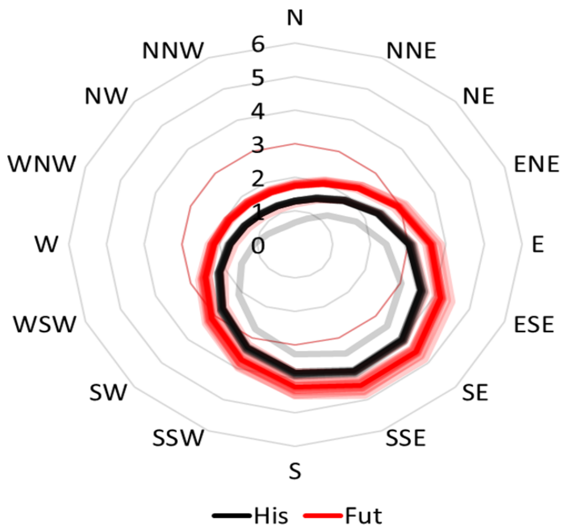
Case	R^2	RMSE (31)	Matches (3)	Matches (5)
Van-His	0.90	0.34	1	3
Van-Fut	0.88	0.35	2	5

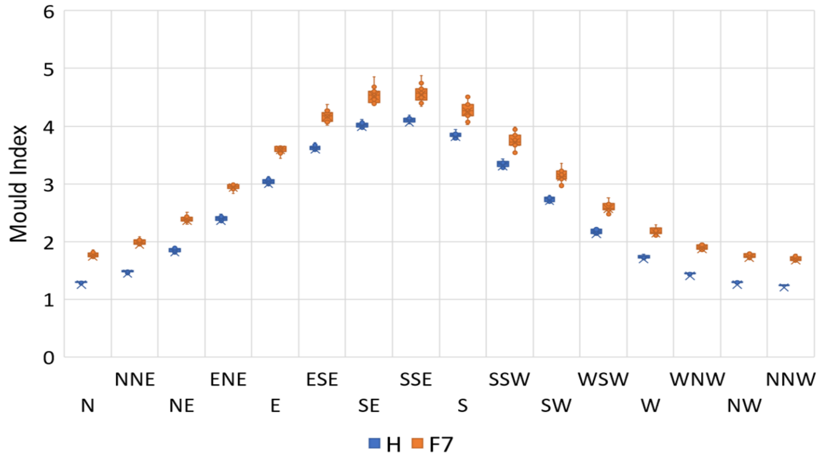
C. Aggarwal, H. Ge, M. Defo, M.A. Lacasse, Hygrothermal performance assessment of wood frame walls under historical and future climates using partial least squares regression, Build. Environ. 223 (May) (2022), 109501, https://doi.org/10.1016/j.buildenv.2022.109501.

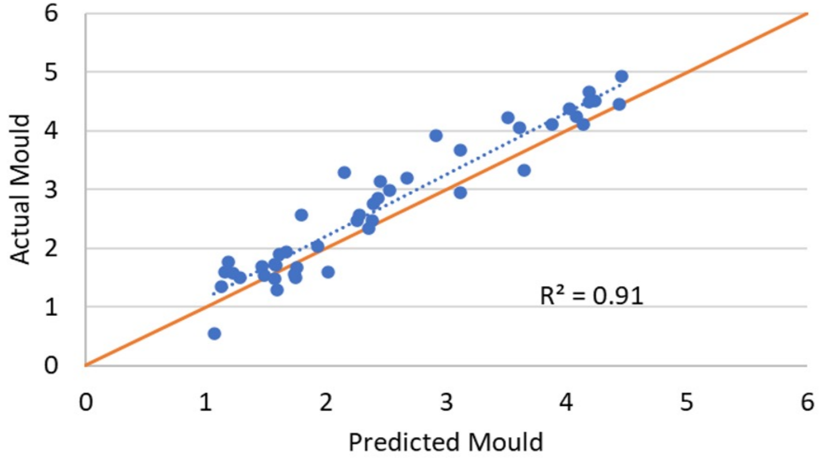
Performance of PLS model

Model trained on median run and prediction on all runs (Vancouver)









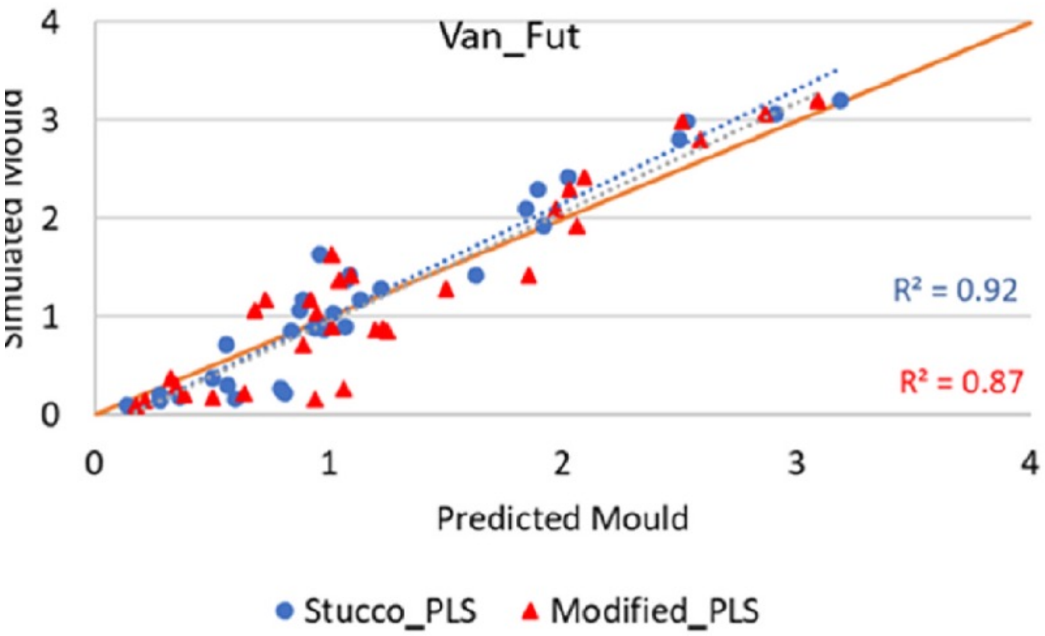
- Random years and wall orientations selected among 15 runs
- Model was able to predict well the mould index for random years, for all runs and wall orientations for historical and future period
- Mould risks increases over the future period

Performance of PLS model

Stucco trained model v/s modified brick PLS model for Vancouver

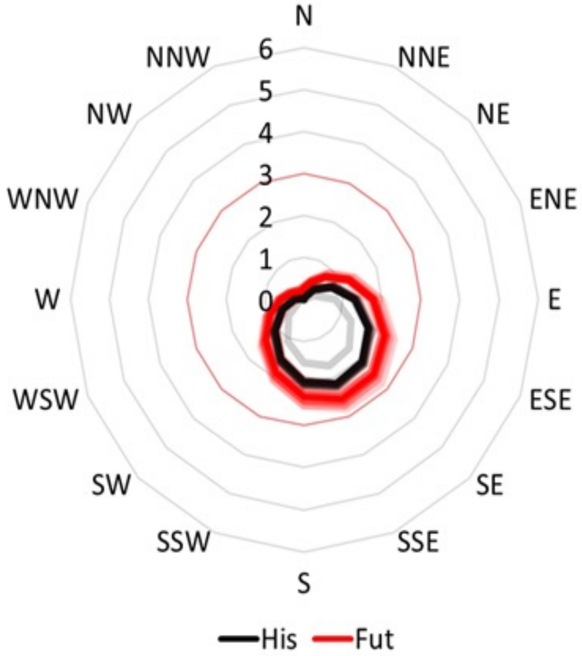
Stucco trained PLS model

$$Mould = -1.4629 + 0.0583 * T_{avg} + 1.8737 * RH_{avg} - 0.0001 * Speed_{avg} + 52.4045 * WDR_{avg} - 0.0091 * Rad_{avg}$$



Modified brick PLS model

$$Mould = -4.205 + 0.0917 * T_{avg} + 3.1063 * RH_{avg} + 0.2907 * Speed_{avg} + 39.8299 * WDR_{avg} + 0.0072 * Rad_{avg}$$

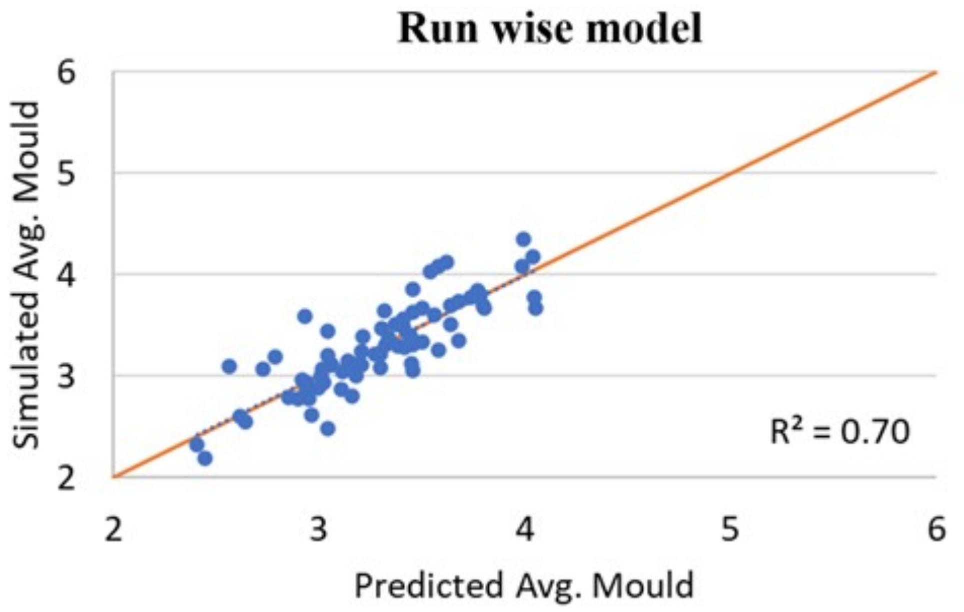


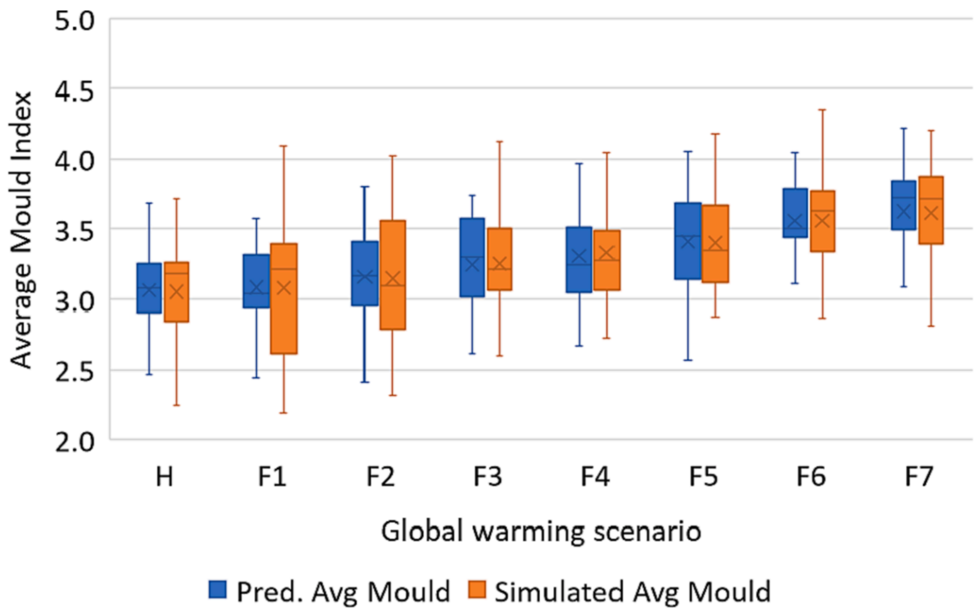
C. Aggarwal, H. Ge and M. Defo, "Assessing mould growth risk of wood-frame walls using partial least squares (PLS) regression considering climate model uncertainties," Build. Environ., vol. 238, no. June, p. 110374, 2023, doi: 10.1016/j.buildenv.2023.110374.

Performance of PLS model

31 consecutive/ run-wise PLS model

- The results shown so far were for yearly simulations. However, for long term performance assessment, run-wise (31 consecutive years) results are needed.
- PLS model developed using average mould index as performance indicator for 15 runs and 8 time periods (historical and 7 global warming periods).





C. Aggarwal, L. Wang, H. Ge, M. Defo, M. Lacasse (2024). Long-term hygrothermal performance assessment of wood-frame walls considering climate uncertainties using partial least squares (PLS) regression. Energy and Buildings, 307(113953). https://doi.org/10.1016/j.enbuild.2024.113953

CONCLUSIONS

New climate-based index (PLS regression model):

- Model was able to predict the mould index within certain range for most of the years
- Model was able to rank well the top 3/5 years
- Model developed using median run can be used for all the runs
- Model developed for brick cladding can be used for stucco cladding wall

Application of PLS regression model to run-wise simulations:

- Developed methodology for yearly simulations can be applied to run-wise simulations
- An R^2 of 0.70 was noted
- The model can rank well the runs in different global warming scenarios

CONCLUSIONS

- **Ease of using PLS model**
  - No prior knowledge of DELPHIN/WUFI needed
  - Practitioner can use the PLS model get results in seconds
- **Model helps in reducing the simulation time exponentially**
  - 31 consecutive years 1D simulations (8 hours for a batch of 15)
  - 1-year 1D simulations (40 minutes for a batch of 31)
  - PLS model (within 2 seconds)
- **Model can be used as an initial screening to reduce the number of simulations**
  - Running PLS model and doing simulations only for cases that requires attention

Frost Damage Assessment of Internally Insulated Historic Solid Masonry under Projected Future Climates in Canada

RESEARCH QUESTIONS:

- Is it safe to internally insulate historic masonry walls under projected future climates in Canada?

OBJECTIVES:

1. **Develop a framework** for the proper assessment of **FT** damage of masonry walls;
   - Evaluate reliability of current MRYs selection methods in assessing **FT** risks;
   - Develop a reliable method for selection of MRY appropriate for assessing **FT** risks;
2. **Assess FT damage risks** of historic masonry wall with interior insulation under historical and projected future conditions;
3. **Investigate and develop best strategies to safely retrofit historic walls with interior insulation – Outcome:** Provide recommendations for optimal wall designs and appropriate types and thicknesses of insulation.

Frost Damage Assessment of Internally Insulated Historic Solid Masonry under Projected Future Climates in Canada

Is it safe to internally insulate historic brick masonry walls?

Assess the impact of interior insulation on the FT risk of historic brick walls under future climates.

How?

1 **PROPER MODELLING OF INPUT PARAMETERS**

- Meteorological Data
- Wall Configuration
- Boundary Conditions

Hygrothermal simulations using?

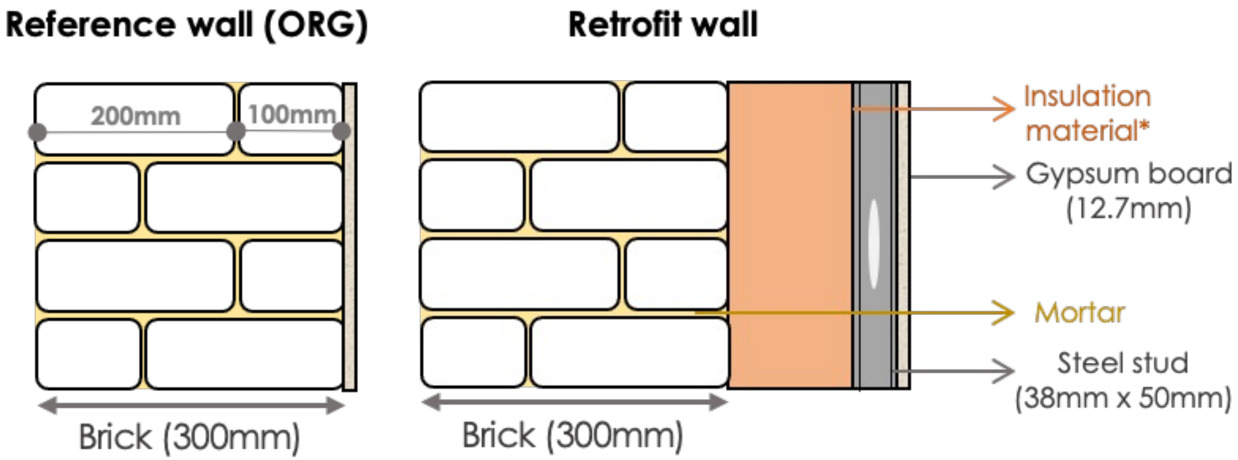
31 years continuous simulations? OR One MRY?

2 **Evaluate the reliability of existing methods to select an MRY appropriate for frost damage analysis**

3 **Develop a methodology for a proper modelling to select an MRY reliable for frost damage analysis**

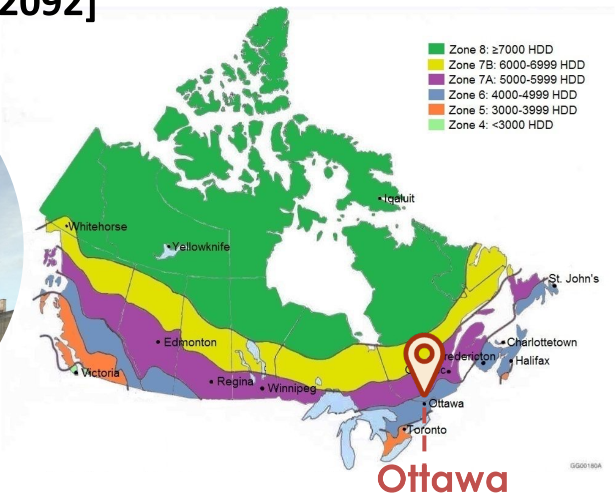
Frost Damage Assessment of Internally Insulated Historical Solid Masonry under Projected Future Climates in Canada

Typical historic brick wall geometry



Weather data:

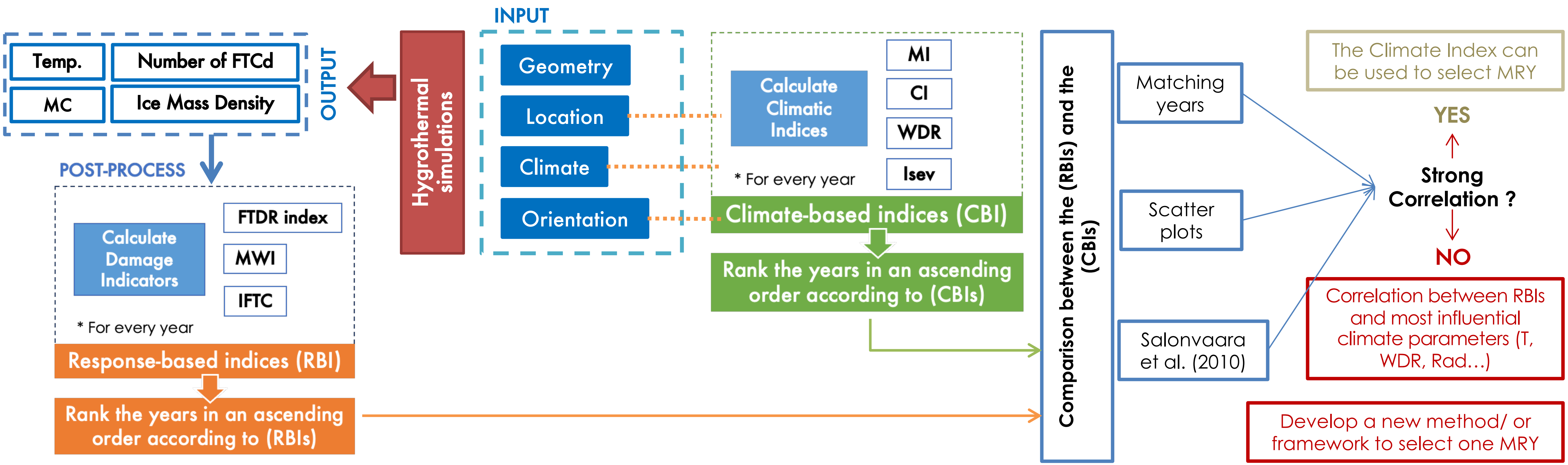
- **Historical period [1986 – 2016]**
- **Future period [2062 – 2092]**



FT damage indicators:

- **FTCcrit:** The number of critical FT cycles calculated when two conditions exist concurrently: 1) $MC_{material}$ > $Scrit_{material}$, and 2) $T_{material}$ fluctuates below and above the $T_{freezing}$ assumed to be 0°C *(Sedlbauer and Künzel, 2000; van Aarle et al., 2015).*
- **FTCd:** The number of FT cycles obtained from DELPHIN *(Nicolai et al., 2013; Sontag et al., 2013).*

I. The reliability of existing methods to select an MRY appropriate for freeze-thaw damage analysis – **METHODOLOGY:**



Sahyoun, S.; Ge, H.; Lacasse, M.A.; Defo, M. Reliability of Existing Climate Indices in Assessing the Freeze-Thaw Damage Risk of Internally Insulated Masonry Walls. *Buildings* 2021, 11, 482. https://doi.org/10.3390/buildings11100482

I. The reliability of existing methods to select an MRY appropriate for freeze-thaw damage analysis – **METHODOLOGY:**

- MRY indices (CBI):

1. Moisture Index (MI):
(Cornick *et al.*, 2003)

$$MI_h = \sqrt{(1 - DI_{h,norm})^2 + (WI_{h,norm})^2}$$

$\Delta p_v = p_{vs} - p_v$

$Rain_{h,norm}$ or WDR_{annual}

2. Severity Index (Isev):
(ASHRAE, 2010)

$$I_{sev} = 108307 - 241.E_v - 1391.I_{cl} - 312326.\phi + 183308.r_{wd} + 15.2.p_v + 27.3.T^2 + 261079.\phi^2 - 0.00972.p_v^2$$

Solar radiation (W/m2) (E_v); Cloud index (0-8) (I_{cl}); 0< RH <1 (ϕ); Vapor pressure (Pa) (p_v); WDR(kg/m2.h) (r_{wd}); Temperature (°C) (T)

3. Climatic Index (CI):
(Zhou *et al.*, 2017)

$$CI = \frac{Annual\ WDR\ load}{Annual\ potential\ evaporation}$$

ASHRAE Standard – 160:

$$R_{WDR} = 0.2\,.\,R_H\,.\,F_E\,.\,F_D\,.\,V_{10}\,.\,cos\theta$$

$$E = \frac{\Delta}{\Delta+\gamma}\cdot\frac{K+L-A}{I} + \frac{\gamma}{\Delta+\gamma}h_m(e_a - e)$$

Radiation   Turbulence

I. The reliability of existing methods to select an MRY appropriate for freeze-thaw damage analysis – **METHODOLOGY:**

- Freeze-Thaw (FT) damage indicators (RBI):

1. **Number of Indicative FT Cycles (IFTC):** (Koci *et al.*, 2017)

$$IFTC = \sum_{i=1}^{8760}[T_i < T_L \cap w_i > w_L]$$

(where freezing must take at least 2 hours, separated by at least 2 hours of thawing)

2. **Modified Winter Index (MWI):** (Koci *et al.*, 2017)

$$MWI = \sum_{i=1}^{8760}(T_L - T_i)(w_i - w_L) \quad when\ [T_i < T_L \text{ and } w_i > w_L]$$

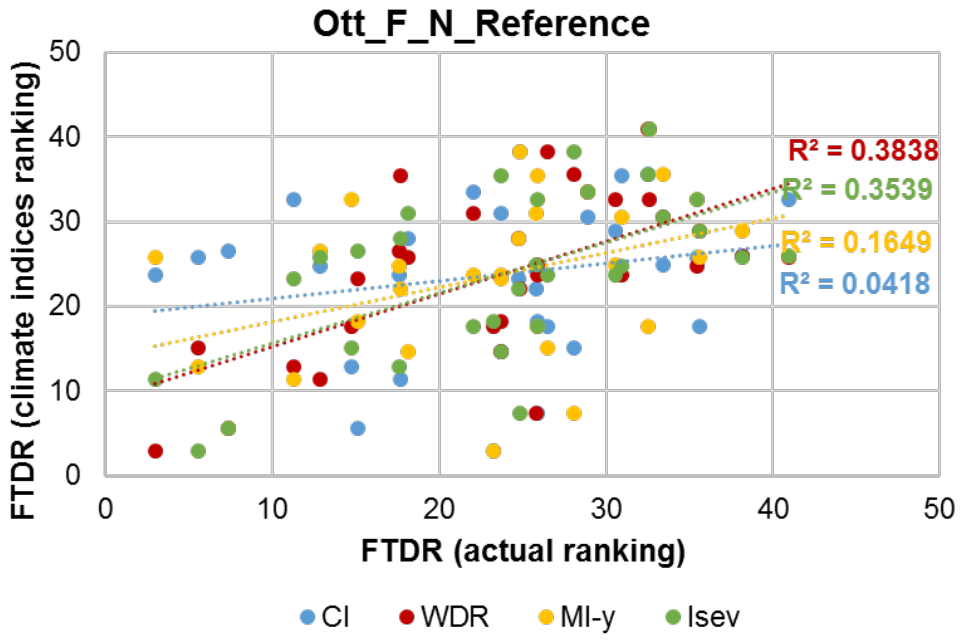
3. **FT Damage Risk (FTDR) index:** (Zhou *et al.*, 2017)

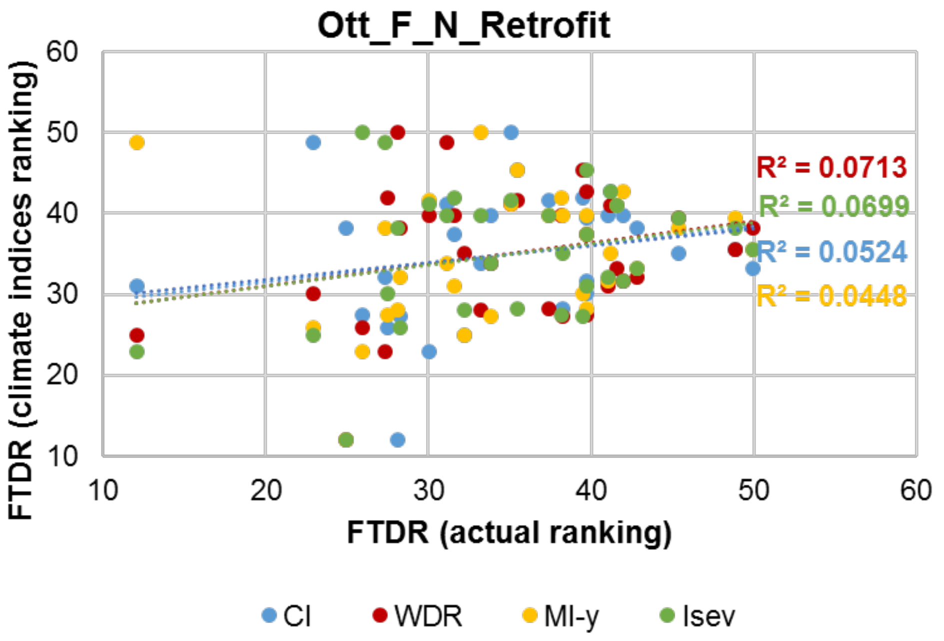
$$FTDR\ index = \sum_{cycle}(S_{ice,max} - S_{ice,min})\ ; \quad for\ (S_{ice,max} - S_{ice,min}) > 0.05$$

Where; $T_L = T_{crit}$ (K); $W_L = W_{crit}$ (% m^3/m^3); $T_i = T_{hourly,pt}$ (K) and $W_i = W_{hourly,pt}$ (% m^3/m^3)

I. The reliability of existing methods to select an MRY appropriate for freeze-thaw damage analysis – **RESULTS:**

The correlation between climate-based indices (CBI) and the response-based indices (RBI): was found weak and not consistent, which means that CBIs alone do not represent the actual performance of the walls; and therefore, cannot be used to select MRY for frost damage.

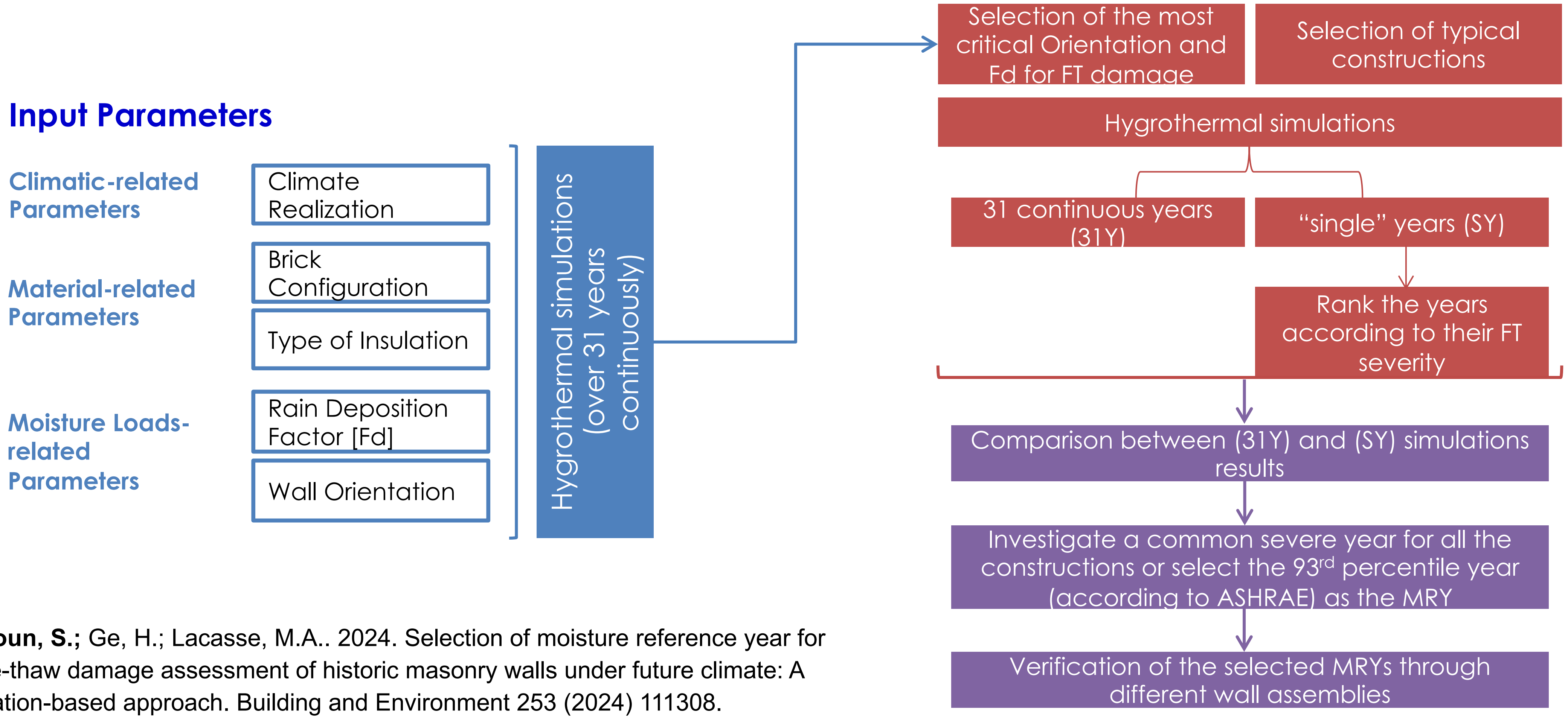




Figures: *Correlation between the actual ranking of FTDR and FTDR based on the climatic indices ranking.*

Sahyoun, S.; Ge, H.; Lacasse, M.A.; Defo, M. Reliability of Existing Climate Indices in Assessing the Freeze-Thaw Damage Risk of Internally Insulated Masonry Walls. *Buildings* 2021, 11, 482. https://doi.org/10.3390/buildings11100482

II. A framework to select an MRY reliable for frost damage analysis – **Simulation based approach**



Sahyoun, S.; Ge, H.; Lacasse, M.A.. 2024. Selection of moisture reference year for freeze-thaw damage assessment of historic masonry walls under future climate: A simulation-based approach. Building and Environment 253 (2024) 111308.

II. A framework to select an MRY reliable for frost damage analysis

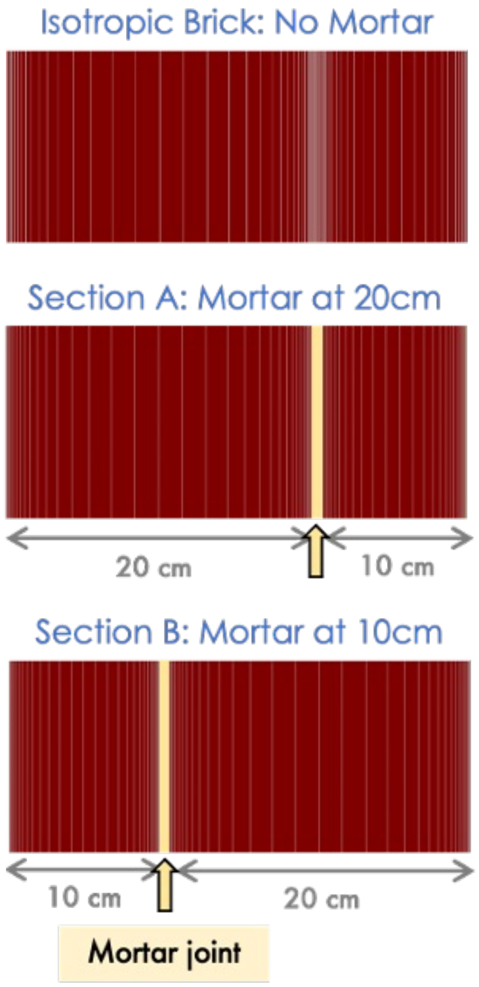
Table 1. 31-year continuous simulations input parameters and their variations.

Input Parameter	Variation	Description
Location	1	Ottawa
Climate realizations	4	Run2, Run4, Run9 and Run10
Time period	2	Historical (1986-2016) Future (2062-2092)
Wall orientation	8	North (N), North-East (NE), East (E), South-East (SE), South (S), South-West (SW), West (W) and North-West (NW)
Rain deposition factor	3	0.35, 0.5 and 1.0
Brick modelling configuration	3	Isotropic brick, brick with mortar at 20cm and brick with mortar at 10cm
Brick property	1	$S_{crit} = 0.55$
Internal insulation type	3	No insulation (ORG), Spray Foam Polyurethane (SPF) and Calcium Silicate (CaSi)

Table 2. Single year's (SY) simulations input parameters and their variations.

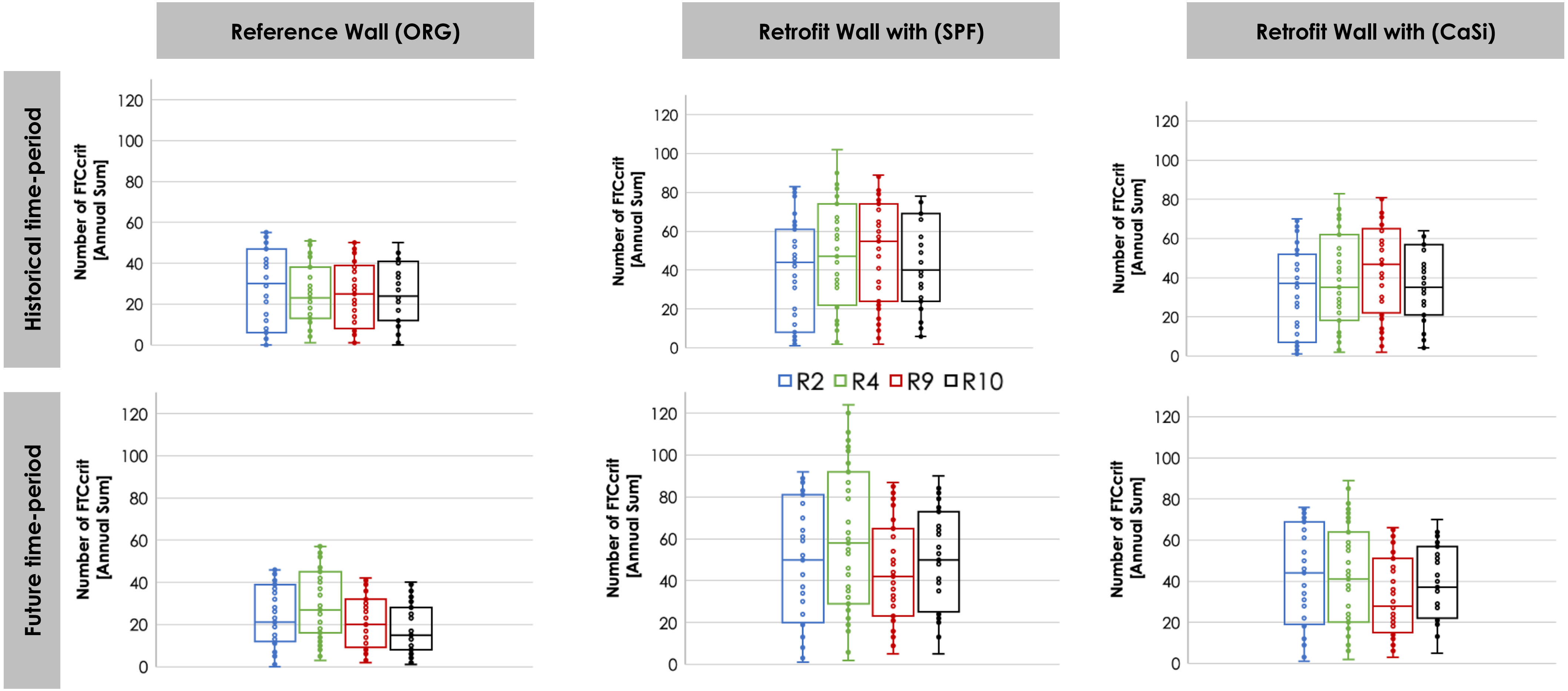
Input Parameter	Variation	Description
Location	1	Ottawa
Climate realizations	1	Run4
Time period	2 x 31	Historical (1986-2016) Future (2062-2092)
Wall orientation	1	East (E)
Rain deposition factor	1	1.0
Brick modelling configuration	1	Brick with mortar at 20cm
Brick property	1	$S_{crit} = 0.55$
Internal insulation type	4	No insulation (ORG), Spray Foam Polyurethane (SPF), Calcium Silicate (CaSi) and Mineral Wool (MW)
Internal insulation thickness	3	50mm, 100mm and 200mm

Configuration of typical brick masonry wall assemblies:



II. A framework to select an MRY reliable for frost damage analysis – **RESULTS:**

A. Impact of different climatic realizations:



II. A framework to select an MRY reliable for frost damage analysis – **RESULTS:**

B. Impact of different brick modeling configuration:

Figure: Correlation between the number of FTC when counting **FTCcrit** and **FTCd** when mortar joint is applied at 20cm and at 10cm from the ext. surface of the brick.

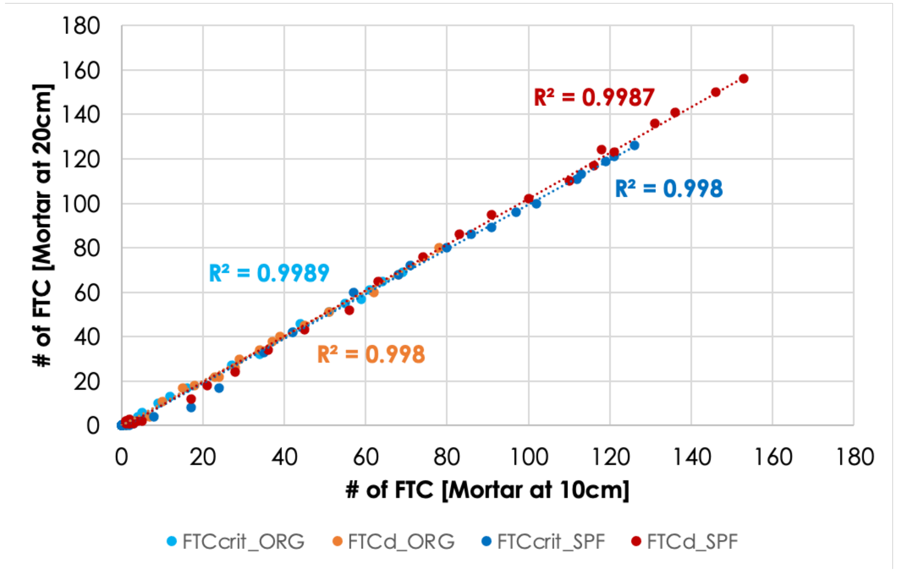
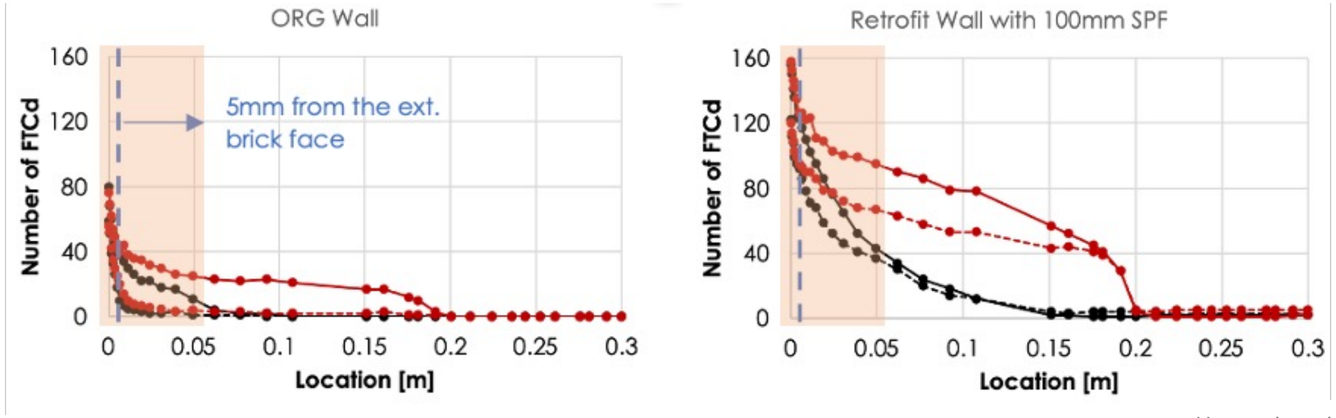


Figure: Comparison between two brick configurations (**with mortar** and **without mortar**) throughout the brick material.



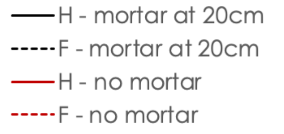
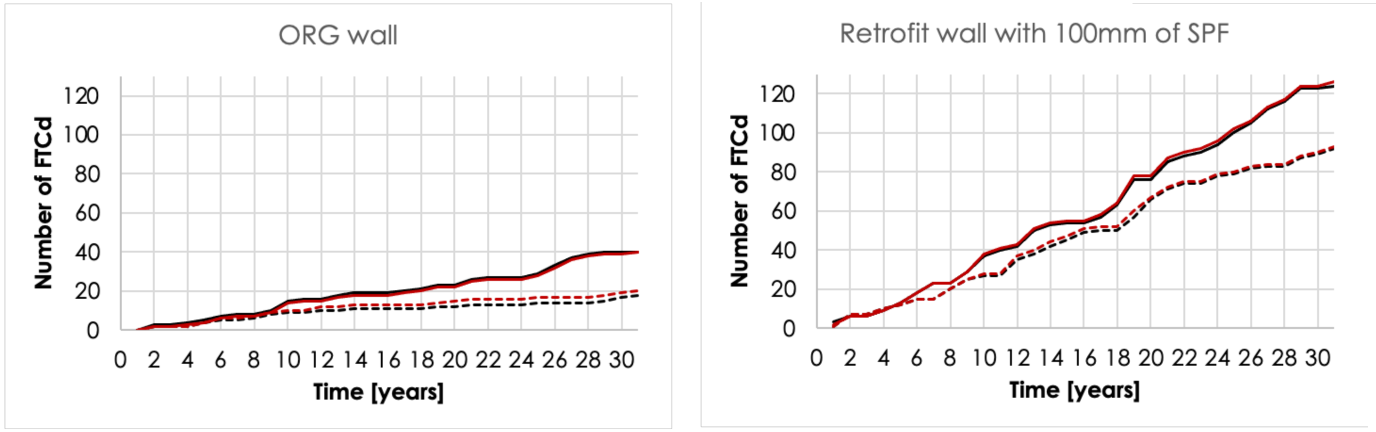
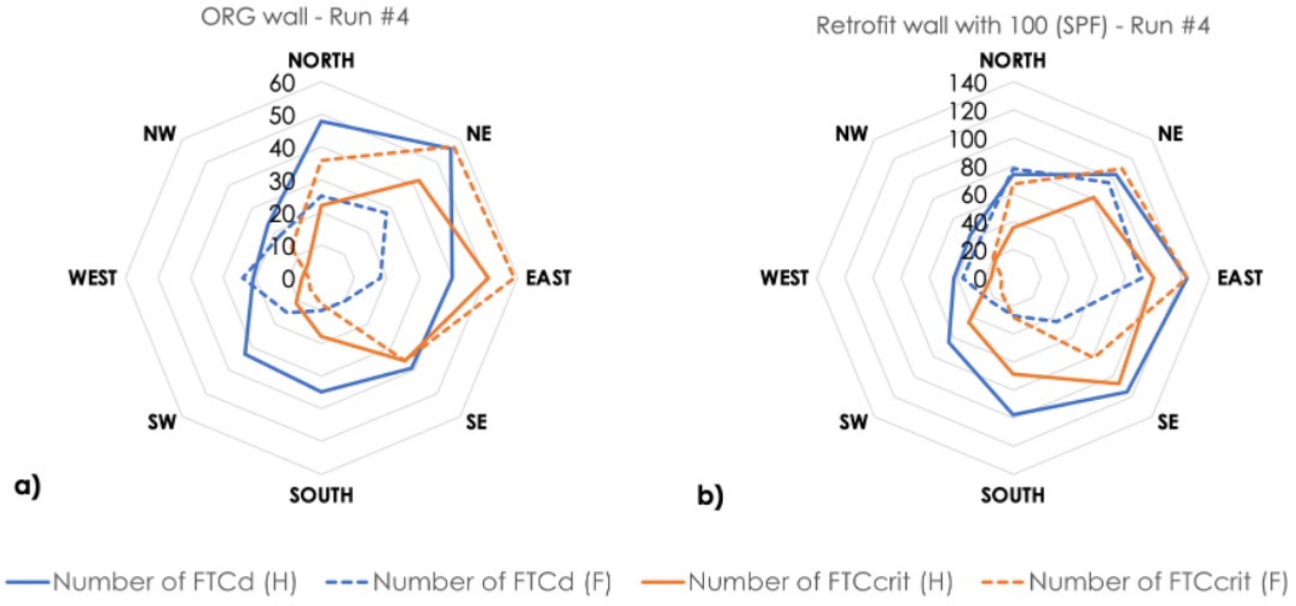


Figure: Comparison between two brick configurations (**with mortar** and **without mortar**) at 5mm from the ext. brick.

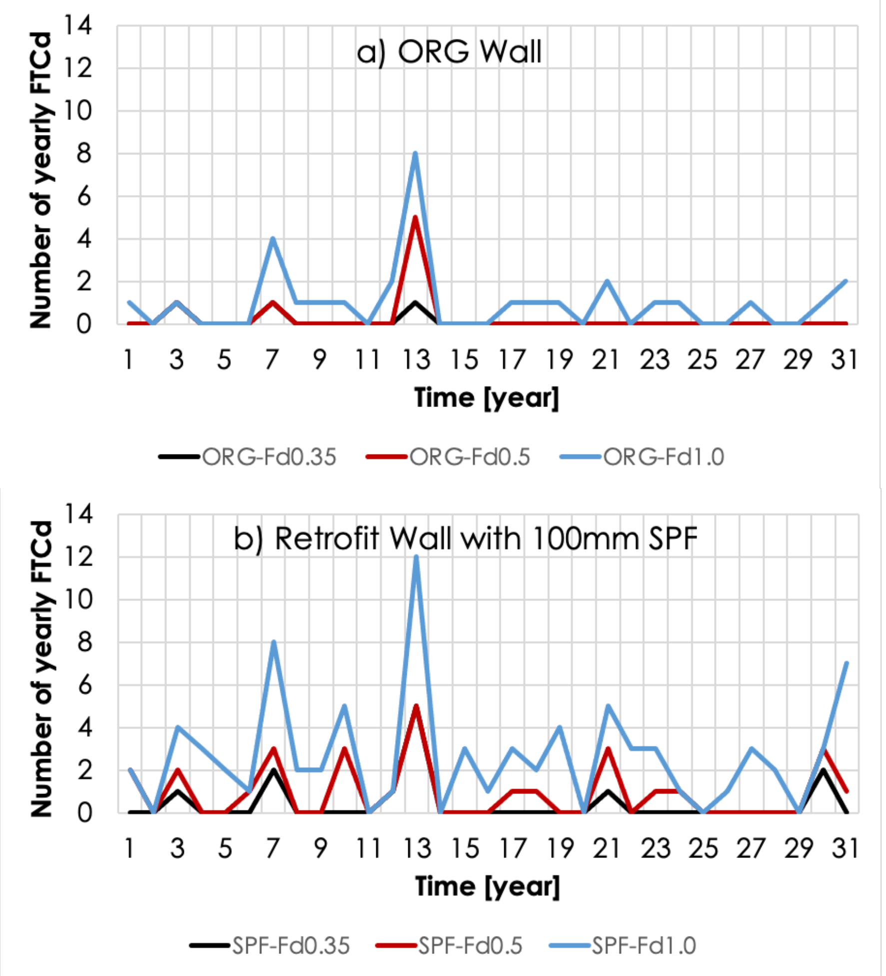


II. A framework to select an MRY reliable for frost damage analysis – **RESULTS:**

C. Impact of different wall orientations:



D. Impact of rain deposition factor [Fd]:



II. A framework to select an MRY reliable for frost damage analysis – **RESULTS:**

E. Comparison between 31Y and single years:

Figure: The total number of FTCd per year following consecutive (31Y), and when each year is simulated alone as (SY).

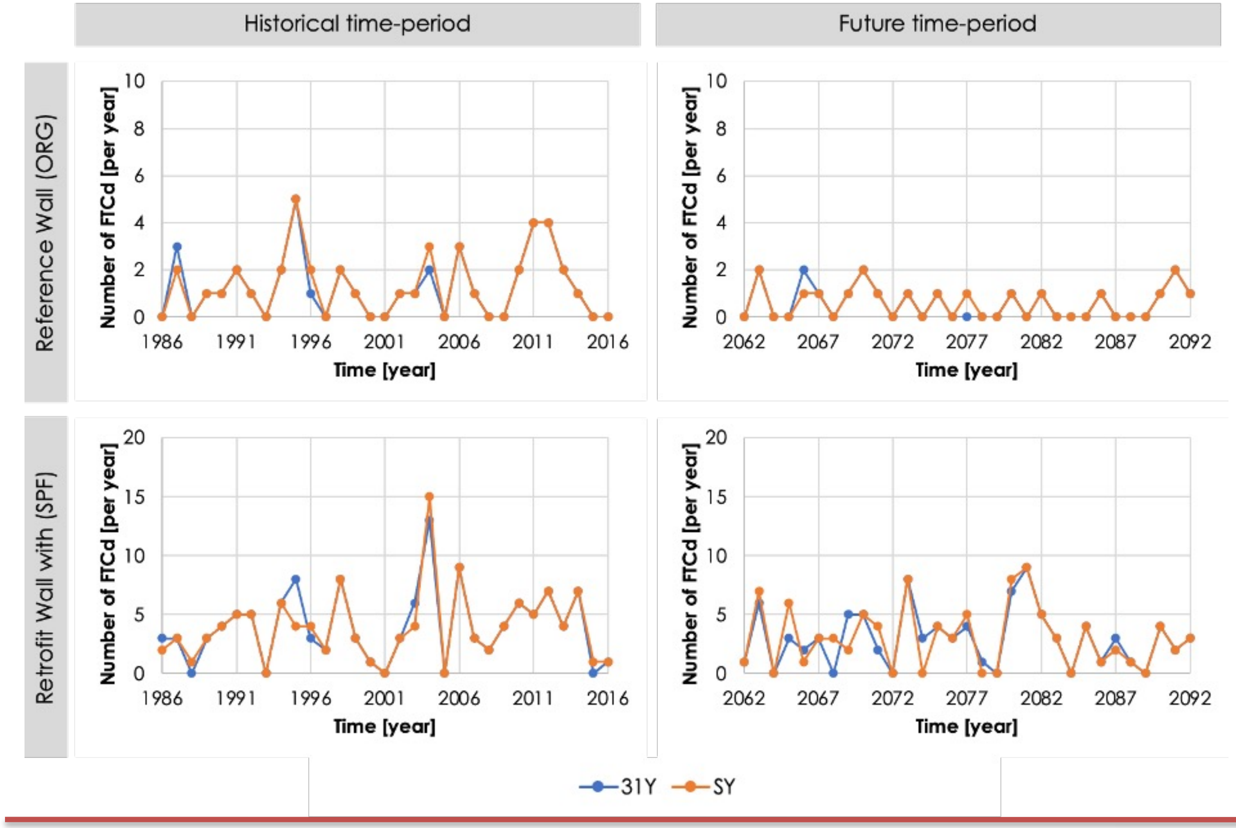


Table: The top four (SY) ranked in a descending order according to their FT damage severity

Climate	Wall type	Ranking of the years (descending order of the FT damage risk)			
		First	Second	Third	Fourth
H	ORG	1995	2012 2011	**2004** **2006**	1987
	SPF	**2004**	**2006**	1998	2012 2014
	CaSi	**2004**	**2006**	2012 2014	1998
	MW	**2004**	**2006**	1998 2012 2014	1991 2010
F	ORG	**2063**	2091	2070	**2080**
	SPF	2081	**2080** 2073	**2063**	2065
	CaSi	**2063**	**2080**	2073	2065
	MW	2081	**2063** 2073 **2080**	2065	2070 2077

II. A framework to select an MRY reliable for frost damage analysis – **MAIN FINDINGS:**

- In contrast to most previous studies assuming the WDR direction as the most critical to the occurrence of FT-related damage, this study shows that the WDR direction during the frost season can better represent the orientation having the highest risk to FT damage. Therefore, both the degree of wetting and temperature fluctuations above and below the freezing point are required.
- FT damage indicators, FTCd and FTCcrit do not provide consistent FT damage risk prediction for future climates although they have a strong correlation.
- The annual FT cycles obtained from 31-year consecutive simulation is very similar to single-year simulation, which indicates that yearly weather variation has little accumulative effect on annual FT cycles, therefore, single-year simulation results can be used to represent long-term performance for the MRY selection.
- The simulation-based MRYs are location, construction and orientation-dependent. The proposed approach for the selection of a simulation-based MRY proved to be applicable for retrofitting decision making.

Conclusions

- Frameworks developed to assess the impact of climate change on overheating and durability and develop mitigation strategies to support climate resilient carbon neutral buildings
  - Methodologies for model automatic calibration and optimization, assessment and passive mitigation measures for overheating under extreme heat events
  - Climate-based index developed based on simulations for MRY selection and prediction mould growth for wood-frame walls under future climates considering climate uncertainty
  - MRY specific for freeze/thaw damage assessment and recommendation on safely retrofitting Historic Solid Masonry with internal insulation under projected future climates in Canada
- Carbon-neutral climate resilient wood-frame constructions: low-carbon building envelope materials and assemblies; nature-based solutions for overheating mitigation and carbon sequestration; building-integrated photovoltaic (BIPV); life-cycle whole building carbon assessment considering both embodied and operational carbon