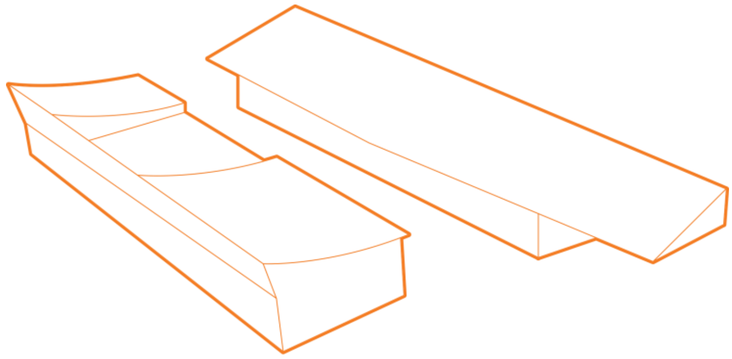

CONDENSATION MITIGATION MODELLING: FINAL REPORT

A REPORT FOR THE AUSTRALIAN BUILDING CODES BOARD

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Executive Summary

This report presents results from a simulation study into the hygrothermal performance of Australian building envelope components under a range of Australian climatic conditions. The study was undertaken by the Sustainable Buildings Research Centre (SBRC) at the University of Wollongong for the Australian Building Codes Board (ABCB). The report is intended to form the technical basis for condensation mitigation provisions for the 2025 update of the National Construction Code (NCC), within the ABCB project 'Condensation Mitigation Stage 3'.

The study included seven separate components, as follows:

1. A literature review focusing on a range of questions provided by the ABCB office related to condensation regulations in other jurisdictions and hygrothermal simulation methods.
2. A primary simulation study involving 2,928 one-dimensional hygrothermal simulations, which predicted the risk of mould growth in cases involving:
    a. Nine typical wall constructions and two typical roof constructions;
    b. Eight Australian locations, each representing one of the eight NCC climate zones;
    c. Three sets of indoor boundary conditions, representing different levels of indoor ventilation and/or different occupant densities;
    d. A range of pliable membrane vapour permeance values; and
    e. Where applicable, constructions both with and without ventilated cavities.
3. An investigation into the risk of condensation runoff on the internal surfaces of three glazing systems and three window frame components, covering a total of 288 cases.
4. A climate sensitivity study, involving 414 one-dimensional hygrothermal simulations, which covered all 69 NatHERS climate zones and was used as the basis for selection of the eight representative locations to simulate in the primary simulation study.
5. An indoor boundary condition sensitivity study involving 96 one-dimensional hygrothermal simulations, which investigated potential issues with standard methods to produce indoor boundary conditions for hygrothermal analysis, and served as the basis for selecting a method for the primary simulation study.
6. A thermal bridging simulation study, which involved 12 two-dimensional hygrothermal simulations of wall constructions with and without studs to investigate the impacts of thermal bridging on the level of mould risk predicted by simulations.

7. Analysis of results from the primary simulation study to investigate the impact of ventilated cavities on heat gains and losses through walls.

It should be noted that results presented in this report are a product of the specific assumptions and settings adopted for the simulations. A detailed consultation process was undertaken between the SBRC, ABCB office, and Condensation Technical Reference Group to decide on these model settings and assumptions. Generally, the adopted approach is relatively conservative (i.e. focused on modelling scenarios with relatively high risk of condensation and mould growth), however an effort was made to focus on typical construction details rather than obscure or rare 'worst case' constructions. Results in this report should be interpreted with this context in mind.

Key findings from the study are summarised under the sub-headings below.

MEMBRANE PERMEANCE

The impact of membrane vapour permeance on the risk of interstitial and surface mould within building envelope constructions has been one of the primary areas of focus in previous simulation studies used to develop NCC condensation provisions. DTS provisions in NCC 2022 focus primarily on the vapour permeance of such membranes as a 'lever' to manage mould and condensation risk.

Results from this study confirmed that limiting the vapour permeance of continuous material layers that can be installed between the primary insulation layer and outdoor environment can be effective in mitigating the simulated risk of mould growth in walls and roofs, especially when combined with other mitigation measures such as cavity ventilation and/or ventilation of the indoor environment.

In Climate Zones 2–8, the simulated risk of mould growth was primarily caused by vapour drive from the indoor environment outwards, so the risk of mould growth could be reduced by selecting membranes with a *high* vapour permeance for installation on the outdoor side of the primary insulation layer. In Climate Zone 1, the simulated risk of mould growth in walls was primarily caused by inward vapour drive, so external membranes with *low* vapour permeance typically produced a lower level of simulated mould risk.

The threshold vapour permeance value, at which an unacceptable level of mould risk was first predicted, varied widely between construction types, climates and indoor humidity conditions. The full set of results are presented graphically in Section 4.

VENTILATED CAVITIES

A substantial body of literature exists demonstrating the effectiveness of drained and ventilated cavities in reducing the risk of condensation and mould growth within walls under certain conditions. Such cavities reduce risk by:

- Forming a 'capillary break' that prevents the transfer of liquid water from the cladding to materials on the indoor side of the cavity;
- Providing a path for any liquid water that penetrates past the cladding to flow downwards and out of the wall assembly under gravity; and
- Enhancing the drying capacity of the wall, as moisture is convected from the cavity with the ventilation air flow.

In this study, these potential benefits were investigated in the Australian context by comparing the level of mould risk predicted by simulations of walls with 'direct-fixed' cladding and those with ventilated cavities located behind the cladding. A similar analysis was also applied to roofs with cathedral ceilings, by comparing cases with and without ventilation of the lower cavity, formed between the membrane and bulk insulation.

In the majority of cases, cavity ventilation was effective at reducing the risk of mould growth in walls. The magnitude of improvement varied, but typically resulted in approximately one 'class' of membrane permeance values (as defined in AS 4200.1) becoming acceptable in terms of the simulated mould risk. For example, where only Class 4 membranes produced acceptably low levels of mould risk, the addition of a ventilated cavity typically rendered most Class 3 and Class 4 membranes acceptable.

The simulated level of mould risk was mitigated even more effectively by cavity ventilation in roofs. Where more than half of the cases simulated without such ventilation produced an unacceptably high level of mould risk, the addition of cavity ventilation to the roof models reduced the simulated level of mould risk to acceptable levels in all cases.

Contrary to the general trends described above, cavity ventilation was found to increase the simulated level of mould risk in several cases simulated in Climate Zone 1. Because vapour drive in Climate Zone 1 was typically directed inwards, air flows through the ventilated cavities enhanced the transfer of vapour from the outdoor environment into the construction. Nevertheless, the magnitude of increased risk was not sufficient in any of the investigated cases to raise the overall level of mould risk to an unacceptable level.

INDOOR VENTILATION

Management of humidity levels indoors through effective ventilation can be another means to mitigate the risk of mould growth. Similar to building codes in the UK, USA and New Zealand, the current (2022) version of the NCC includes minimum ventilation requirements to maintain adequate indoor air quality (IAQ). However, while codes from the UK and New Zealand draw an explicit link between the ventilation requirements and humidity management, NCC 2022 does not.

The majority of simulations in this study were repeated with several different sets of indoor boundary conditions, which could represent different levels of indoor ventilation for a given building. The severity of indoor humidity conditions can be characterised using the Indoor Humidity Risk Rating (H), which combines the effects of dwelling size, number of occupants, building use type, and total indoor ventilation rate, into a single value. Thus, while the cases investigated in this study (Indoor Humidity Risk Rating $H = \{10, 5, 3.33\}$) can be taken to represent a single dwelling archetype with three different levels of ventilation, they also represent three dwellings with different occupant densities. Section 2.5.1 provides a more detailed explanation of H and how it can be interpreted.

Results from the primary simulation study demonstrated that adequate levels of ventilation can be extremely effective at mitigating the simulated risk of mould growth, especially when combined with other mitigation measures, such as appropriate membrane selection and ventilated cavities. The magnitude of improvement varied substantially between cases (see Section 4), but an illustrative example is provided below.

Example: A 90 m^2, three-bedroom dwelling with 0.2 air changes per hour (ACH) infiltration and no other ventilation would create a relatively severe indoor environment in terms of mould risk, with $H = 10$. By introducing additional ventilation with an average flow rate of 24 L s^{-1} using a 'balanced' ventilation system, or 34 L s^{-1} using an 'unbalanced' ventilation system, H can be reduced to 3.33. Simulations in this study indicate that such a reduction in H would reduce the risk of mould growth substantially for most constructions in most climate zones, e.g. for masonry veneer walls in Climate Zone 4, it was predicted to widen the range of membrane permeance values that produce an acceptably low mould risk from only Class 4 to include Class 3 and Class 4 membranes.

Results in this study provide a quantitative basis for condensation and mould risk mitigation to be incorporated into the minimum ventilation requirements in future releases of the NCC. If this was to occur, a decision would need to be made as to whether natural ventilation should continue to be allowed as an acceptable means of ventilation under the DTS provisions. Codes in other jurisdictions have taken varied approaches to this issue (see Section 3.1).

CONDENSATE RUNOFF FROM WINDOWS

Simulations of three glazing systems, and three window sills, of varying levels of thermal performance, were used to estimate the proportion of time that condensation could be expected to form and 'runoff' from the indoor side of each component under various sets of boundary conditions. The occurrence of condensate runoff was selected as the performance criteria, since water flowing from windows can accumulate and cause mould growth, rot and corrosion.

Results from these simulations demonstrated a large difference in the performance of each window component:

- The 'low-performance' components (i.e. aluminium sill and single glazing) were predicted to cause condensate runoff very frequently (from 2 % to 76 % of the time) in all cases involving Climate Zones 2–8 and Indoor Humidity Risk Ratings exceeding 1.67.
- The 'medium-performance' components produced mixed results, with condensate runoff predicted relatively frequently (from 0.5 % to 35 % of the time) in simulations of double glazing in Climate Zones 2–8 when the Indoor Humidity Risk Rating exceeded 5, and significantly less frequently (0.1 % to 3.5 % of the time) in simulations of a thermally-broken aluminium sill in Climate Zones 2, 4, 7 and 8 when the Indoor Humidity Risk Rating exceeded 6.67.
- The 'high-performance' components (i.e. uPVC sill and argon-filled double glazing with low-emittance coating) were not predicted to cause condensate runoff in any of the simulated cases.

The complete set of results presented in Section 4.3 not only demonstrates the significant reduction in condensate runoff risk that can be achieved by selecting windows with superior thermal performance, but also quantifies the level of condensate runoff risk in each of the eight NCC climate zones, and under various the indoor humidity conditions. These results could form the basis for provisions aimed at mitigating condensation-related issues caused by windows in future versions of the NCC.

CLIMATE SENSITIVITY

Results from the climate sensitivity study demonstrated that the eight existing NCC climate zones correlate relatively well with the level of simulated mould risk in masonry veneer and fibre-cement-clad walls. While simulations of different locations within each NCC climate zone did produce different results, those differences were typically minor in comparison to differences between locations in different NCC climate zones.

Based on results from the climate sensitivity study, the eight locations listed in Table 1 were selected to be modelled in the primary simulation study. These locations represent the 90th percentile of simulated mould risk within each NCC Climate Zone, based on population (see Section 5.4 for a more comprehensive description of the selection methodology).

Table 1: Locations selected to represent each climate zone.

NCC climate zone	NatHERS climate zone	Location
1	1	Darwin
2	9	Amberley
3	19	Charleville
4	20	Wagga Wagga
5	15	Williamtown
6	62	Moorabbin
7	66	Ballarat
8	25	Cabramurra

INDOOR BOUNDARY CONDITION SENSITIVITY

The generation of realistic indoor boundary conditions for hygrothermal simulations is not trivial, since conventional hygrothermal simulations typically only include a single building element so the complete thermal performance of the building is not modelled. Simulations presented in this report followed the 'intermediate method' prescribed in AIRAH DA07 for producing indoor humidity boundary conditions.

However, the unrealistic nature of boundary conditions produced using this method when applied to especially severe indoor humidity conditions, as was the case in this study, was demonstrated by members of the Condensation Technical Working Group during the early stages of this project. To address these concerns, a small study was undertaken to investigate the nature of boundary conditions produced using the standard 'intermediate method' and two alternative methods.

Results from this analysis demonstrated that alternative approaches, such as the 'hybrid' approach proposed in this report, can produce indoor humidity conditions that are: i) more closely aligned with measured indoor conditions from Europe and the USA, and ii) qualitatively more realistic in terms of the direction of vapour drive through the building envelope and the fluctuations in indoor relative humidity. This hybrid approach is based on measured data from Europe and the USA as well as the physics-based model on which the 'intermediate method' is based. Comparisons of hygrothermal simulations run using this hybrid method and those run using the standard ‘intermediate method’ demonstrated that the choice of method can have significant effects on the level of simulated mould risk in certain cases—it caused a change in the overall pass/fail result in 5 of the 48 cases investigated.

Ultimately, the standard ‘intermediate method’ was adopted for this study, primarily because it matches verification methods specified in clauses H4V5 and F8V1 of NCC 2022. Future studies should investigate alternative methods to generate indoor boundary conditions, including the ‘hybrid’ method proposed here, for potential inclusion in AIRAH DA07 and/or future versions of the NCC.

THERMAL BRIDGE IMPACTS ON MOULD RISK

The majority of simulations conducted in this study were one-dimensional, and therefore did not model the impacts of thermal bridges. Potential mechanisms by which thermal bridges could impact the hygrothermal performance of a building component include the following:

1. The thermal bridges are likely to influence temperatures within the component, which could modify the local relative humidity;
2. Hygric ‘buffering’ by timber thermal bridges could dampen humidity fluctuations within the component; and
3. Thermal bridges formed by materials with relatively high sensitivity to mould growth, such as timber, could increase the risk of mould growth within the construction.

To investigate the overall impact of these three effects in realistic scenarios, results from 12 two-dimensional simulations of timber and steel wall studs were compared to ‘baseline’ simulations run without any thermal bridges. Within this relatively small set of cases, the thermal bridges typically reduced the simulated level of mould risk; however, in several locations the level of risk was increased.

The thermal impact of the thermal bridges (i.e. mechanism 1 in the list above) reduced the local relative humidity on the cold side of the thermal bridge and increased the relative humidity on the warm side of the thermal bridge. Since the highest risk of mould growth is typically at locations on the cold side of the construction (e.g. at the membrane/insulation interface in Climate Zone 7, and at the plasterboard/insulation interface in Climate Zone 1), this risk was reduced by the thermal impacts of the thermal bridges.

The impact of hygric ‘buffering’ (i.e. mechanism 2 in the list above) was evident in the relative humidities simulated in constructions with a timber thermal bridge. However, this effect appeared to primarily dampen diurnal cycles of relative humidity, and the seasonal cycles remained relatively unchanged. In most cases investigated, the seasonal cycle had much more effect on the risk of mould growth than the diurnal cycle, and therefore the hygric 'buffering' effect appears to have had little impact on the overall level of simulated mould risk in walls with thermal bridges.

The relatively high sensitivity of timber to mould growth (i.e. mechanism 3 in the list above) increased the level of mould risk at locations within the timber thermal bridge, but did not impact the level of risk elsewhere within the walls (e.g. at the centre of the span between studs). However, the combined effect of the increase in mould risk caused by the timber sensitivity (i.e. mechanism 3) and the decrease in mould risk caused by the thermal effects of the thermal bridge (i.e. mechanism 1) was a net decrease in mould risk in three of the four investigated cases (focused on a masonry veneer wall in Climate Zone 1 and fibre-cement-clad wall in Climate Zones 1 and 7) and a net increase in one case (focused on a masonry veneer wall Climate Zone 7). While this analysis was limited in scope, it demonstrates that the interplay between these two effects can either increase or decrease the level of simulated mould risk relative to a one-dimensional simulation that ignores thermal bridging, depending on the specific characteristics of the scenario that is being simulated. Further work in this area is recommended.

In summary, results from the thermal bridging study demonstrated that the one-dimensional simulations that comprised the majority of this project:

- Slightly over-predict the level of mould risk in cases with metal thermal bridges; and
- Can slightly under- or over-predict the level of mould risk in cases with timber thermal bridges.

If the mould sensitivity class of materials in the walls had been set to 'sensitive' (equivalent to that of timber), rather than 'medium resistant' (which is appropriate for the other materials in the walls, except for the plasterboard), a significantly higher risk of mould growth would have been predicted in one-dimensional simulations in all climate zones except for Climate Zone 1 (where the primary risk was already within a 'sensitive' material, i.e. the plasterboard). Results from this thermal bridging study indicate that such an approach would be strongly conservative, producing mould risk predictions much higher than those that would be produced by a two-dimensional simulation in which the timber thermal bridge is modelled more realistically. However, that approach would mitigate the risk that a one-dimensional simulation may under-predict the risk of mould growth in a construction with a timber frame.

THERMAL IMPACTS OF VENTILATED CAVITIES

Analysis of data from the primary simulation study revealed that the simulated total heat gains and losses to/from the indoor environment was typically reduced when a ventilated cavity was added to the model of a wall; i.e. the ventilated cavities appear to have increased the effective thermal resistance (R-value) of the walls.

The magnitude of reduction in heat gains/losses varied between wall types and climate zones, but was in the order of 10 % in the majority of cases. It ranged from close to 0 % to 10 % in simulations of a metal-clad wall, and from 1 % to 32 % in simulations of walls clad with timber and fibre-cement.

A different trend was observed in results from simulations of a wall clad with a 75 mm autoclaved aerated concrete (AAC) panel, because the R-value of that cladding (0.52 m^2 K W^{-1}) was significant relative to the R-value of the bulk insulation (2–2.5 m^2 K W^{-1}). Thus, cavity ventilation in that wall bypassed a significant proportion of the wall's overall R-value when it convected heat to or from the wall. The impact of cavity ventilation on annual heat gains and losses was mixed in this case, with a net increase in heat gains in the order of 20 % in all climate zones except Climate Zone 8, and a mixture of slight increases and decreases to annual heat losses.

Importantly, the specific cases modelled in this study were designed to present relatively high risk of mould growth, e.g. by modelling south-facing walls with low solar absorptance and significant shading by eaves. Therefore, the data on ventilated cavity thermal effects presented here represent cases with relatively little annual heat gains. The impacts of cavity ventilation on annual heat gains in more typical scenarios could be larger.

NEED FOR FURTHER WORK

While this study has produced a relatively comprehensive dataset that can be used as the technical basis for condensation provisions in NCC 2025, it also highlighted several topics that require further investigation. Future studies could further advance our understanding of mould and condensation issues in the Australian building stock, and strengthen the relevant codes and standards, by adopting the following aims:

- Generate reliable statistical evidence showing the prevalence of mould in existing Australian buildings, to allow meaningful comparison with results from simulation studies such as those presented here. Ideally, this work should:
  - Investigate interstitial mould as well as mould on exposed surface;
  - Diagnose the cause(s) of mould in each case; and

  - Collect comprehensive metadata on each dwelling, including orientation, building use, ventilation usage, etc.
- Develop reliable experimental data and models to allow air flows to be modelled accurately in hygrothermal simulations of Australian envelope constructions, including cavity ventilation and other fugitive air flows.
- Collect existing and/or new data on the indoor vapour pressure excess in Australian buildings, together with comprehensive metadata on the building characteristics, usage, etc.
- Build on the indoor boundary condition sensitivity study in this report to develop an improved method to specify indoor boundary conditions in AIRAH DA07 and/or the NCC.
- Develop standard weather data files for hygrothermal analysis in Australia.
- Build on the thermal bridging study in this report by investigating a broader set of thermal bridging cases, including linear and point thermal bridges and additional climate zones.
- Develop a comprehensive database containing the hygrothermal properties of typical Australian building materials.

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List of Abbreviations

AAC	Autoclaved aerated concrete
ABCB	Australian Building Codes Board
ACH	Air changes per hour
AFRC	Australian Fenestration Rating Council
BMT	Base metal thickness [mm]
BOM	Bureau of Meteorology
DTS	Deemed to satisfy
EIFS	External insulation finishing system
EPS	Expanded polystyrene
ETICS	External thermal insulation composite system
EWIS	External wall insulation system
NatHERS	Nationwide House Energy Rating Scheme
NCC	National Construction Code
NFRC	National Fenestration Rating Council
R-value	Thermal resistance [m^2 K W^{-1}]
SBRC	Sustainable Buildings Research Centre
sd-value	Vapour diffusion resistance, normalised by the vapour diffusion resistivity of air [m]
TMY	Typical meteorological year
uPVC	Unplasticised polyvinylchloride
U-value	Thermal transmittance [W m^{-2} K^{-1}]

1 Introduction

This report outlines the methodology and results from an investigation into the hygrothermal performance of construction systems in Australian residential buildings. The project was undertaken by the Sustainable Buildings Research Centre (SBRC) at the University of Wollongong for the Australian Building Codes Board (ABCB), and will form the technical basis for the ABCB project 'Condensation Mitigation Stage 3', which aimed to develop condensation mitigation provisions for the 2025 update of the National Construction Code (NCC).

Several interim reports have been produced leading up to this final report for the project. These have included the following:

a) A Return Brief and Work Plan, outlining the proposed aims, objectives, and methodology for the study (v1 February 2023)
b) A peer review of previous hygrothermal modelling undertaken for the ABCB (v2 March 2023)
c) Preliminary results from an indoor boundary condition sensitivity study (v1 April 2023)
d) Preliminary results from a climate sensitivity study (v2 May 2023)
e) A literature review (v1 July 2023)
f) Preliminary results from the primary set of one-dimensional hygrothermal simulations (v1 July 2023)
g) Preliminary results from hygrothermal simulations indicating the thermal impacts of ventilated cavities in walls (v1 August 2023)

Since issuing the Return Brief (a), the scope and methodology of the study have evolved. The most significant changes were made in response to feedback on the Return Brief from the Condensation Technical Reference Group (TRG). For example, in May 2023 the scope of the project was extended to include the following:

- Additional one-dimensional hygrothermal simulations investigating:
  - Different approaches to generate indoor boundary conditions;
  - The performance of east-facing constructions in tropical climates (in addition to the south-facing simulations already included in the project scope);
  - Pre-cast concrete walls;
  - Roofs with ventilated cavities; and

    - Combinations of mitigation measures (e.g. scenarios including both enhanced indoor ventilation and ventilated wall cavities).
- A literature review.

A range of smaller changes were also made to the project methodology in response to TRG feedback.

This report presents the aims, methodology, and results of the entire project as it was implemented, including the additional items listed above.

1.1 AIMS

The aims of the study were as follows:

1. Review published scientific and grey literature to investigate the following five topics:
    a. Current overseas regulation on background ventilation, and how it compares to current NCC requirements.
    b. Experimental testing undertaken to determine condensation and mould risks for construction typologies in hot and humid (e.g. tropical) climate zones.
    c. Experimental studies undertaken to determine the benefits of ventilated wall cavities for construction types and climate zones similar to those found in Australia.
    d. Experimental studies undertaken to validate hygrothermal models, with a focus on construction typologies being modelled in this project.
    e. Sensitivity studies on the risk of condensation in typical Australian wall systems with varying climatic conditions (if any exist).
2. Quantify the potential reduction in mould risk provided to Australian residential and ‘residential-like’ buildings (i.e. building classes 1, 2, 3, 4 and 9c) by the following five mitigation measures:
    a. Continuous ‘background’ mechanical ventilation of the indoor space;
    b. Source ventilation for areas with extreme sources of water vapour (i.e. ‘wet areas’, including kitchens, bathrooms and laundries);
    c. Drained and ventilated wall cavities;
    d. Additional vapour permeance requirements for walls and/or roofs, including in tropical and sub-tropical climates; and
    e. Increasing energy efficiency requirements for windows (e.g. reduced U-values or the use of thermally broken frames).
3. Investigate the sensitivity of simulated mould risk to the following three factors:

   a. Spatial variations in climate within Australia, including variations within each of the 8 NCC Climate Zones;
   b. The method used to generate indoor boundary conditions; and
   c. The hygrothermal impacts of typical 'repeating' thermal bridges, such as wall studs, which are typically ignored in hygrothermal simulations.
4. Extract what information is available from the simulations undertaken to address aim 2 to investigate the impact of ventilated cavities on heat transfer through walls.

1.2 OBJECTIVES

The following objectives were set for the study:

1. Undertake a literature review covering the topics listed under item 1 in Section 1.1.
2. Undertake transient hygrothermal simulations to quantify the potential mitigation of mould risk provided by the mitigation measures listed under item 2 in Section 1.1.
3. Conduct a climate sensitivity study, to quantify the variance in simulated mould risk across a broad range of Australian climates, and to determine eight representative locations within Australia for inclusion in the primary simulation study.
4. Investigate methods to generate indoor boundary conditions for hygrothermal simulations, and run a sensitivity study to quantify any impacts on simulated levels of mould risk.
5. Conduct a thermal bridging sensitivity study, to quantify the impacts of typical 'repeating' thermal bridges (i.e. steel and timber wall studs penetrating bulk insulation) on the simulated risk of mould growth in a small set of wall types and climates.
6. Analyse results from Objective 2 to investigate the impact of ventilated cavities on the rate of heat transfer through walls.

1.3 SCOPE

The investigation was limited to the following scope:

- Building classes 1, 2, 3, 4 and 9c, as defined in the NCC.
- Eleven construction systems that are currently common in Australia, plus three glazing systems and three window sills.
- The climate sensitivity study investigated 69 locations within Australia, aligned with the 69 NatHERS Climate Zones, but the primary simulation study was limited to 8 locations.

- It was not feasible to include experiments within this study, so the analysis was limited to simulated data.
- Simulations included the following sources of moisture, modelled in accordance with AIRAH DA07 [1]:
  - ‘Built in’ moisture (i.e. moisture contained in the building materials at the start of occupancy);
  - Vapour convection and diffusion between the outdoor and indoor environments and the exposed surfaces of the construction;
  - Wind-driven rain absorbed by the external surface of the construction (if the outermost material allows such absorption);
  - Penetration of a small quantity of wind-driven rain past the outermost material layer (e.g. cladding); and
  - Convection of water vapour between the outdoor environment and any ventilated cavity in the construction.

  Other moisture sources, such as severe leaks of rain water or from plumbing, or ‘rising damp’ were not modelled.
- The majority of the analysis was one-dimensional; two-dimensional simulations were only applied when assessing mould growth risk on window frames, and in a sensitivity analysis focused on the impacts of thermal bridges.

1.4 REPORT OUTLINE

Section 2 of this report outlines the methodology adopted for each of the project’s objectives.

Section 3 presents the literature review (Objective 1).

Section 4 presents results from the primary simulation study (Objective 2).

Section 5 presents the climate sensitivity study (Objective 3).

Section 6 presents the indoor boundary condition sensitivity study (Objective 4).

Section 7 presents results from the investigation into thermal bridging (Objective 5).

Section 8 presents an analysis of thermal impacts of ventilated cavities in walls (Objective 6).

Section 9 sums up the key findings and conclusions from the study.

2 Methodology

This section outlines the methodology adopted for the study.

2.1 SIMULATION METHODOLOGY

The study was primarily conducted using the one-dimensional transient hygrothermal simulation software WUFI Pro v6.6. However, the analysis of window systems and thermal bridges required different approaches; further details are provided in Sections 2.1.2 and 2.1.5, respectively. Simulations were conducted in accordance with AIRAH DA07 'Criteria for moisture control design analysis in buildings' [1].

Transient time series of temperature and humidity data generated by the simulations were used to calculate the 'mould index', as specified in AIRAH DA07 and related literature [2–4], at the following locations within the simulated constructions:

1. When simulating constructions with a pliable membrane:
    a. On the interior surface of the pliable membrane, and
    b. On the surfaces of each material layer between the pliable membrane and indoor environment; and
2. When simulating constructions without a pliable membrane:
    a. On the interior surface of the outermost material layer (e.g. cladding), and
    b. On the surfaces of each material layer between that outermost material layer and indoor environment.

The relative level of risk predicted by each simulation was assessed based on the maximum mould index value reached during 10 simulated years of operation. This approach matches the verification method specified in clauses H4V5 and F8V1 of NCC 2022.

2.1.1 Primary Simulation Study

Each of the 11 construction systems described in Section 2.2 was simulated:

- With eight different membrane vapour permeance values (in constructions that include a membrane) and/or with no membrane (see Section 2.2 for further details);
- In eight climate zones selected based on the climate sensitivity study (see Sections 2.4 and 5);
- With three sets of indoor boundary conditions as described in Section 2.5; and

- Both with and without a ventilated cavity behind the cladding (in construction systems for which both configurations are common in Australia; see Section 2.2 for further details).

This approach involved a total of 2,928 one-dimensional hygrothermal simulations, as detailed in Table 2-1.

Table 2-1: Primary simulation study overview.

Construction	Construction details				Climate Zones	Indoor boundary conditions	Total
	Without ventilated cavity		With ventilated cavity				
	Membrane permeance values	No membrane	Membrane permeance values	No membrane			
Masonry veneer wall			8	1	8	3	216
Cavity masonry wall				1	8	3	24
Concrete block wall				1	8	3	24
Timber-clad wall	8		8	1	8	3	408
Fibre-cement-clad wall	8		8	1	8	3	408
Metal-clad wall [A]	8		8	1	8	3	408
AAC-clad wall	8[A]		8	1	8	3	408
EIFS wall	8				8	3	192
Prefabricated concrete wall				1	8	3	24
Tiled roof with cathedral ceiling	8[A]	1[A]	8		8	3	408
Metal-clad roof with cathedral ceiling [A]	8[A]	1[A]	8		8	3	408
						Grand total	**2928**

[A] A low level of ventilation was modelled in cavities formed behind the metal wall cladding, and below tiled and metal roof cladding, representing the air flow that would be permitted by small openings created by typical construction tolerances. These cases differed from the corresponding cases with ventilated cavities in that the latter were modelled with much higher ventilation flow rates typical of cavities with intentional ventilation openings.

2.1.2 Simulation of Window Systems

The three glazing systems and three window sills described in Section 2.2.12 were each simulated:

- In the same eight climate zones included in the primary simulation study; and
- With the same three sets of indoor boundary conditions included in the primary simulation study, with an additional three sets to improve the resolution of the results; see Section 2.5 for further details.

This resulted in a total of 288 simulations of window components.

A hybrid method was adopted for these simulations, combining the National Fenestration Rating Council (NFRC) 'condensation index' with boundary conditions defined according to AIRAH DA07

[1], and using the threshold for condensation runoff defined in BS 5250 [5]. The method involves two primary steps:

1. Calculate/simulate the minimum dimensionless surface temperature (i.e. condensation index) of each glazing system and window frame using the software WINDOW v7.8, and THERM v7.8, respectively, in accordance with NFRC procedures [6,7].
2. For each case of interest (i.e. each combination of indoor and outdoor boundary conditions) simulate the accumulation and drying of a film of condensate on the indoor surface of the window component through 1 year of operation. This process involved the following steps, applied to each 1 h timestep sequentially:
    a. Start with an 'initial guess' of the internal and external surface temperatures of the window component.
    b. Based on the indoor humidity boundary condition and the minimum surface temperature, calculate the rate at which condensate would evaporate or condense during that timestep.
        i. If evaporation is predicted and any condensate existed on the surface at the end of the previous timestep, allow it to be evaporated at the calculated rate but limit any evaporation to avoid a negative condensate load on the component, and
        ii. If condensation is predicted, allow it to occur at the calculated rate.
    c. Calculate the minimum surface temperature on the component, adopting a quasi-steady assumption (i.e. assuming that the component is at hygrothermal equilibrium with its surroundings), and including any latent heat absorption or release due to condensation or evaporation.
    d. Iteratively loop through steps b and c above, until convergence is reached (i.e. until a quasi-steady thermal equilibrium is reached and a condensation/evaporation rate is established for the timestep.
    e. Track the accumulation and drying of condensate through time by marching through the set of 8760 timesteps, but wherever the condensate load is predicted to exceed 30 g m^{-2}, assume that runoff has occurred and set the condensate mass load to 30 g m^{-2} at the start of the next timestep.
3. The performance criterion used to compare the different glazing and frame components was the number of hours during which condensate runoff was predicted during a year.

Wherever possible in these simulations, the same models and assumptions applied in the primary simulation study (using WUFI Pro) were adopted. For example, the same equations for radiant and convective exchanges with the outdoor and indoor environments were used.

Appendix A provides a more detailed explanation of the simulation method.

2.1.3 Climate Sensitivity Study

Prior to the primary simulation study, a set of simulations was run to investigate the variance in simulated mould risk across the 69 NatHERS Climate Zones, and select eight representative locations to include in the primary simulation study and window simulations.

Two construction systems, including a masonry veneer wall and a fibre-cement-clad wall with ventilated cavity (described in Sections 2.2.1 and 2.2.6, respectively), were simulated with three different membrane permeance values (0.0022, 0.1429 and 1.1403 $\mu g\ N^{-1}\ s^{-1}$) in all 69 NatHERS Climate Zones, producing a total of 414 simulated cases. The data produced was then used to analyse the variance in simulated mould risk within each NCC Climate Zone, and to select eight representative locations to proceed with.

The walls simulated in the Climate Sensitivity Study needed to be modelled with exactly the same construction details across all 69 NatHERS Climate Zones, to ensure that any variation in the simulation results was caused by differences in climate alone. For example the walls were simulated with the insulation specified for NCC Climate Zone 7 (Section 2.2) in all locations for the Climate Sensitivity Study.

2.1.4 Indoor Boundary Condition Sensitivity Study

Before undertaking the primary simulation study, the suitability of the 'intermediate method' specified for the generation of indoor boundary conditions in AIRAH DA07 [1] was investigated, and a set of simulations were run to compare this standard method with a possible alternative method, as described in Section 6.

A total of 96 simulations were run, including the masonry veneer and fibre-cement-clad walls in eight locations, with three different membrane vapour permeance values (0.0022, 0.1429 and 1.1403 $\mu g\ N^{-1}\ s^{-1}$), and with two different candidate methods for generating indoor boundary conditions. Through analysis of the results and consultation with the ABCB Office and Condensation TRG, an indoor boundary condition generation method was then selected for use in the primary simulation study, window simulations, climate sensitivity study, and thermal bridging study.

2.1.5 Thermal Bridge Sensitivity Study

Due to the limited time available and priorities set for the project, a comprehensive analysis of thermal bridging impacts on condensation and mould risk could not be included. Instead, 12 cases were simulated using the software WUFI 2D v4.4, to provide an initial indication of the type and magnitude of effects that thermal bridging may have, and the implications for typical one-dimensional hygrothermal simulations (which ignore such effects).

These two-dimensional simulations included the masonry veneer and fibre-cement-clad walls (described in Sections 2.2.1 and 2.2.6, respectively), both with Class 4 membranes (vapour permeance 1.1403 $\mu g\ N^{-1}\ s^{-1}$); in three thermal bridging scenarios:

- No thermal bridges (to act as a 'base case'),
- With a timber stud thermal bridge (representing 35 mm × 90 mm untreated radiata pine studs at 450 mm centres), and
- With a steel stud thermal bridge (representing 40 mm × 90 mm × 0.75 mm BMT cold-formed steel studs at 450 mm centres);

and each within two climate zones (NCC Climate Zones 1 and 7).

In cases with a steel stud, the stud was modelled as an 'equivalent rectangle' as defined in NZS 4214 [8]; i.e. a rectangle with equivalent thermal conductance to the thin-walled steel stud that it represents. We have found this approach to produce equivalent results to simulations that fully resolve the geometry of a steel stud in previous thermal bridging studies [9], and since steel is not hygroscopic (i.e. does not adsorb moisture from vapour) nor permeable to vapour or liquid water, this simplified approach is unlikely to introduce additional inaccuracy to a hygrothermal simulation.

Contact thermal resistances equal to 0.03 $m^2\ K\ W^{-1}$ were included between the studs and adjacent material layers (i.e. plasterboard and pliable membrane). Such thermal resistances arise due to the imperfect thermal contact between such materials, and are in line with values measured by Trethowen et al. [10], and specified in NZS 4214 [8]. These contact resistances were modelled within WUFI 2D by including a 1.3 mm-thick layer of mineral wool insulation between the studs and adjacent material layers.

2.1.6 Analysis of Thermal Impacts of Ventilated Cavities

Results from the primary simulation study were also analysed to investigate the impact of ventilated cavities on heat transfer rates through walls. This analysis included each of the four wall constructions that were simulated both with and without a ventilated cavity, i.e. the timber-clad, fibre-cement-clad, metal-clad, and AAC-clad walls.

The simulated heat flux between the indoor space and indoor surface of the walls, from cases with ventilated cavities, were compared to corresponding data from the corresponding simulations without ventilated cavities, thus measuring the simulated impacts of the ventilated cavities on heat gains and losses to/from the indoor space.

2.1.7 On the Limitations of Hygrothermal Simulations

It should be noted that the approach to mould risk assessment adopted in this study has limitations, just as it has advantages. While transient hygrothermal simulations provide much greater accuracy and fidelity than the steady-state calculation methods used previously, and are much faster and cheaper to undertake than physical experiments, caution is needed when relying on simulated data as a proxy for experimental evidence.

Two primary issues can lead to variation in hygrothermal simulation results between different studies, and/or inaccurate simulation results:

1. Hygrothermal simulations can be extremely sensitive to a range of modelling assumptions and settings, many of which are not standardised within protocols such as AIRAH DA07.
2. Several physical parameters and processes are either ignored or modelled in a simplistic fashion within current software and protocols; for example, typical models of indoor boundary conditions (see Section 2.5), ventilation of cavities within constructions (see Section 2.6), air-filled cavities, and mould growth, are highly simplified versions of reality.

To address the first of these issues, care needs to be taken when establishing model settings. Choices such as the building volume, infiltration rate, indoor paint layer vapour resistance, cavity ventilation rates, and mould index decline coefficient can have a large impact on the simulated risk of mould growth [11]. Moreover, such details can vary widely within the building stock, which gives rise to the question: should model inputs used for NCC development be based on the absolute 'worst-case' scenario, an 'average' scenario, or something in between? Combination of many 'worst case' assumptions could produce models that are unrealistic, whereas simulation of a 'typical' scenario could produce results that are overly optimistic for a large number of buildings. Guided by the ABCB Office and Condensation TRG, we sought in this project to strike an appropriate balance between absolute 'worst case' and 'typical' scenarios.

The second issue listed above is also difficult to address. In many cases, the simplistic aspects of WUFI Pro and AIRAH DA07 may not degrade the accuracy of results significantly, as demonstrated in several previous validation studies (see Section 3.4). However, such simplifications can have larger impacts in certain cases. For example, it has been reported that agreement between hygrothermal simulations and experiments can be difficult to achieve when investigating lightweight wall assemblies, unless the models are carefully calibrated experimental data [12,13].

Therefore, the methodology adopted for this study was designed as a benchmarking process, rather than an attempt to determine the exact mould risk in each simulated case. Uncertainty in how closely the simulations represent the distribution of real Australian buildings will need to be addressed in future investigations, ideally involving substantial and rigorous experimental campaigns covering a range of Australian construction systems and climates.

2.2 CONSTRUCTIONS FOR INVESTIGATION

Nine wall systems, two roof systems, three glazing systems, and three window frames, were selected for investigation in the study. Details of these construction systems are provided in Sections 2.2.1 to 2.2.12, and the properties of materials are summarised in Section 2.3.

Limitations in the hygrothermal simulation software and methods currently available prevented the inclusion of any pitched roofs over horizontal ceilings. Therefore, both of the included roof systems have been specified with cathedral ceilings. This is an active area of research at the SBRC; improved hygrothermal models for pitched roof systems with horizontal ceilings will be available for use in future studies.

When developing the set of construction systems, our aim was to define systems that are common in Australia currently, but where certain construction details vary within common Australian building practice, the ‘worst case’ practice (i.e. the practice that is likely to give rise to the highest risk of mould growth) was selected. For example, the construction systems have been specified:

- Facing south in all cases, except for in Climate Zone 1 where both south-facing and east-facing constructions were simulated and the case producing the highest simulated mould risk was selected for presentation in this report;
- Without a drained and ventilated cavity where this is allowed under NCC 2022; and
- Matching the minimum energy efficiency standards defined by NCC 2022 DTS elemental provisions, but with priority given to:
    - Relatively low solar absorptance values; and

- Relatively large eave overhangs.

Therefore, the construction systems do not necessarily represent the most typical building practice for each climate zone, nor do they represent the absolute 'worst case' allowed under NCC 2022. We have endeavoured to strike an appropriate balance between typical practice and 'worst case' practice.

Table 2-2 summarises the insulation R-values, solar absorptance values, and eave overhangs selected for each combination of construction system and climate zone. The minimum R-value for construction/climate combinations not covered explicitly in the NCC 2022 DTS elemental provisions were determined by adjusting the requirements for similar constructions in the relevant climate zone, as recommended by Isaacs [14]. Minimum insulation R-values were then rounded up to the nearest value corresponding to products available in Australia currently, as outlined in Table 2-2. In the climate sensitivity study, values listed for Climate Zone 7 were applied in all locations.

Table 2-2: Solar absorptance, eave overhang and insulation R-values to be modelled in each construction system within each NCC Climate Zone, based on NCC 2022 DTS elemental provisions. To align with products currently available, batt insulation R-values have been rounded up to the nearest value within the set {1.5, 2, 2.5, 2.7, 3, 3.5, 4, 4.5, 5} $m^2 K W^{-1}$, and rigid foam insulation R-values have been rounded up to the nearest value within the set {0.26, 0.66, 1.1, 1.75, 2.14, 2.86} $m^2 K W^{-1}$.

		NCC Climate Zone							
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Solar absorptance [A]		0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33
Eave overhang [mm]		500	500	500	450	500	300	500	450
Insulation R-value [$m^2 K W^{-1}$]	Masonry veneer wall	2	2	2.5	2	2	2.5	2	2.5
	Cavity masonry wall	0.66	0	1.75	0.26	0.26	1.1	1.1	1.1
	Concrete block wall	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Prefabricated concrete wall	1.5	1.5	2	1.5	1.5	1.5	1.5	1.5
	Timber-clad wall	2	2.5	2.5	2.5	2.5	2.7	2.7	2.7
	Fibre-cement-clad wall	2	2.5	2.5	2.5	2.5	2.7	2.7	2.7
	Metal-clad wall	2	2.5	2.5	2.5	2.5	2.7	2.7	2.7
	AAC-clad wall	2	2	2.5	2	2	2.5	2	2.5
	EIFS wall [B]	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
	Tiled roof with cathedral ceiling	3.5	3.5	5	4	3	4	4.5	4
	Metal-clad roof with cathedral ceiling	3.5	3.5	5	4	3	4	4.5	4

[A] Uncoated masonry constructions (i.e. the masonry veneer wall and cavity masonry wall) was modelled with a solar absorptance value of 0.68, rather than the values shown in this table.

[B] R-values included in this table for EIFS walls refer to the mineral wool batts installed between frame members; these walls include an additional 60 mm of expanded polystyrene (EPS) insulation as cladding.

In the thermal bridging study, NCC DTS provisions required the walls with steel frames to include a thermal bridging mitigation measure, of which we chose to include reflective (i.e. low-emittance) membranes. In all other simulations, the membranes were simulated with high thermal emittance.

For construction systems including a pliable membrane, nine scenarios were modelled: one scenario with no pliable membrane installed, and 8 scenarios including polymer-based, pliable membranes with the vapour permeance values outlined in Table 2-3. These permeance values were selected to provide relatively fine resolution across the broad range of typical membranes (with relatively even spacing on a logarithmic scale), and to include the threshold values between each consecutive pair of membrane classes under AS 4200.1 [15]. The reason for simulating so many membrane scenarios was twofold:

i) To allow the potential benefits of additional membrane permeance requirements to be evaluated (i.e. addressing item 2d in Section 1.1); and
ii) To improve the sensitivity and accuracy of comparisons between other mitigation measures and the baseline cases.

Table 2-3: Vapour permeance and class of pliable membranes to be simulated.

Pliable membrane vapour permeance [µg N^{-1} s^{-1}]	**Classification under AS 4200.1**
0.00055	Class 1
0.0022	Class 2*
0.0089	Class 2
0.0360	Class 2
0.1429	Class 3*
0.4000	Class 3
1.1403	Class 4*
4.5000	Class 4

* *Values marked with an asterisk represent the minimum permeance value within each membrane class under AS 4200.1.*

2.2.1 Masonry Veneer Wall

The masonry veneer wall was modelled with the material layers outlined in Table 2-4, as illustrated in Figure 2-1. All cases included a 40 mm ventilated cavity.

Table 2-4: Material layers in the masonry veneer wall.

Layer	Material	Thickness [mm]
A	Extruded clay brick	110
B	Cavity	40
C	Pliable membrane	1
D	Mineral wool insulation	90
E	Plasterboard	10
F	Indoor paint, 3 coats[1]	0.075

[1] Finish on the interior surface was not included as a material layer in the model, but its influence on vapour diffusion was modelled using a surface resistance.

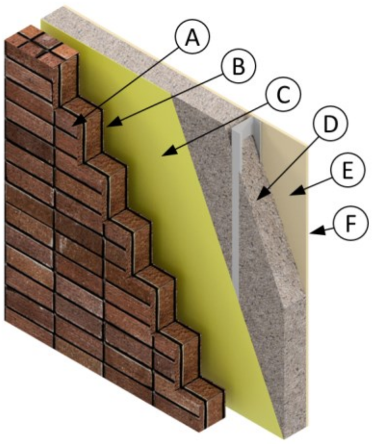


Figure 2-1: Masonry veneer wall.

2.2.2 Cavity Masonry Wall

The cavity masonry wall was modelled with the material layers outlined in Table 2-5, as illustrated in Figure 2-2. All cases included a 40 mm ventilated cavity, therefore the distance between the inner and outer brick leafs was adjusted to accommodate the 40 mm cavity and whatever thickness of insulation was required for the climate zone being simulated.

Table 2-5: Material layers in the cavity masonry wall.

Layer	Material	Thickness [mm]
A	Extruded clay brick	110
B	Cavity	40
C	Rigid foam insulation[2]	0–40[2]
D	Extruded clay brick	110
E	Plasterboard	10
F	Indoor paint, 3 coats[1]	0.075

[1] Finish on the interior surface was not included as a material layer in the model, but its influence on vapour diffusion was modelled using a surface resistance.
[2] Insulation only modelled in some Climate Zones (Table 2-2); thickness depends on required R-value (Table 2-16).

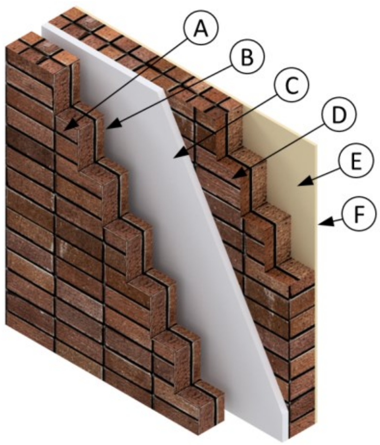


Figure 2-2: Cavity masonry wall.

2.2.3 Concrete Block Wall

The concrete block wall was modelled with the material layers outlined in Table 2-6, as illustrated in Figure 2-3. The insulation required to meet DTS provisions was modelled on the indoor side of the concrete blocks, where it could be installed between battens or clips.

Table 2-6: Material layers in the concrete block wall.

Layer	Material	Thickness [mm]
A	Exterior paint, 3 coats[1]	0.075
B	Acrylic render	8
C	Concrete block, core filled	200
D	Mineral wool insulation	75
E	Plasterboard	10
F	Indoor paint, 3 coats[1]	0.075

[1] *Finish on the interior and exterior surfaces was not included as material layers in the model, but its influence on vapour diffusion was modelled using a surface resistance.*

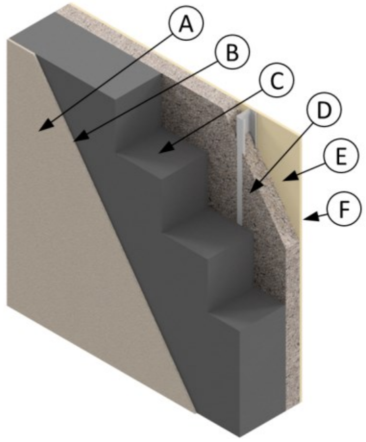


Figure 2-3: Concrete block wall.

2.2.4 Prefabricated Concrete Wall

The prefabricated concrete wall was modelled with the material layers outlined in Table 2-12, as illustrated in Figure 2-9. The thickness of the internal insulation was varied to meet the requirements of each climate zone.

Table 2-7: Material layers in the prefabricated concrete wall.

Layer	Material	Thickness [mm]
A	Exterior paint/sealer[1]	0.075
B	Acrylic render	8
C	Concrete, prefabricated slab	150
D	Mineral wool insulation	75-90[2]
E	Plasterboard	10
F	Indoor paint, 3 coats[1]	0.075

[1] *Finish on the interior and exterior surfaces was not included as material layers in the model, but its influence on vapour diffusion was modelled using a surface resistance.*

[2] *Batt insulation installed in cavity formed by battens, clips or studs; thickness either 75 mm or 90 mm, depending on required batt thickness for the climate zone.*

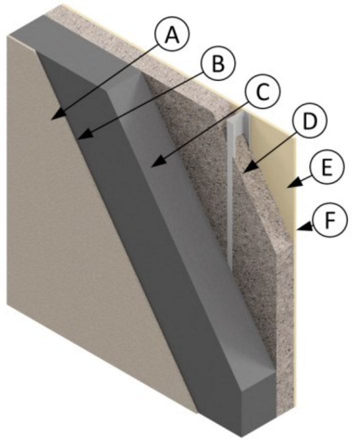


Figure 2-4: Prefabricated Concrete Wall.

2.2.5 Timber-Clad Wall

The timber-clad wall was modelled with the material layers outlined in Table 2-8, as illustrated in Figure 2-5. The 'baseline' timber-clad wall was modelled with its cladding fixed directly to the pliable membrane (i.e. without a battened-out cavity). In such an arrangement, some timber cladding products (such as traditional weatherboards) are likely to form a small cavity, despite the absence of battens, due to the geometry of the rear surface of the cladding. However, the 'baseline' timber-clad wall was modelled with no such cavity, to represent products that would make more complete contact with the membrane, such 'shiplap' or 'rusticated' weatherboards. In cases with a drained and ventilated cavity, the timber-clad wall was modelled with a 20 mm cavity between the cladding and pliable membrane.

Table 2-8: Material layers in the timber-clad wall.

Layer	Material	Thickness [mm]
A	Exterior paint, 3 coats[1]	0.075
B	Softwood weatherboards	19
V[2]	Ventilated cavity	20
C	Pliable membrane	1
D	Mineral wool insulation	90
E	Plasterboard	10
F	Indoor paint, 3 coats[1]	0.075

[1] *Finish on the interior and exterior surfaces was not included as material layers in the model, but its influence on vapour diffusion was modelled using a surface resistance.*
[2] *The ventilated cavity (layer V) was only included in simulations investigating the benefits of a ventilated cavity.*

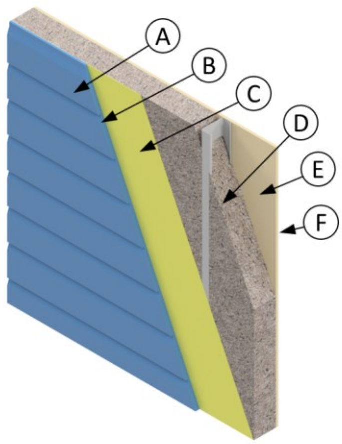


Figure 2-5: Timber-clad wall.

2.2.6 Fibre-Cement-Clad Wall

The fibre-cement-clad wall was modelled with the material layers outlined in Table 2-9, as illustrated in Figure 2-6. The 'baseline' fibre-cement-clad wall was modelled with its cladding fixed directly to the pliable membrane (i.e. without a battened-out cavity). In cases with a drained and ventilated cavity, the fibre-cement-clad wall was modelled with a 20 mm cavity between the cladding and pliable membrane.

Table 2-9: Material layers in the fibre-cement-clad wall.

Layer	Material	Thickness [mm]
A	Exterior paint, 3 coats[1]	0.075
B	Fibre-cement sheet	6
V[2]	Ventilated cavity	20
C	Pliable membrane	1
D	Mineral wool insulation	90
E	Plasterboard	10
F	Indoor paint, 3 coats[1]	0.075

[1] *Finish on the interior and exterior surfaces was not included as material layers in the model, but its influence on vapour diffusion was modelled using a surface resistance.*
[2] *The ventilated cavity (layer V) was only included in simulations investigating the benefits of a ventilated cavity.*

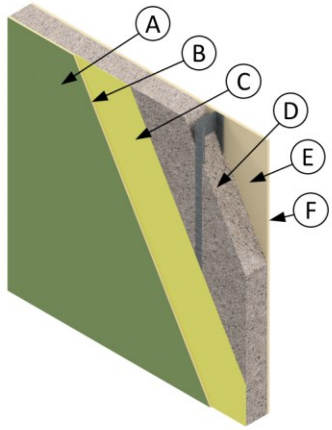


Figure 2-6: Fibre-cement-clad wall.

2.2.7 Metal-Clad Wall

The metal-clad wall was modelled with the material layers outlined in Table 2-10, as illustrated in Figure 2-7. The 'baseline' metal-clad wall was modelled with its cladding fixed directly to the pliable membrane (i.e. without a battened-out cavity); however, due to the profile of the cladding, a small (5 mm-deep) cavity was modelled on the outdoor side of the pliable membrane in this case. In cases with a drained and ventilated cavity, the metal-clad wall was modelled with a 20 mm cavity between the cladding and pliable membrane.

Table 2-10: Material layers in the metal-clad wall.

Layer	Material	Thickness [mm]
A	Profiled steel sheet cladding[1]	0.48
B[2]	Cavity	5-20
C	Pliable membrane	1
D	Mineral wool insulation	90
E	Plasterboard	10
F	Indoor paint, 3 coats[1]	0.075

[1] *Finish on the interior surface, and the metal cladding, was not included as material layers in the model, but their influence on vapour diffusion was modelled using surface resistances.*
[2] *The cavity (layer B) was modelled 5 mm deep in the 'baseline' cases, and 20 mm deep in simulations investigating the benefits of a ventilated cavity.*

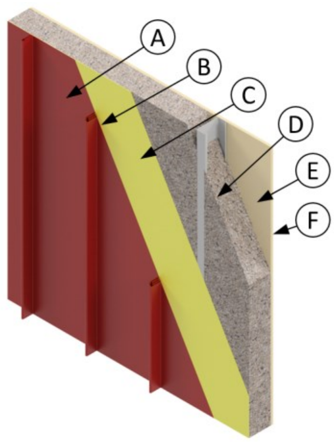


Figure 2-7: Metal-clad wall.

2.2.8 AAC-Clad Wall

The wall with autoclaved aerated concrete (AAC) cladding was modelled with the material layers outlined in Table 2-11, as illustrated in Figure 2-8. The 'baseline' AAC-clad wall was modelled with a 25 mm unventilated cavity, representing a so called 'face-sealed' system. In cases investigating the potential benefits of a drained and ventilated cavity, this cavity was ventilated, representing a wall with openings at top and bottom to allow ventilation.

Table 2-11: Material layers in the wall with autoclaved aerated concrete (AAC) cladding.

Layer	Material	Thickness [mm]
A	Exterior paint/sealer[1]	0.075
B	Acrylic render	8
C	AAC panel	75
D	Cavity[2]	25
E	Pliable membrane	1
F	Mineral wool insulation	90
G	Plasterboard	10
H	Indoor paint, 3 coats[1]	0.075

[1] Finish on the interior and exterior surfaces was not included as material layers in the model, but its influence on vapour diffusion was modelled using a surface resistance.

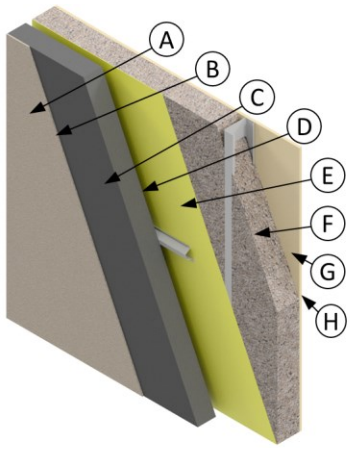


Figure 2-8: Wall with autoclaved aerated concrete (AAC) cladding.

2.2.9 EIFS Wall

The wall with an external insulation finishing system (EIFS; also known as ETICS and EWIS) was modelled with the material layers outlined in Table 2-12, as illustrated in Figure 2-9. The EIFS wall was not modelled with a ventilated cavity, since ventilation behind the external insulation would be likely to severely degrade the thermal resistance of the wall.

Table 2-12: Material layers in the wall with external insulation finishing system (EIFS).

Layer	Material	Thickness [mm]
A	Exterior paint/sealer[1]	0.075
B	Acrylic render	8
C	Expanded polystyrene (EPS)	75
D	Pliable membrane	1
E	Mineral wool insulation	75
F	Cavity	15
G	Plasterboard	10
H	Indoor paint, 3 coats[1]	0.075

[1] Finish on the interior and exterior surfaces was not included as material layers in the model, but its influence on vapour diffusion was modelled.

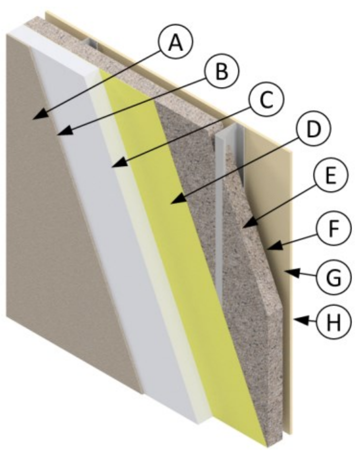


Figure 2-9: Wall with external insulation finishing system (EIFS).

2.2.10 Tiled Roof with Cathedral Ceiling

The tiled roof with cathedral ceiling was modelled with the material layers outlined in Table 2-13, as illustrated in Figure 2-10. It was modelled with a pitch of 15 degrees, facing south. All roofs, regardless of the insulation thickness, were modelled as if constructed 190 mm rafters and 40 mm roof battens. Therefore, the size of the cavity below the membrane was adjusted depending on the thickness of the insulation below it. The 'baseline' tiled roofs were modelled with a low level of ventilation above the membrane, representing flow through gaps and cracks formed in the roof structure due to construction tolerances, and no ventilation below the membrane. Versions of the tiled roof were also modelled with intentional ventilation of the cavity below the membrane, to investigate the potential benefits of such ventilation.

Table 2-13: Material layers in the tiled roof.

Layer	Material	Thickness [mm]
A	Roof tiles	20
B	Cavity	22
C	Pliable membrane	1
D	Cavity	40–80
E	Mineral wool insulation[1]	135–175[1]
F	Plasterboard	10
G	Indoor paint, 3 coats[2]	0.075

[1] *Thickness of insulation varies between climate zones (Table 2-2 and Table 2-16).*
[2] *Finish on the interior surface was not included as a material layer in the model, but its influence on vapour diffusion was modelled using a surface resistance.*

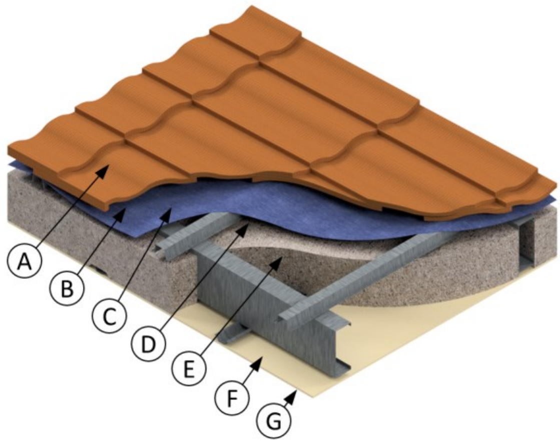


Figure 2-10: Tiled roof with cathedral ceiling.

2.2.11 Metal-Clad Roof with Cathedral Ceiling

The metal-clad roof with cathedral ceiling was modelled with the material layers outlined in Table 2-14, as illustrated in Figure 2-11. It was modelled with a pitch of 3 degrees, facing south. All roofs, regardless of the insulation thickness, were modelled as if constructed 190 mm rafters and 40 mm roof battens. Therefore, the size of the cavity below the membrane was adjusted depending on the thickness of the insulation below it. The cavity above the membrane was always modelled with a depth of 22 mm, representing an average membrane sag of 15 mm combined with an average cladding profile height of 7 mm. The 'baseline' metal-clad roofs were modelled with a low level of ventilation above the membrane, representing flow through gaps and cracks formed in the roof structure due to construction tolerances, and no ventilation below the membrane. Versions of the metal-clad roof were also modelled with intentional ventilation of the cavity below the membrane, to investigate the potential benefits of such ventilation.

Table 2-14: Material layers in the metal-clad roof.

Layer	Material	Thickness [mm]
A	Corrugated steel cladding[1]	0.48
B	Cavity	22
C	Pliable membrane	1
D	Cavity	40–80
E	Mineral wool insulation	135–175[1]
F	Plasterboard	10
G	Indoor paint, 3 coats[1]	0.075

[1] *Finish on the interior surface, and the metal cladding, were not included as material layers in the model, but their influence on vapour diffusion was modelled using surface resistances.*

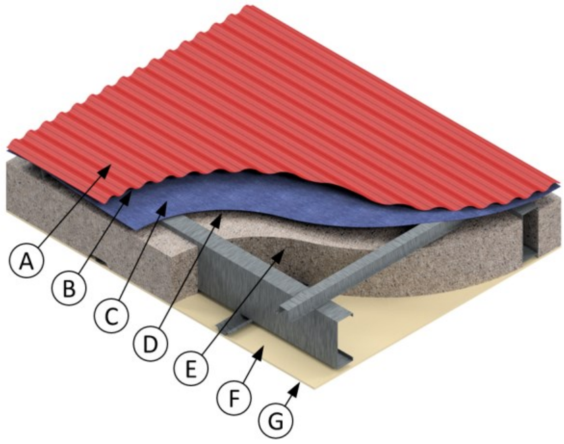


Figure 2-11: Metal-clad roof with cathedral ceiling.

2.2.12 Window Systems

The three glazing systems and three window frame components investigated are described in Table 2-15. The frame cross-sectional geometries were taken from products currently commercially available in Australia.

Table 2-15: Descriptions of the glazing systems and window frames to be simulated.

Description	System to be Simulated
Low-performance glazing	Single glazed (6 mm clear glass)
Moderate-performance glazing	Double glazed (6 mm clear glass; 12 mm air-filled cavity; 6 mm clear glass)
High-performance glazing	Double glazed, low-e (6 mm clear glass; 12 mm low-emittance, argon-filled cavity (e_1=0.84, e_2=0.08); 6 mm clear glass)
Low-performance frame	Aluminium sill
Moderate-performance frame	Thermally-broken aluminium sill
High-performance frame	uPVC sill with steel core

2.3 MATERIAL PROPERTIES

Table 2-16 summarises the properties of each material that was simulated. Our aim was to specify material properties that represent typical Australian building products. However, a comprehensive database containing the hygrothermal properties of Australian building materials has not yet been established. Therefore, material data in Table 2-16 have been taken from several sources, as follows:

- Where possible, density, thermal conductivity and specific heat capacity values were taken from the AIRAH Technical Handbook [16].
- The material database included with the software WUFI Pro, which primarily contains data from European and North American building materials, was then inspected for data for the appropriate type of material and with properties similar to those already extracted from the AIRAH Technical Handbook. For example, if several types of plasterboard were found in the WUFI database, the type that most closely matched the density, thermal conductivity and specific heat capacity values reported in the AIRAH Technical Handbook was selected. Values for the remaining hygrothermal material properties, including vapour diffusion resistance, moisture capacity and porosity, were taken from the selected WUFI database entry.

Default 'air layer' materials from the WUFI Pro materials database were modified in two ways:

1. The free saturation moisture content was increased from 17 g m^{-3} to 24 g m^{-3}, to align more closely with the saturation vapour content of air at temperatures likely to occur within construction systems in Australian climatic conditions.
2. The porosity of the material was reduced from 99 % to a value slightly higher than the free saturation moisture content (0.00241 %), to prevent an unrealistic quantity of liquid water from accumulating in the cavities.

A more comprehensive explanation of the rationale behind these changes can be found in our previous report [11].

Table 2-17 outlines the surface resistances that were used to model paint and metal cladding in this study. Previous investigations have shown that the simulated risk of mould growth in traditional Australian construction systems can be very sensitive to the vapour diffusion resistance value used to model the indoor paint layer [11,17]. Based on our recent review of published values [17], the value we have applied here (i.e. a sd-value of 0.45 m) corresponds approximately to the average of measured values published for relevant paint systems (i.e. 1 coat of acrylic undercoat followed by 2 coats of interior acrylic paint, where each coat comprises 25 µm of the 75 µm dry paint thickness).

Table 2-16: Summary of material properties. Source of data were include the AIRAH Technical Handbook [16] *and the WUFI Pro material database.*

Material	**Density [kg m^{-3}]**	**Thermal conductivity [W m^{-1} K^{-1}]**	**Specific heat capacity [J kg^{-1} K^{-1}]**	**Vapour diffusion resistance factor**	**Free saturation moisture content [kg m^{-3}]**	**Porosity [%]**
AAC panel	500	0.144	1104	18.58	381.8	79.12
Acrylic render	1795	0.371	840	86.7	269.25	27.5
Concrete block, core filled	1526	0.95	880	182.5	64.82	12.96
Concrete, prefabricated slab	2400	1.44	880	248	147	18
Expanded polystyrene (EPS)	16	0.035	1470	73.01	3.05	99
Extruded clay brick	1690	0.65	958	9.5	370	41
Fibre-cement sheet	1270	0.25	840	990.9	470	47.9
Mineral wool ceiling batt (R3, 135 mm)	10	0.045	880	1.3	44.8	95
Mineral wool ceiling batt (R3.5, 140mm)	14	0.040	880	1.3	44.8	95
Mineral wool ceiling batt (R4, 140 mm)	23	0.035	880	1.3	44.8	95
Mineral wool ceiling batt (R4.5, 158mm)	23	0.035	880	1.3	44.8	95
Mineral wool ceiling batt (R5, 175 mm)	23	0.035	880	1.3	44.8	95
Mineral wool wall batt (R1.5, 75 mm)	7	0.05	880	1.3	44.8	95
Mineral wool wall batt (R2, 90 mm)	10	0.045	880	1.3	44.8	95
Mineral wool wall batt (R2.5, 90 mm)	20	0.036	880	1.3	44.8	95
Mineral wool wall batt (R2.7, 90 mm)	33	0.033	880	1.3	44.8	95
Plasterboard	880	0.17	1050	6	400	65
Pliable membrane	130	2.3	2300	varies [A]	0.0471	0.1
Rigid foam insulation (R0.26, 10 mm)	16	0.038	1470	73.01	3.05	99
Rigid foam insulation (R0.66, 25 mm)	16	0.038	1470	73.01	3.05	99
Rigid foam insulation (R1.1, 25 mm)	32	0.022	1470	72	2.15	99
Rigid foam insulation (R1.75, 40 mm)	32	0.022	1470	72	2.15	99
Steel (cold-formed) frame [B]	7800	47.5	1470	72	2.15	99
Softwood weatherboards	506	0.12	2090	1734.1	300	85.8
Untreated radiata pine framing timber [B]	506	0.12	2090	1734.1	300	85.8
5 mm non-reflective cavity	1.2	0.047	1000	0.79	0.024	0.00241
15 mm non-reflective cavity	1.2	0.101	1000	0.645	0.024	0.00241
20 mm non-reflective cavity	1.2	0.13	1000	0.56	0.024	0.00241
20 mm -reflective cavity [B]	1.2	0.0345	1000	0.56	0.024	0.00241
22 mm non-reflective cavity	1.2	0.14	1000	0.54	0.024	0.00241
25 mm non-reflective cavity	1.2	0.155	1000	0.51	0.024	0.00241
30 mm non-reflective cavity	1.2	0.18	1000	0.46	0.024	0.00241
37 mm non-reflective cavity	1.2	0.215	1000	0.404	0.024	0.00241
40 mm non-reflective cavity	1.2	0.23	1000	0.38	0.024	0.00241
40 mm reflective cavity [B]	1.2	0.0656	1000	0.38	0.024	0.00241
60 mm non-reflective cavity	1.2	0.337	1000	0.27	0.024	0.00241
65 mm non-reflective cavity	1.2	0.369	1000	0.25	0.024	0.00241
75 mm non-reflective cavity	1.2	0.43	1000	0.215	0.024	0.00241
100 mm non-reflective cavity	1.2	0.59	1000	0.15	0.024	0.00241

[A] *The vapour diffusion resistance factor of pliable membranes was varied to produce the desired vapour permeance.*

[B] *Frame members and reflective cavities were only modelled in the thermal bridging study.*

Table 2-17: Surface vapour diffusion resistances used to model paint and metal cladding.

Material layer	**Sd-value[A] [m]**	**Vapour permeance [μg N^{-1} s^{-1}]**
Indoor paint	0.45	0.0437
Exterior paint	0.3	0.0655
Steel cladding	10000	1.97×10^{-14}

[A] *An sd-value represents the thickness of a layer of stagnant air that would pose an equal resistance to vapour diffusion than the material layer in question.*

The mould sensitivity class and mould index decline coefficient (as defined in AIRAH DA07) of each material was set as follows:

- Timber and plasterboard (which is typically coated in paper) was categorised as 'sensitive';
- Glass, aluminium and steel were categorised as 'resistant'; and
- All other materials included in this study was categorised as 'medium resistant'.

The allocation of different material types to mould sensitivity classes is defined relatively clearly in AIRAH DA07 and the related literature [2,4]. However, there is much more uncertainty surrounding the correct choice of mould index decline coefficient, which can influence the level of simulated mould risk significantly. While developers of the model recommend a default value of 0.25 in cases where reliable data are not available for the material of interest, and suggest that this choice of value is conservative (i.e. likely to overpredict the level of mould risk) [2,4], AIRAH DA07 (and ASHRAE 160 on which it is based) recommends an even more conservative default value of 0.1. Data to support the choice of a more accurate (and therefore less conservative) value appear to be extremely rare. Therefore, the default value of 0.1 was adopted for all materials in this study.

The solar absorptance of materials exposed to the outdoor space is outlined in Table 2-2. The thermal emittance of all materials was assumed to equal 0.9, except for glass which was modelled with a thermal emittance of 0.84.

2.4 OUTDOOR BOUNDARY CONDITIONS

The outdoor boundary conditions were set using TMY (typical meteorological year) weather data files taken from the OneBuilding database [18]. Data representing one year of typical conditions in each of the 69 locations used to represent each climate zone within NatHERS was extracted from the database. These data are generated according to TMY/ISO 15927-4:2005 protocols from hourly surface weather observations collected over the 15 year period from 2007 to 2021 by the Australian

Bureau of Meteorology (BOM). They include realistic rainfall data, whereas the current NatHERS weather data files do not include any rainfall data.

The generation of 'typical' weather data from historic records involves the 'weighting' (i.e. prioritisation) of different weather parameters over others. For example, most data files generated for building energy modelling prioritise the accuracy of parameters such as outdoor air temperature and solar heat flux over outdoor humidity and rainfall intensity. Therefore, the OneBuilding TMY data files do not necessarily include annual or monthly rainfall totals that are strictly 'typical'. To address this possibility, the rainfall intensity values contained in the OneBuilding TMY data files were rescaled to set each monthly total rainfall equal to the corresponding median historic monthly totals reported for each location by the BOM [19].

The intensity of wind-driven rain on the external surfaces of each construction was modelled according to AIRAH DA07. The building height was assumed to be less than 10 m, and the exposure was categorised as 'medium', producing a 'rain exposure factor' of 1. The rain deposition factor was set to 0.5, representing 'walls below a low-slope roof'. Absorption of wind-driven rain by the external surface was modelled in simulations of the masonry veneer wall and cavity masonry wall, since all other constructions were modelled with a coating or finish that would prevent such absorption. When absorption was modelled, the 'adhering fraction of rain' (i.e. fraction of wind-driven rain incident on the construction that is assumed to adhere) was 0.7.

As per AIRAH DA07, rain penetration was also modelled. One percent of the wind-driven rain incident on each construction was assumed to leak past the outer (cladding) layer. In simulations with a pliable membrane, this penetrating rain was applied in the 1 mm of material immediately adjacent to, and on the outdoor side of, the pliable membrane. In simulations of constructions without a membrane, it was deposited in the outermost 1 mm of the material layer on the indoor side of the cladding layer.

Within WUFI Pro, shading (e.g. from eave overhangs) is modelled by multiplying short-wave (i.e. solar) and long-wave radiant heat fluxes by a constant factor. This is a relatively simplistic approach, which does not take the direction of solar irradiance into account. In this study we applied shading correction factors to walls to represent the eave depths outlined in Table 2-2. A shading factor of 1 (i.e. no shading) was applied to models of roofs.

2.5 INDOOR BOUNDARY CONDITIONS

After undertaking the indoor boundary condition sensitivity study (Section 6), indoor boundary conditions for subsequent simulations were defined using methods specified in AIRAH DA07, including the 'intermediate method' for calculation of indoor humidity. The building was modelled with heating and air conditioning. Thus, the indoor air temperature was set 2.8 °C warmer than the 24-hour running average outdoor air temperature, except when that value fell below the heating setpoint of 21.1 °C, or rose above the cooling setpoint of 23.9 °C, at which times the indoor temperature was set equal to the relevant setpoint temperature.

According to the AIRAH DA07 'intermediate' method, when air conditioning is not active, the indoor water vapour pressure boundary condition is given by:

$$p_i = \overline{p_o} + \frac{c_1 \dot{m}}{Q} \tag{1}$$

where:

p_i is the indoor vapour pressure [Pa],

$\overline{p_o}$ is the running average outdoor vapour pressure over the preceding 24 h [Pa],

$c_1 = 1.36 \times 10^5$ Pa m^3 kg^{-1} is treated as a constant based on an assumed standard pressure and temperature,

$\dot{m}$ is the rate of water vapour generation indoors [kg s^{-1}], and

Q is the total ventilation volume flow rate [m^3 s^{-1}].

And Q is given by:

$$Q = c_2 I V \tag{2}$$

where:

$c_2 = 1/3600$ h s^{-1} is a constant used to convert from air changes per hour (ACH) to air changes per second,

I is the assumed constant rate of infiltration and ventilation [ACH], and

V is the volume of the indoor space within the building being modelled [m^3].

Further to Equations *1* and *2*, the indoor humidity is prevented from exceeding 70 % relative humidity, and a separate model is used to calculate the indoor humidity boundary condition when air conditioning is active, which typically sets a constant value of approximately 40 % relative humidity at such times.

This is a relatively simplistic model, as compared to the airflow network models often incorporated in building performance simulations for example. It inherently assumes the following:

- Indoor relative humidity is somehow prevented from exceeding 70 %;
- Windows and doors are not used to ventilate the building;
- Moisture generation within the building is effectively constant;
- The indoor environment is 'well-mixed' (i.e. its temperature, humidity, and concentrations of contaminants, are spatially uniform); and
- Infiltration rates are effectively constant, and are typically based on nominal values that do not necessarily represent typical Australian construction practices.

The limitations of this method are discussed further in Section 6.

2.5.1 Indoor Humidity Risk Rating

To simplify the interpretation of indoor boundary conditions in this report, we have presented results in terms of an 'Indoor Humidity Risk Rating', which is defined as:

$$H = \frac{c_3 \dot{m}}{Q} \tag{3}$$

where:

c_3 = 1000 $m^3\ kg^{-1}$ is a constant used to normalise the metric;

$\dot{m}$ [$kg\ s^{-1}$] is the same indoor moisture generation rate as in Equation *1*, which can be estimated using Table 2-18; and

Q [$m^3\ s^{-1}$] is the same indoor ventilation rate as in Equations *1* and *2*.

Table 2-18: Assumed indoor moisture generation rates based on the number of bedrooms in a dwelling, copied from AIRAH DA07. For each additional bedroom beyond the sixth, 0.01 kg s^{-1} should be added to $\dot{m}$.

Number of bedrooms	Assumed number of occupants	$\dot{m}$ [$kg\ s^{-1}$]
1	2	0.00008
2	3	0.00010
3	4	0.00012
4	5	0.00013
5	6	0.00014
6	7	0.00015

By presenting results in terms of the Indoor Humidity Risk Rating, rather than the indoor ventilation rate, the relative impact of building volume, ventilation/infiltration rate, and occupant density, are all communicated using a single value. Results presented in this report can therefore be applied directly to a much wider variety of buildings.

The primary set of Indoor Humidity Risk Ratings investigated in this study were as follows:

- H = 10, representing a relatively high-risk 'baseline' such as:
  - A 60 m^2, one-bedroom dwelling with 0.2 ACH infiltration and no other ventilation;
  - A 75 m^2, two-bedroom dwelling with 0.2 ACH infiltration and no other ventilation;
  - A 90 m^2, three-bedroom dwelling with 0.2 ACH infiltration and no other ventilation;
  - A 97.5 m^2, four-bedroom residence with 0.2 ACH infiltration and no other ventilation.
- H = 5, representing a property at lower risk such as:
  - Any of the 'baseline' dwellings listed above, but with infiltration rates of 0.4 ACH.
  - The 60 m^2 'baseline' dwelling listed above, but with additional ventilation at:
    - 8 L s^{-1} balanced, or
    - 13.9 L s^{-1} unbalanced.
  - The 75 m^2 'baseline' dwelling listed above, but with additional ventilation at:
    - 10 L s^{-1} balanced, or
    - 17.3 L s^{-1} unbalanced.
  - The 90 m^2 'baseline' dwelling listed above, but with additional ventilation at:
    - 12 L s^{-1} balanced, or
    - 20.8 L s^{-1} unbalanced.
  - The 97.5 m^2 'baseline' dwelling listed above, but with additional ventilation at:
    - 13 L s^{-1} balanced, or
    - 22.5 L s^{-1} unbalanced.
- H = 3.3 representing a property at even lower risk such as:
  - Any of the 'baseline' dwellings listed above, but with infiltration rates of 0.6 ACH.
    The 60 m^2 'baseline' dwelling listed above, but with additional ventilation at:
    - 16 L s^{-1} balanced, or
    - 22.7 L s^{-1} unbalanced.
  - The 75 m^2 'baseline' dwelling listed above, but with additional ventilation at:
    - 20 L s^{-1} balanced, or
    - 28.3 L s^{-1} unbalanced.

- The 90 m^2 'baseline' dwelling listed above, but with additional ventilation at:
  - 24 L s^{-1} balanced, or
  - 34 L s^{-1} unbalanced.
- The 97.5 m^2 'baseline' dwelling listed above, but with additional ventilation at:
  - 26 L s^{-1} balanced, or
  - 36.8 L s^{-1} unbalanced.

The examples listed above were calculated using an assumed ceiling height of 2.4 m, and using the equations suggested by Sherman et al. [20] for combining balanced and unbalanced ventilation rates with infiltration rates. The labels 'balanced' and 'unbalanced' ventilation refer to whether the system includes provisions to allow flow to both enter and exit the building (balanced) or only drives flow in one direction and relies on small gaps and cracks in the building envelope to allow flow in the other direction (unbalanced).

2.6 CAVITY VENTILATION

Cavities that are assumed to be ventilated were modelled with realistic transient ventilation rates, generated using models developed previously at the SBRC [11,17,21]. This approach involves several steps:

1. The geometry of the cavity, and any openings allowing ventilation, are defined.
2. Equations are developed to characterise the combined aerodynamic resistance (i.e. pressure-flow relationship) arising along the cavity ventilation flow path, due to 'fittings' (e.g. flow through narrow openings, or past obstructions such as battens) and friction within the boundary layer flow.
3. A precursor WUFI Pro simulation is run with a constant cavity ventilation rate.
4. The timeseries of temperature and humidity values simulated at the centre of the cavity are used, together with wind speed and direction data from the weather data file, to calculate the pressure difference that would drive flow through the cavity. This calculation includes contributions from:
   a. Thermal buoyancy;
   b. Hygric buoyancy (i.e. differences in the density of air due to differences in the water vapour content); and
   c. Pressure exerted on the outside of the building by wind.

5. The cavity ventilation rate at each simulation timestep is calculated based on a quasi-steady equilibrium between the driving pressure and aerodynamic resistance to flow.
6. The WUFI Pro simulation is re-run with the updated (transient) cavity ventilation rates.
7. Steps 4–6 are repeated in an iterative process until the root-mean-square change in cavity ventilation rates calculated for consecutive simulations is less than 1 % of the mean ventilation rate, at which point the model is considered to have converged to an acceptable degree.
8. Results from the final simulation, obtained with a converged set of transient ventilation rates, are used.

This approach was used to model ventilation of the following cavities:

A. The cavities within the masonry veneer and cavity masonry walls were modelled with 760 mm^2 weep holes spaced at 1.2 m centres along the base of the wall, and openings of equivalent size at the top.
B. The small cavity formed between the profiled metal cladding and pliable membrane in the metal-clad wall with 'direct-fixed' cladding was modelled with 2 mm-wide continuous slot openings at the top and bottom.
C. The timber-clad, fibre-cement-clad, metal-clad, and AAC-clad walls were modelled with ventilated cavities in some cases, to investigate the potential benefits of such ventilation; in such cases, these walls were modelled with 5 mm-wide continuous slot openings at the top and bottom.
D. The narrow cavities above the membrane in the tiled and metal-clad roofs were modelled with openings equivalent to a 16 mm-wide continuous slot at the lower edge of the roof (i.e. near the gutter) and an 8 mm-wide continuous slot opening at the higher edge of the roof.
E. In cases where the cavities below the pliable membrane in the tiled and metal-clad roofs were ventilated, ventilation opening sizes were modelled based on the NCC 2022 DTS provisions, i.e. a 25 mm-wide continuous slot openings at the low level of the tiled roof, a 5 mm-wide continuous slot opening at the high edge of the tiled roof, and 25 mm-wide continuous slot openings at the high and low edge of the metal-clad roof.

2.7 INITIAL CONDITIONS

The initial temperature and moisture content of materials within each construction at the start of each simulation was set according to AIRAH DA07 as follows:

- The initial temperature was set to 22 °C.

- The initial moisture content of each material was set to a value equal to:
  - Two times the equilibrium moisture content at 90 % relative humidity for concrete; and
  - Two times the equilibrium moisture content at 80 % relative humidity for all other materials.

These settings are designed to include the additional moisture that materials may accumulate during the construction process if procedures are not followed to protect them from wetting.

2.8 SIMULATION APPROACH AND NUMERICAL SETTINGS

All simulations were run with the 'explicit radiation balance' model within WUFI Pro, which includes separate calculations for the rates of radiant and convective heat transfer between the construction and the outdoor environment.

An indoor 'film resistance' of 0.12 m^2 K W^{-1} was applied, in accordance with AS 4859.2 [22]. The wind-dependent convective heat transfer coefficient included in WUFI Pro was applied to the outdoor surface of each construction, and the ground surrounding the building was modelled with a short-wave reflectance of 0.2, and a long-wave emittance of 0.9, and a long-wave reflectance of 0.1.

Simulation timesteps of 15 min were used in all simulations. However, time-step adaptation was enabled, so smaller sub-timesteps were employed when needed to achieve convergence of the model.

3 Literature Review

This literature review focuses on five specific topic areas listed under project aim 1 in Section 1.1, which have been repeated here for convenience:

1. Current overseas regulation on background ventilation, and how it compares to current NCC requirements.
2. Experimental testing undertaken to determine condensation and mould risks for construction typologies in hot and humid (e.g. tropical) climate zones.
3. Experimental studies undertaken to determine the benefits of ventilated wall cavities for construction types and climate zones similar to those found in Australia.
4. Experimental studies undertaken to validate hygrothermal models, with a focus on construction typologies being modelled in this project.
5. Sensitivity studies on the risk of condensation in typical Australian wall systems with varying climatic conditions (if any exist).

Published academic and grey literature relevant to these five topic areas was reviewed, with a focus on mould and condensation risk in residential buildings.

This review builds on previous studies of mould and condensation risk in the Australian context, as reviewed by Coulburn and Miller [23], and including studies investigating the prevalence and causes of mould in Sydney public housing [24,25], the relationship between airtightness and mould/condensation risk [26], and links between weather tightness and mould and other types of water damage in Australian residential buildings [27]. By drawing on published research, and building codes and standards, from other jurisdictions with similar construction practices and/or climates to Australia, this review is intended to support the development of improved standards and codes in Australia.

3.1 VENTILATION REGULATIONS IN OTHER JURSDICTIONS

This section presents a review of ventilation requirements in current building codes from Britain, New Zealand and the USA. A summary and comparison with NCC 2022 is provided in Section 3.1.4.

3.1.1 Britain

British building regulations include separate clauses to cover the requirement for ventilation to ensure adequate indoor air quality (IAQ), and for the harmful effects of surface and interstitial condensation to be avoided.

Building regulations applicable to England and Wales are set out in The Building Regulations 2010 [28]. Clause F1(1) of Schedule 1 reads as follows:

> *"There shall be adequate means of ventilation provided for people in the building."*

Whereas the requirement for walls, floors and roofs to protect the building and people from the harmful effects of interstitial and surface condensation (as well as ground moisture, precipitation and leaks) is included in Clause C2 of Schedule 1.

New buildings in Scotland are regulated through The Building (Scotland) Regulations 2004 [29]. Paragraph 3.14 of Schedule 5 requires the following:

> *"Every building must be designed and constructed in such a way that the air quality inside the building is not a threat to the health of the occupants or the capability of the building to resist moisture, decay or infestation."*

Whereas the risk of condensation is covered in Paragraph 3.15 of Schedule 5, as follows:

> *"Every building must be designed and constructed in such a way that there will not be a threat to the building or the health of the occupants as a result of moisture caused by surface or interstitial condensation."*

Guidance on how to comply with these regulations is published in two separate versions of Approved Document F, applying to England [30] and Wales [31], respectively, and in the Domestic Technical Handbook which applies to Scotland [32].

Details of the performance requirements and prescriptive measures outlined in these guidance documents are summarised in the following sub-sections.

Performance Requirements

While the regulations outlined above treat ventilation requirements and condensation mitigation requirements separately, Approved Document F [30,31] and the Domestic Technical Handbook [32] both state that the intention of the ventilation provisions includes the regulation of indoor humidity and mitigation of risks associated with mould growth.

Appendix B of Approved Document F sets out performance criteria for adequate indoor ventilation of dwellings. Clause B2 reads:

> *"The performance criterion for moisture is that there should be no visible mould on the inner surfaces of the external walls of a properly heated dwelling with typical moisture generation."*

And Clause B3 sets the following limits on 'surface water activity' (which is a measure of moisture availability at a surface, equal to relative humidity under steady-state conditions):

- 0.75 average over any 1 month period;
- 0.85 average over any 1 week period; and
- 0.95 average over any 1 day period.

The performance requirements for adequate ventilation also include maximum allowable concentrations of several pollutants.

The Domestic Technical Handbook (applicable to dwellings in Scotland) does not appear to contain anything equivalent to a performance requirement for ventilation. However, it does include quantitative prescriptive solutions, as explained below.

Prescriptive Solutions

Both Approved Document F [30,31] and the Domestic Technical Handbook [32] include detailed prescriptive solutions for indoor ventilation systems.

In England and Wales (under Approved Document F) new dwellings require all three of the following:

- Mechanical exhaust ventilation in all kitchens, utility rooms, bathrooms and sanitary compartments; these must:
  - Be vented to the outdoors, and
  - Achieve specified flow rates (expressed in L s^{-1}), with different values required if the system is designed for continuous or intermittent operation.
- Systems to achieve continuous supply ventilation of the entire building; these systems:
  - Provide ventilation either through:
    - Continuously running supply fans, or
    - 'Background ventilators' (i.e. small ventilation openings designed to provide controllable ventilation) to allow natural ventilation;

    - Supply at least:
        - 19, 25, 31, 37 or 43 L s^{-1} air flow for dwellings with 1, 2, 3, 4 or 5 bedrooms, respectively, and
        - 0.3 L s^{-1} air flow per square metre of floor area;
    - Include 10 mm gaps under all internal doors to allow indoor air circulation.
- Systems to allow 'purge ventilation' (i.e. intermittent ventilation used to remove pollutants from occasional activities, such as fumes from painting); purge ventilation systems must:
    - Exist in each habitable room;
    - Provide ventilation either through:
        - Openings (e.g. windows and doors) with specified areas per unit floor area, or
        - A mechanical exhaust fan; and
    - Achieve an air change rate of at least 4 ACH.

In Scotland, the Domestic Technical Handbook requires new dwellings to be built with the same three types of ventilation system as outlined above (i.e. exhaust ventilation in certain room types, continuous supply ventilation in the whole building, and provisions to allow purge ventilation of all habitable rooms). However, one important point of difference relevant to this review is that the Scottish provisions limit the types of ventilation systems that are allowed to provide continuous ventilation to the whole building based on the designed and verified building envelope air tightness, as follows:

1. Natural ventilation with intermittent mechanical exhaust is permitted in buildings with an infiltration rate ≥ 5 m^3 h^{-1} m^{-2} @ 50 Pa.
2. Continuous mechanical exhaust ventilation is permitted in buildings with an infiltration rate ≥ 3 m^3 h^{-1} m^{-2} @ 50 Pa.
3. Continuous mechanical supply and extract ventilation (i.e. 'balanced' mechanical ventilation) is permitted in all buildings.

Therefore, the Scottish prescriptive solutions force the designers of buildings that are relatively air tight to use continuous 'background' mechanical ventilation, and the system must be balanced in buildings that are very air tight.

Another difference between the Scottish and English/Welsh prescriptive solutions is in the minimum ventilation rates for continuous supply ventilation system. In Scotland, they must supply at least:

- 13, 19, 25, 31 or 37 L s^{-1} air flow for dwellings with 1, 2, 3, 4 or 5 bedrooms, respectively (note that these values are lower than those required in England and Wales); and
- 0.3 L s^{-1} air flow per square metre of floor area.

A range of additional requirements for exhaust, supply and purge ventilation systems are specified the Domestic Technical Handbook. However, they are broadly equivalent to those specified in Approved Document F, so they have not been described in detail in this review.

Further Reading

- The British Standards Institution published an informative white paper in 2019, proposing a more wholistic approach to moisture management regulations and standards in Britain [33].
- Altamirano-Medina et al. [34] authored a comparison of prescriptive provisions and those requiring dynamic hygrothermal models in the context of British building regulations on condensation and mould.
- Bonderup and Middlemiss [35] recently published an insightful comparison of representations of mould risk in Denmark and England, which has implications for building codes.

3.1.2 New Zealand

The New Zealand Building Code, contained in Schedule 1 of New Zealand Building Regulations 1992 [36], includes regulations relating to indoor moisture management and ventilation as follows.

Clause E3 is designed with the objective to *"safeguard people against illness, injury, or loss of amenity that could result from accumulation of internal moisture …"*. It is accompanied by the functional requirement E3.2: *"Buildings must be constructed to avoid the likelihood of: fungal growth or the accumulation of contaminants on linings and other building elements …"*.

Clause G4 sets ventilation requirements, with the objective to *"safeguard people from illness or loss of amenity due to lack of fresh air"*. It is accompanied by functional requirement G4.2: *"Spaces within buildings shall be provided with adequate ventilation consistent with their maximum occupancy and their intended use."*

Performance Requirements

A range of performance requirements are specified in Clauses E3 and G4 of the New Zealand Building Code, including the following three which are relevant to this review:

E3.3.1: *"An adequate combination of thermal resistance, ventilation, and space temperature must be provided to all habitable spaces, bathrooms, laundries, and other spaces where moisture may be generated or may accumulate."*

G4.3.1: *"Spaces within buildings shall have means of ventilation with outdoor air that will provide an adequate number of air changes to maintain air purity."*

G4.3.3: *"Buildings shall have a means of collecting or otherwise removing the following products from the spaces in which they are generated ... moisture from laundering, utensil washing, bathing and showering ..."*

Prescriptive Solutions

Under the New Zealand Building Code, the 'deemed to comply' compliance pathway includes approved verification methods and prescriptive 'acceptable solutions' (which are equivalent to verification methods and DTS provisions in the Australian NCC, respectively).

Performance requirement E3.3.1, which deals with the accumulation of moisture, is currently only covered by Acceptable Solution E3/AS1. The only provision addressing indoor ventilation in E3/AS1 simply states that the Acceptable Solution G4/AS1 (which addresses Clause G4 and deals with ventilation) must be followed. Therefore, while a link is drawn between the need for adequate ventilation and moisture management objectives, the prescriptive requirements for ventilation systems are all contained in G4/AS1.

Acceptable Solution G4/AS1 allows practitioners to adopt natural, mechanical, or mixed-mode ventilation systems for residential buildings, with the following requirements:

- Natural ventilation systems must:
  - Include ventilation openings equal to at least 5 % of the floor area, except when 'trickle ventilators' are adopted in residences with only one external wall, in which case a separate requirement for the ventilator opening area must be followed.
  - Include mechanical extract fans in spaces that contain cooktops, showers and/or baths. These fans must achieve minimum flow rates of 25 L s^{-1} for showers and baths, and 50 L s^{-1} for cooktops.
- Mechanical ventilation systems must be designed according to standards NZS 4303 [37] and/or AS 1668.2 [38]; both of these standards outline minimum ventilation rates and methods to achieve acceptable IAQ, but neither appears to be based on an analysis of moisture management requirements to mitigate the risk of condensation and mould growth.

Further Reading

- BRANZ have undertaken extensive work on condensation and mould risk in New Zealand buildings, some of which is directly relevant to the regulations described above. For example, Overton published a paper in 2019 exploring the possibility that hygrothermal modelling could be introduced as a verification method under the New Zealand Building Code [39].
- Buet and Isaacs published a paper in 2020 exploring the sensitivity of hygrothermal modelling to indoor boundary condition assumptions in the New Zealand context [40].
- A substantial body of literature exists discussing the technical basis for, and implications of the standard ASHRAE 62.2, on which NZS 4303 is based. For example, Walker and Sherman published on the implications of ASHRAE 62.2 minimum ventilation rates on indoor humidity in 2007 [41].

3.1.3 United States

Building regulations in the USA are set by individual states or municipalities, and they therefore vary significantly across the country. The International Building Code [42] (with similar scope to NCC vol. 1), and International Residential Code [43] (with similar scope to NCC vol. 2), are each in use or adopted in at least 49 states within the USA, according to the International Code Council's website [44]. However, it appears that many jurisdictions have only adopted parts of these codes, and/or are currently using previous editions of the codes (from years 2006–2018) [45].

The ANSI/ASHRAE Standard 62.2 [46] is another important document relevant to ventilation requirements in the USA. Historically, ventilation requirements in the International Residential Code were aligned with those in ANSI/ASHRAE 62.2, however the fresh air (i.e. ventilation rate) requirement in the 2013 edition of ANSI/ASHRAE 62.2 was increased substantially, whereas the corresponding value in the International Residential Code has since remained the same. Several articles have been published documenting the differences in opinions among experts on this issue, e.g. [47].

The sub-sections below focus on both the 2021 edition of the International Residential Code (IRC) [43] and 2022 version of ANSI/ASHRAE 62.2 [46].

Performance Requirements

The IRC is primarily a prescriptive code, as opposed to a performance-based code such as the Australian NCC. It does not appear to contain any performance requirements regarding ventilation and condensation/mould risk mitigation.

ANSI/ASHRAE 62.2 is also prescriptive in its language, and does not appear to contain any relevant performance requirements.

Neither the IRC nor ANSI/ASHRAE 62.2 appear to draw a direct link between the specified ventilation requirements and the aim of moisture management and/or condensation/mould risk mitigation. ANSI/ASHRAE 62.2 defines its scope as "*chemical, physical, and biological contaminants that can affect air quality*" and states that "*while acceptable IAQ is the goal of this standard, it will not necessarily be achieved even if all requirements are met … because of the many other factors that may affect occupant perception and acceptance of IAQ, such as air temperature, humidity …*". It does not appear to contain any references to mould, condensation or indoor moisture management. As noted above, the IRC has historically mirrored the ANSI/ASHRAE 62.2 ventilation requirements, and has kept a lower ventilation requirement than ANSI/ASHRAE 62.2 in recent years. Therefore, while the IRC does not identify the purpose of the ventilation that it specifies, it does not appear to be based on a specific quantified requirement for condensation/mould risk mitigation.

Prescriptive Solutions: IRC

The IRC requires new dwellings to be mechanically ventilated. Clause R303.4 requires any dwellings that meet the envelope air tightness requirements in clause N1102.4.1 to be provided with 'whole-house' mechanical ventilation, and clause N1102.4.1 requires:

- Specific air tightness construction practices to be followed;
- An air leakage test (i.e. 'blower door' test) to be conducted on all new dwellings; and
- The measured air leakage rate to not exceed 5 ACH, or 0.0079 $m^3\ s^{-1}\ m^{-2}$ permeability (equal to 28.44 $m^3\ h^{-1}\ m^{-2}$), at 50 Pa (or 3 ACH at 50 Pa for the majority of climate zones if the prescriptive compliance pathway is being used for energy efficiency).

Therefore, in jurisdictions where clauses R303.4 and N1102.4.1 are both adopted, a minimum standard of air tightness and 'background' mechanical ventilation are both mandatory.

Mechanical ventilation systems are required to provide air continuously, or intermittently, with an average ventilation rate of at least (clause M1505):

$$Q_{min} = 0.05A + 3.5(N_b + 1) \quad (4)$$

where Q_{min} is the minimum time-averaged ventilation rate [L s^{-1}], A is the floor area of the dwelling [m^2], and N_b is the number of bedrooms in the dwelling.

The minimum flow rates determined using Equation 4 can be reduced by 30 % for mechanical systems that are balanced (i.e. those that include both supply and exhaust fans driving an equal flow rate) and deliver air via ducts directly to all bedrooms and at least one of either a living room, dining room, or kitchen.

Mechanical systems that operate intermittently must operate for at least 25 % of each 4-hour period.

Clause M1505.4.4 also specifies minimum flow rates for 'local exhaust' (i.e. kitchen range hoods and bathroom exhaust fans), when it is installed. In our opinion, the IRC is ambiguous as to whether such local exhaust is a mandatory component of the continuous/intermittent mechanical ventilation systems.

Requirements for the size of openings to provide natural ventilation are specified in clause R303.1 (including 4 % of the floor area for habitable rooms and 0.15 m^2 for bathrooms). However, dwellings with complying mechanical ventilation systems are exempt from these requirements.

Thus, the ventilation requirements set out in the IRC appear to include mandatory continuous or intermittent mechanical ventilation, with optional source extract ventilation and optional natural ventilation.

Our review did not reveal a summary of which jurisdictions within the USA have adopted the mandatory continuous/intermittent mechanical ventilation specified in the IRC, and detailed review of each jurisdiction's building code was outside of the scope of this review. However, we did find evidence that at least some jurisdictions have adopted these clauses, including New York [48], Montana [49], and California [50].

Taking Florida as an example of a jurisdiction applying a version of the IRC to climates similar to those in regions of Northern Australia, it can be observed that [51]:

1. Mechanical 'background' ventilation is only mandated for dwellings with a measured envelope air leakage rate of less than 3 ACH at 50 Pa.
2. Provision for natural ventilation is required in buildings without mechanical ventilation.
3. Additional clauses are included in the local version of the IRC specifying energy efficiency requirements for dehumidifiers; however, dehumidifiers are not mandated.

As discussed in Section 3.2, the risk of condensation and mould in hot, humid climates can arise through processes that are fundamentally different to those in colder climates, because air flows and diffusion can transport significant quantities of vapour from outdoors into the dwelling when air conditioning is used. Therefore, dehumidification is often recommended when air conditioning is used in such climates, to remove the excess humidity introduced by the ventilation, and naturally ventilated dwellings (without frequent use of air conditioning or dehumidification) are also common. The Florida Building Code allows either approach to be taken, except in especially air-tight dwellings where mechanical ventilation is required to remove internally generated moisture.

Prescriptive Solutions: ANSI/ASHRAE 62.2

ANSI/ASHRAE 62.2 specifies ventilation systems very similar to those specified in the IRC, except for the requirement for a significantly higher ventilation rate. Section 4 of ANSI/ASHRAE 62.2 requires "*each dwelling to be provided with a mechanical ventilation system*" (i.e. mandates 'background' mechanical ventilation), and Section 5 requires a "*local mechanical exhaust system*" (either demand-controlled or continuously operated) to be installed in each kitchen and bathroom.

Detailed requirements and calculation methods are specified to cover issues such as infiltration/air-tightness, limitations on the types of building where exhaust-only systems are permitted, intermittent/variable operation of ventilation systems, filtration, etc.

The minimum ventilation rates specified in ANSI/ASHRAE 62.2 are significantly higher than those specified in the IRC. They are given by an equation identical to Equation 4, except that the first constant on the right-hand side is 0.15 instead of 0.05.

Within the scope of this review, we were unable to determine how many jurisdictions in the USA have adopted ventilation requirements from ANSI/ASHRAE 62.2 rather than those in the IRC. However, we are aware that California has [50].

Further Reading

- Several guidance documents have been published on methods to avoid condensation and mould in US buildings, including a position document by ASHRAE [52], a guide by the EPA [53], and an article by the Building Science Corporation [54].
- Several papers have also been published on the basis for, and implications of, provisions in ANSI/ASHRAE 62.2, e.g. [20,55].

3.1.4 Summary and Comparison with NCC 2022

In summary, indoor ventilation requirements in building codes from Britain, New Zealand and The USA can be contrasted to those in the 2022 version of the Australian NCC as follows:

- The **stated purpose of ventilation provisions** in all of the reviewed codes is to maintain adequate IAQ. However, while some codes explicitly refer to moisture management as part of that purpose, others do not. For example, the code applicable to England and Wales sets quantitative performance requirements for ventilation in terms of surface water activity (which is linked to mould risk), and the New Zealand Building Code sets a qualitative requirement for "*an adequate combination of thermal resistance, ventilation, and space temperature ... to all ... spaces where moisture may be generated or may accumulate*", whereas codes in the USA do not appear to draw an explicit link between ventilation requirements and moisture management. NCC 2022 is similar to the US codes in this regard, since performance requirement F6P3–F6P5 and H4P5 in NCC 2022 do not mention moisture management or mould/condensation risk mitigation.
- While ventilation of habitable rooms is mandatory under all of the reviewed codes, the codes treat **mechanical 'background' ventilation** differently, as follows:
  - The codes applicable to England, Wales and New Zealand leave the option of natural ventilation open to practitioners (i.e. they do not mandate mechanical background ventilation);
  - The code applicable to Scotland only mandates mechanical background ventilation for buildings with envelope permeability < 5 m^3 h^{-1} m^{-2} @ 50 Pa (confirmed by blower door test), and mandates that the system be balanced for buildings with envelope permeability < 3 m^3 h^{-1} m^{-2} @ 50 Pa (buildings with permeability greater than 5 m^3 h^{-1} m^{-2} @ 50 Pa can rely on natural ventilation);
  - The International Residential Code, on which many jurisdictions within the USA base their building codes, mandates mechanical background ventilation for all dwellings; it appears that several jurisdictions (e.g. New York and California) have adopted this requirement, whereas others (e.g. Florida) have not.

  In this regard, NCC 2022 is similar to the Scottish code. Verification methods J1V4 and H6V3 outline requirements for blower door testing and require mechanical background ventilation systems in cases where the measured envelope permeability is ≤ 5 m^3 h^{-1} m^{-2} @ 50 Pa. However, such blower door tests are currently not mandatory under the NCC, so these provisions for mechanical background ventilation are not applied to all practitioners.
- **Exhaust ventilation in kitchens, bathrooms, etc.** is also treated differently across the reviewed codes:

- Mechanical exhaust fans are required in such spaces by the British and New Zealand building codes;
- Natural or mechanical ventilation of such spaces appears to be permitted under the International Residential Code (versions of which are adopted by many jurisdictions in the USA), although the code is ambiguous on this point in our opinion.

NCC 2022 is similar to our reading of the USA provisions in this regard, since clause F8D4, and parts 10.6.2 and 10.8.2 of the Housing Provisions, allow practitioners to choose natural or mechanical ventilation systems for kitchens, bathrooms, sanitary compartments and laundries.

3.2 MOULD RISK IN HOT, HUMID CLIMATES

This section of the review focuses on mould risk in hot, humid climates, such as those in northern Australia. It provides a brief overview of the relevant failure mechanisms and design guidance published for such climates, and then reviews relevant published studies involving experiments and/or analysis of field data.

The risk of mould caused by leaking rain water, ground water, or plumbing leaks, are very similar across all climates—although some differences do exist, e.g. the risk of water freezing in pipes in colder climates, and severe wind-driven rain risk in regions prone to cyclones. Therefore, provisions to manage these risks are typically very similar across all climates.

However, the mechanisms by which air movement and vapour diffusion create risks of mould and condensation can be fundamentally different in hot, humid climates, as compared to cooler climates. When the indoor space is air-conditioned, intended ventilation and unintended infiltration can both bring humid outdoor air into contact with relatively cool indoor surfaces, leading to high relative humidity and increased risk of mould growth. Air conditioning can also create a vapour pressure gradient across the building envelope that drives vapour diffusion towards the relatively cool material layers on the indoor side of the envelope, also leading to high relative humidity and mould risk. Thus, most published descriptions of condensation and mould in hot, humid climates focus on the indoor side of envelope assemblies, often between the paint and the internal lining (e.g. plasterboard), or between the internal lining and insulation. Condensation can also occur on HVAC ducts, and refrigerant or chilled water lines.

Notably, naturally ventilated buildings in hot, humid climates are unlikely to suffer from the same issues, since indoor surfaces are not cooled far below the outdoor air temperature. Methods suggested to mitigate mould risk in such naturally ventilated buildings include the use of materials with relatively high resistance to mould growth (e.g. avoiding the use of paper-faced plasterboard and fabric curtains) [56].

Design guidance provided for hot, humid climates in the USA typically focuses on air-conditioned buildings [52–54,57,58]. The guidance is relatively consistent, typically including some or all of the following design principles:

- An effective air control layer (e.g. pliable membrane) should be installed on the outdoor side of the primary thermal control layer (e.g. wall insulation).
- Materials with high vapour diffusion resistance (e.g. vinyl wallpaper) should not be installed on the indoor side of the primary thermal control layer.
- Ventilation systems should not depressurise the indoor space (i.e. exhaust-only ventilation systems should not be used), and should ideally pressurise the indoor space slightly (e.g. by 2-3 Pa), to prevent humid outdoor air from being sucked through gaps in the building envelope, past cold surfaces.
- Rooms containing significant sources of humidity in the home, such as bathrooms and kitchens, should have exhaust ventilation installed.
- When air-conditioned, the indoor space should also be dehumidified, either using the air conditioning equipment or a dedicated dehumidifier, to remove humidity introduced into the space by ventilation and indoor human activity.

Such guidance appears to be based on experience in diagnosing and addressing moisture-related building failures in southern USA, as well as analysis of moisture transport processes within buildings. Anecdotal evidence is provided in several guidance documents, such as the following:

- "*Ventilation without dehumidification has been responsible for major mold growth problems in hot and humid climates*" [52]
- "*Wholesale adoption of prescriptive vapor barrier requirements generated for cold climates have proven to be destructive for buildings in hot and humid climates*." [52]
- "*... installation of vinyl wall coverings on the inside of air-conditioned assemblies (a practice that has been linked with moldy buildings)*" [58]

However, our review uncovered very few publications reporting scientific studies that investigated mould risk in hot, humid climates using data from experiments or field surveys. This finding is aligned with those of a recent literature review focused on mould in Australian housing [23], which found the vast majority of previous Australian studies on that topic had focused on cooler/mild/warm-temperate climates, with no studies covering NCC Climate Zone 1, and only 1 study covering NCC Climate Zone 2. The relevant studies we reviewed are summarised in the following paragraphs.

Strang et al. recently investigated the risk of mould growth in cross-laminated timber (CLT) walls under hot, humid conditions, through a simulation study [59] and an experimental study supported by simulations [60]. The experiments focused on moisture accumulation during the construction of a CLT building, rather than during typical operation, and included two test cells (one installed outdoors, one installed in a climate chamber), and one real building. Key findings from the tests demonstrated the benefits of:

- Insulation on the indoor side of the CLT structure in tropical climates;
- Airtight and vapour resistant membranes on the outdoor side of the CLT structure;
- Effective indoor ventilation; and
- Drained and ventilated cavities behind cladding.

Alaldroos and Mosly [61] investigated the competing needs in educational buildings in hot humid climates for: a) high ventilation rates to ensure adequate IAQ, and b) limited ventilation rates to manage the risk of mould growth. They monitored indoor conditions in three classrooms before and after a retrofit that included significant increases to the ventilation rate. While CO_2 concentrations were reduced to acceptable levels by the additional ventilation, indoor humidity levels increased to unacceptable levels, causing visible mould growth on the ceilings of the classrooms. Building performance simulations were then used to develop suggested optimum ventilation rates for such educational buildings in hot, humid climates—results were in the range of 2–3.5 ACH for occupancy densities in the range 0.2–0.5 people per m^2.

Zhan et al. [62] exposed four steel-framed walls with lightweight cladding to one year of real outdoor conditions in Guangzhou, China, with intermittently controlled and free-running indoor conditions exploring several indoor operational scenarios. Two walls were clad with fibre-cement over a ventilated cavity, while the other two were rendered; one wall with each type of cladding had XPS external insulation while the remaining walls had no external insulation. Ventilated cavities were found to reduce the amount of time that inner material layers were wet by improving the wall's resistance to rainwater penetration. In cases with no ventilated cavities, the external insulation also reduced the duration of wetness within materials on the indoor side of the exterior insulation.

Several publications from Malaysia [63–66] provide case studies of mould and moisture-related problems in buildings under tropical conditions. However, these works cover a relatively narrow range of scenarios, and involve construction details that are not common in Australian residential building practice. The primary value of these studies in the context of this review appears to be in demonstrating the risks of condensation when an air-conditioned space is not adequately insulated from adjacent spaces with no air conditioning.

Udawattha et al. [67] ran experiments to compare the rate of mould and moss growth on various building materials exposed to outdoor conditions in a tropical climate. Results indicated that the porosity, roughness and organic matter content of the materials correlated most strongly with the rate of mould growth.

While not in the scope of this review, which was focused on studies involving experiments and field surveys, we have listed several simulation studies with relevant findings below.

- Hall et al. simulated a lightweight stucco wall in various climates, and with various exterior and interior coatings [68]. Results from simulations of Miami Florida demonstrated the increase in moisture accumulation caused by internal vapour-resistive barriers in hot, humid climates.
- De Castro Silveira et al. simulated a residential building with single skin masonry walls in a tropical climate, and investigated the impact of wall orientation and insulation configuration (internal, external, or none) on the mould risk [69]

3.3 BENEFITS OF DRAINED AND VENTILATED CAVITIES

This section of the review focuses on the impacts that drained and ventilated cavities, located behind wall cladding, can have on the wall's thermal and hygric performance. The primary focus is on studies involving experiments, and on studies of climates and construction systems similar to those in Australia.

3.3.1 Hygric benefits

The hygric (i.e. moisture-related) benefits of air-filled cavities behind wall cladding, with effective drainage and ventilation, are typically claimed to include the following [70–74]:

1. The formation of a 'capillary break' that prevents the transfer of liquid water from the cladding to materials on the indoor side of the cavity;

2. Improved resistance to rain penetration, as any liquid water that penetrates past the cladding can flow downwards and out of the wall assembly under gravity; and
3. Enhanced drying capacity, as moisture is convected from the cavity with the ventilation air flow.

However, the authors of at least two papers [75,76] have also warned that cavity ventilation has the potential to increase mould and condensation risks under certain conditions (e.g. if the ventilation openings allow increased rates of exfiltration through the assembly). These comments appear to have been based on scenarios involving ventilated cavities directly adjacent to insulation (i.e. without a membrane or other type of air barrier installed on the indoor side of the cavity), so they do not necessarily apply to typical Australian construction practices. Nevertheless, it has been shown that cavity ventilation is not appropriate under all circumstances, and its suitability for the construction system and climate should ideally be assessed before it is employed [75].

A substantial body of literature exists to support the claimed benefits and risks of drained and ventilated cavities outlined above. We have summarised some of the most relevant experimental studies below.

In 2004, ASHRAE Research Project 1091 'Development of Design Strategies for Rainscreen and Sheathing Membrane Performance in Wood Frame Walls' produced a comprehensive 12-part final report, including the following sections:

- Report 3 [77] details laboratory tests of the drying rate of a simplified wall specimen, including plexiglass cladding. Tests were run with various membranes, ventilation opening configurations, cavity depths, and cavity ventilation flow rates. Results demonstrated the increase in wall drying rate caused by cavity ventilation, albeit under idealised conditions.
- Report 4 [78] describes laboratory testing of ventilation air flows behind vinyl (i.e. PVC) cladding. Results indicated that significant ventilation flow rates occur, even in cases where no ventilation openings were intentionally included in the cladding layer (i.e. where the only openings were caused by construction tolerances). The addition of a 19 mm cavity behind the cladding increased the ventilation flow rates by at least three orders of magnitude, as compared to walls with 'direct-fixed' cladding.
- Report 6 [79] describes field testing of cavity ventilation rates in masonry veneer walls, with 20 mm and 50 mm-deep cavities, both with a fan driving the flow (to quantify the pressure–flow relationship), and without any mechanical ventilation (to quantify the cavity ventilation flow rates arising naturally due to wind and buoyancy forces). The walls had open head joints

at both the top and bottom to allow ventilation. Results were used to validate semi-analytical models developed previously, and indicated ventilation rates of 0 to 0.5 L s^{-1} per m^2 of wall under the naturally occurring conditions during the tests.

- Report 7 [80] details experiments undertaken in a climate chamber. Walls clad with sheet metal and two types of vinyl cladding were tested with two types of pliable membrane, various forced ventilation rates, and under four sets of simulated weather conditions. Results confirmed that cavity ventilation increases the rate that moisture can escape the wall under all tested conditions except for the coldest scenario (in which the outer layers of the walls remained below 0 °C.
- Report 8 [81] details experiments undertaken under real outdoor conditions in Ontario, Canada. The ability of three masonry veneer walls and two walls with vinyl cladding to dry was compared after water was applied to the rigid sheathing in each wall at three times of year. The tests were repeated with various membranes and cavity ventilation configurations. Results indicated that:
  - Cavity ventilation does increase the rate of drying;
  - Masonry veneer walls with large ventilation openings at the top and bottom of the wall allow faster drying than those with openings only at the bottom of the wall; and
  - Moisture in outer layers of a wall can be driven inwards during periods of high solar irradiance, so rapid drying of any water in the outer layers is desirable.

Bassett and McNeil [82], used a tracer gas method to measure cavity ventilation flow rates in two masonry veneer walls and five fibre-cement-clad walls exposed to real outdoor conditions in New Zealand. The walls were built either with ventilation openings at the top and bottom, or at the bottom only. However, comparison of the measured ventilation rates with a semi-analytical model indicated that even the walls with no intentional top ventilation openings probably had small openings that facilitated ventilation, due to construction tolerances. The average measured ventilation rates were in the order of 0.4 L s^{-1} per m of wall width in walls with no intentional top openings, and 1.4 L s^{-1} per m of wall width in walls designed with both top and bottom openings. Results from the study were also used to validate cavity ventilation rate calculations described in a companion publication [83].

A later study by Bassett and McNeil [84] applied the same tracer gas method to measure cavity ventilation rates in ten walls with either masonry veneer, fibre-cement cladding, or external insulation finish systems (EIFS). Results from this study also corresponded closely to calculated cavity ventilation rates.

Straube [72] undertook laboratory experiments into liquid water drainage from very narrow (approximately 1.0 mm deep) drainage planes, and deeper (10 mm deep) drained and ventilated cavities. The impacts of cavity ventilation on the drying rate after drainage had ceased was also investigated. It was concluded that even the narrow 1 mm drainage planes were likely to provide sufficient drainage for walls in Canada, provided that such narrow gaps could be reliably constructed. However, Straube also found that cavity ventilation enhanced the drying rate in both narrow 1 mm drainage planes and deep 10 mm cavities, and suggested that further work was needed to determine whether the deeper cavity may provide superior performance due to higher ventilation rates.

Künzel et al. [75] used simulations to investigate why drained and ventilated cavities were widely considered to be beneficial in North America, while previous studies and construction practices from Central Europe indicated that they were not beneficial. While not an experimental study, we have included this paper in our review due to its relevance. The authors concluded that the discrepancy was primarily due to differences in the types of wall construction being used in the two regions rather than differences in climate (the archetypal Central European wall investigated was a masonry cavity wall, while the archetypal North American wall had lightweight cladding and reconstituted timber rigid sheathing). The study suggested that drained and ventilated cavities would also reduce the risk of condensation and mould in Central Europe, in buildings with walls similar to the archetypal North American wall.

Langmans and Roels [85] measured cavity ventilation rates in masonry-veneer and fibre-cement-clad walls using four different methods, including tracer gas, differential pressure measurement, anemometers, and inference based on temperature and humidity measurements. They compared the suitability of each method.

Vanpachtenbeke et al. [86] undertook field testing of masonry veneer walls, with different numbers of open head joints at the top and bottom of the wall, in Belgium. It was found that cavity ventilation was not very effective at drying the entire outer leaf of bricks, but it did reduce the humidity levels in the cavity, and therefore reduced the exposure of internal material layers to moisture. The study also demonstrated that buoyancy played a larger role than wind in driving cavity ventilation in the investigated cases. A later paper by the same authors [87] used the same experimental data to validate hygrothermal simulation methods involving cavity ventilation, and demonstrated that typical, simplistic approaches to model cavity ventilation can produce inaccurate results.

Falk and Sandin [88,89] have investigated the nature and benefits of cavity ventilation in Sweden. However, the Swedish climate is arguably not similar enough to Australian climates to justify the inclusion of those studies in this review. We have mentioned them here for the benefit of any readers seeking further studies.

3.3.2 Thermal benefits

Cavities can also impact the effective thermal resistance (R-value) of a wall. Cavities that are completely unventilated, which is arguably rare in practice due to construction tolerances, contribute an R-value that can be predicted relatively accurately using standard approaches (e.g. those in AS/NZS 4859.2 [22], ISO 6946 [90], or various technical guides [16,91,92]).

However, the impact of ventilated cavities on the R-value of a wall can vary significantly through time in response to the conditions, and can increase or decrease the wall effective R-value at different times [21,93]. For example, when a wall is heated by the sun, cavity ventilation can remove heat from behind the cladding extremely effectively via convection, thereby reducing solar heat gains to the indoor space and increasing the effective R-value of the wall under those conditions. Conversely, when solar irradiance and long-wave radiant exchange between the wall and its surroundings are weak, cavity ventilation can reduce the wall's effective R-value by enhancing heat transfer between the outdoor air and material layers within the wall.

The potential benefits of cavity ventilation in terms of increased R-values have been demonstrated in several experimental studies [94–98]. However, they are not yet taken into account in AS/NZS 4859.2, which is referenced in the NCC as the accepted R-value calculation method. This standard currently follows the approach prescribed in ISO 6946, which assumes that any ventilation above a certain rate will always reduce the R-value of a building assembly. Thus, NCC practitioners are currently disincentivised from designing buildings with ventilated cavities, despite the potential (hygric and thermal) benefits of cavity ventilation demonstrated by many of the studies reviewed here.

Further work is needed to quantify the dynamic annual impact of cavity ventilation on the R-value of typical Australian constructions, under a range of Australian climatic conditions. Such data could facilitate the development of improved R-value calculation methods for implementation in AS/NZS 4859.2 and/or the NCC.

3.4 VALIDATION OF NUMERICAL HYGROTHERMAL MODELS

This section of the review focuses on previous experimental validation of dynamic hygrothermal simulation models, such as WUFI Pro. The validation of such models can be divided into two categories:

1. Fundamental validation of the simulation engine, which tests whether the governing equations and solution method, as implemented in the software, can accurately model simple heat and moisture transfer scenarios, typically involving a single material and simple boundary conditions; and
2. Application-focused validation, which tests whether the model can accurately predict heat and moisture transport that occurs in real building assemblies, e.g. including multi-layer constructions and complex, transient boundary conditions.

These two categories could also be described as 'material scale' and 'wall scale', as was suggested by Busser et al. [99].

The first of these types of validation is necessary because, while all hygrothermal models are based on well-established physical principles including the conservation of mass and energy, various approaches can be taken when applying these principles to the transport and storage of heat and moisture in building materials. For example, WUFI [100,101] is based on an approach that:

- Assumes materials exhibit a single monotonically increasing relationship between moisture content and local relative humidity;
- Models supersaturation of materials by allowing relative humidity to reach 101 % and defining moisture storage functions of materials so that the range from 100 to 101 % relative humidity spans the difference from free saturation to maximum supersaturation;
- Models so-called 'surface diffusion' and capillary conduction using a single term in its governing equations, expresses this term as if its driving potential were relative humidity, and assigns one of two different coefficients to this term depending on whether or not the material is in contact with liquid water at its boundary;
- Includes latent heat release and absorption as water is adsorbed and desorbed by hygroscopic materials;
- Includes variations in material properties with changes in temperature and moisture content;
- Models air-filled cavities as an 'equivalent solid', which results in a simplified representation of radiant and convective exchanges in the cavity;

- Does not model ‘contact resistances’ to heat or liquid water transport due to small gaps between adjacent material layers;
- Does not model heat or moisture transport via convection within materials (i.e. air flow is not modelled explicitly by the governing equations);
- Does not model hydraulic flow (i.e. liquid water flow due to total pressure gradients or gravity);
- Does not model liquid water transport due to electrokinesis or osmosis;
- Employs the finite volume method to discretise the governing equations in space; and
- Employs the ‘backward Euler’ (also known as ‘fully implicit’) solution method to solve the governing equations at each timestep.

Other hygrothermal models do not necessarily employ the same assumptions. Therefore fundamental validation of hygrothermal simulation engines using simple test cases, such as those defined in EN 15026 [102], is a vital first step when proving that a particular approach produces accurate results.

Such fundamental validation is not the focus of this review. For the interested reader, a comprehensive literature review of hygrothermal model validation by Busser et al. [99] provides information on fundamental validation studies prior to 2018.

The second stage of validation listed above, i.e. application-focused validation, is the focus of this review. Whereas the fundamental validation described above tests whether a particular model can accurately predict the coupled processes of heat and moisture storage and transport in materials, application-focused validation tests whether the application of that model to a realistic scenario can produce results that match reality. Thus, application-focused validation not only tests whether the model is accounting for all significant processes involved, it also tests whether modelling decisions made by the user of the software were appropriate for the scenario being modelled.

A large proportion of the published application-focused validation studies have been based on strongly heating-dominated climates (e.g. Scandinavia [103–105], Central Europe [106], and colder regions of North America [107–109]), and/or construction systems that are not common in Australia (e.g. highly-insulated timber-framed walls [103,104,108,110–112], novel walls incorporating aerogel [113,114], log construction [105], green roofs [115], etc.). Nevertheless, several trends that are potentially also relevant to the Australian context can be identified in the findings of those studies, for example:

- The qualitative agreement between simulated and measured data is typically reasonably close; however, significant discrepancies are not uncommon. Many authors attribute such discrepancies to uncertainties in the model inputs (e.g. boundary conditions, initial conditions and material properties). It has been noted that model calibration is typically required to achieve satisfactory agreement between a simulation and a specific experiment [12].
- The importance of accurate material properties is often noted [99,103,105,108,111].
- The importance of accurate boundary conditions is often noted [103,111].
- Many studies have demonstrated that air flows need to be modelled reasonably accurately [12,103–105,109,110].
- The VTT mould index model [2,3], which is prescribed in ASHRAE 160 [116] and AIRAH DA07 [1], has typically been shown to produce more accurate predictions of mould growth than simpler methods used previously [12,107].
- In a review of many previous hygrothermal model validation studies, Busser et al. [99] noted a relatively consistent trend for humidity changes to be overdamped (i.e. slow, in comparison to reality) in simulations. They also noted that models that include hysteresis effects in the moisture storage functions of materials, and contact resistances between materials, typically produced more accurate results than the models that did not.

In addition to these broad findings from the larger body of literature, several validation studies have particular relevance to Australian construction practices and/or climates, as outlined in the following paragraphs.

In New Zealand, Overton [39,117] compared data from 16 fibre-cement-clad test walls exposed to real outdoor conditions with WUFI Pro. The walls had different orientations (north or south), frame materials (timber or steel), pliable membrane types (none, sheathing-integrated or separate), rigid sheathing material (none, plywood or 10 mm XPS), batt insulation R-value (R1.8 or R2.8), and internal vapour control layers (with plasterboard either painted or not, and an internal 'smart' vapour barrier membrane installed or not). The authors concluded that agreement between simulated and measured temperature and humidity values was generally close, except for humidity levels in the sheathing and cavity behind the cladding, which were significantly higher in reality than was predicted by the model. The simulations did not include driving rain deposition, or ventilation/infiltration within the walls, which the authors acknowledged as a limitation of the validation exercise, but suggested may not have been the primary cause of the observed discrepancies.

Also in New Zealand, Buet and Isaacs [40] compared indoor boundary conditions prescribed by ASHRAE 160 (and therefore also prescribed by AIRAH DA07, which is a local Australian adoption of ASHRAE 160) with measured conditions inside one house. While this was not a validation of a hygrothermal simulation engine, we have mentioned it here since it is in some senses a validation of the standard methodology for hygrothermal simulations in Australia. Results from this relatively narrow comparison demonstrated that the simplistic indoor temperature and humidity conditions specified in ASHRAE 160 do not necessarily match those in real buildings. Further work would be needed to broaden the scope of the comparison and/or produce improved indoor boundary conditions models for standards such as ASHRAE 160.

Strang et al. [60] recently compared results from WUFI Pro simulations to measured drying rates of CLT walls under hot, humid conditions typical of Queensland. The authors were unable to calibrate the models to match the majority of experiments, and found that the simulations predicted a significantly faster drying rate than was measured. Nevertheless, they were able to conclude that the initial moisture content assumptions prescribed in ASHRAE 160 (and AIRAH DA07) were appropriate for the specific cases they investigated.

Zhan et al. [62] compared WUFI 2D models to the measured performance of four steel-framed walls in the hot, humid climate of Guangzhou, China. Two walls were clad with fibre-cement over a ventilated cavity, while the other two were rendered; one wall with each type of cladding had XPS external insulation while the remaining walls had no external insulation. A calibration procedure was undertaken to match simulation results as closely as possible to the experiments. Remaining discrepancies between the calibrated model and experiments were greatest during times of rapid change in moisture content, and in certain materials (including the stucco/render). The authors concluded that overall, the model was valid for predictions of condensation and mould risk in hot, humid climates.

3.5 SENSITIVITY OF MOULD/CONDENSATION RISK IN AUSTRALIAN CONSTRUCTION SYSTEMS TO OUTDOOR CLIMATE

This section of the review focuses on the sensitivity of mould and condensation risk to the outdoor climate, with a particular focus on construction systems that are in common use in Australia, e.g. those being simulated in this project.

Previous studies have investigated the risk of condensation and mould in a wide variety of building assemblies and climates. However, it is typically not possible to directly compare results from different studies to infer their sensitivity to outdoor climate, since each study is based on a different methodology and set of assumptions (e.g. the construction details investigated, material properties, indoor boundary conditions, initial conditions, etc.). Therefore, reliable data on the sensitivity of mould/condensation risk to outdoor climate can typically only be taken from individual studies that covered several climates. Moreover, only a small proportion of previous studies investigated construction systems that are common in Australia.

Therefore, for inclusion in this section of the review, publications needed to describe studies that:

1. Applied the same assumptions and methodology to several different climates; and
2. Investigated construction systems relevant to the Australian context.

Very few publications that met both of these criteria were identified. Those that did are summarised below.

In their review of previous research into mould in Australian housing, Coulburn et al. [23] did not identify any published analysis that clearly compared the risk of mould growth across various Australian climates, other than the ABCB Nationwide Condensation Survey undertaken in 2015 and 2016. Results from that survey are summarised in the Scoping Study report by Dewsbury et al. [118]. Whilst not a targeted investigation of certain construction systems, and focused more on indoor mould than on interstitial mould, this survey provides a useful indication of perceptions and experiences with mould across Australia's climate zones. A similar survey has also been conducted in Europe [119].

Brambilla and Gasparri [120–122] used WUFI Pro to investigate the risk of mould growth in timber-framed walls with lightweight cladding (material unspecified) and mass-timber (i.e. CLT) walls in NCC Climate Zones 1, 2, 5, 6 and 7 (although Climate Zone 1 was only investigated in one of the three papers reviewed [122]). Several different approaches were tested to generate indoor boundary conditions, and to define failure criteria. The results presented in these publications do not appear to be consistent. The two earlier papers [121,122] predict a higher risk in hot climates, whereas the most recent paper [120] indicates a relatively low risk in Climate Zone 2, a moderate risk in Climate Zone 5, and a high risk of mould growth across Climate Zones 6 and 7. We were unable to determine the cause of this discrepancy during our review.

The SBRC has also undertaken several hygrothermal simulation studies spanning a range of Australian climates [11,17,21]. These studies used WUFI Pro and AIRAH DA07 protocols, including the VTT mould index model, and focused on walls with steel or fibre-cement cladding, with or without ventilated cavities, and with pliable membranes with various vapour permeance values. Results have indicated a high risk of mould growth in walls with no ventilated cavity or a membrane with low vapour permeance (e.g. Class 2) in Climate Zones 4, 6 and 7, and a moderate risk for such walls in Climate Zone 5. Walls with a ventilated cavity and membrane with high vapour permeance (e.g. Class 4) have shown a very low risk of mould growth in the cases investigated. Results from Climate Zones 1 and 3 have shown a low risk of mould growth.

Overton [117] used WUFI Pro to compare the mould growth risk (using a metric prescribed in ASHRAE 160 prior to the introduction of the VTT mould index model) in 11 locations within New Zealand, spanning International Energy Conservation Code (IECC) climate zones 3C, 4A, 4C, 5A and 5C. They modelled "wall constructions similar to those tested in the experiment [described in the same report]", which implies the wall constructions were fibre-cement-clad with either 10 mm, 30 mm or 50 mm XPS rigid sheathing, plywood rigid sheathing, or a pliable membrane installed on the outdoor side of the frame, and with either R1.8 or R2.8 batt insulation. They also tested two different indoor boundary condition settings: one with the standard 70 % cap on relative humidity, and one without that cap. The authors reported relatively little difference in the predicted level of mould risk across the 11 climates, which was expected given the relatively similar climatic conditions (as indicated by the narrow range of IECC climate zones represented). Based on the failure criteria used, which has since been replaced in ASHRAE 160, all of the simulated cases were predicted to fail (i.e. to have an unacceptably high risk of mould growth).

Several studies, e.g. [123], have also investigated the sensitivity of mould risk to projected future climate change. Such impacts are predicted to be complex, and are outside of the scope of this review.

4 Results

This section of the report contains results from the primary simulation study and window simulations. Results from simulations of the walls, roofs and windows are presented in Sub-sections 4.1, 4.2 and 4.3, respectively.

As explained in Section 2.1.7, these results should not be interpreted as definitive indications of absolute risk. The data are a product of the specific assumptions and settings used in the simulations. They are likely to provide a relatively accurate indication of relative risk between different construction types and climates, but they do not indicate the performance of all such constructions in reality, due to the vast variation in construction details and environmental conditions that occur in real buildings. Further work is needed to determine what proportion of the Australian building stock can be accurately characterised using the simulated data presented here.

4.1 WALLS

Figures 4-1 to 4-18 (starting on page 60) present the maximum mould index reached within the nine wall constructions, with and without ventilated cavities where relevant, during 10-years of simulated operation. The data have been graphed with Indoor Humidity Risk Rating on the horizontal axis, and membrane permeance on the vertical axis (in cases where the construction included a membrane), with separate results presented for each climate zone.

4.1.1 Location of Highest Mould Index within the Wall

In simulations of the walls with membranes, the highest mould index values arose at the interface between membrane and insulation, except for in Climate Zone 1 where the highest mould index values arose at the interface between the plasterboard and insulation. Simulations of walls without membranes produced similar trends, with the highest mould index arising on the outdoor side of the insulation in all climate zones except Climate Zone 1, where it arose on the indoor side of the insulation.

These trends are consistent with evidence from previous studies and typical guidance on mould risk reduction in wall constructions. In cases with a hot, humid outdoor environment and an indoor environment that is cooled for a large proportion of the year, vapour is primarily driven from outdoors inwards, creating regions of high relative humidity where the vapour arrives at a relatively cold surface, i.e. on the indoor side of the primary insulation layer. In cold climates, vapour is primarily driven from the relatively warm and humid indoor environment outwards, creating regions of high relative humidity on the outdoor side of the primary insulation layer. Results from this study indicate that even in Climate Zones 2 and 3, which are relatively warm but do require some heating in winter to stay within the indoor temperature control band defined in AIRAH DA07, the primary mould risk in walls is caused by outward vapour drive during cold periods.

It should be noted that if buildings are operated much differently to the assumed usage in this study (i.e. frequent heating and air conditioning to stay within a narrow temperature range, and very limited indoor ventilation), the nature of the mould risk is likely to change, potentially including changes in the location of highest risk within a wall. For example, if buildings in Climate Zones 2 or 3 are frequently air conditioned but rarely heated, the location of highest mould risk could be on the indoor side of the primary insulation layer, not the outside.

4.1.2 Wall Orientation

While all walls simulated in Climate Zones 2–8 were modelled facing south, both south-facing and east-facing versions of each wall were simulated in Climate Zone 1. This approach was based on experience from previous studies, which had demonstrate that the highest mould risk was simulated in south-facing walls in most Australian Climates, the exception being tropical regions, where simulations of east-facing walls can sometimes produce higher mould index values than simulations of south-facing walls.

In this study, the orientation of walls in Climate Zone 1 was found to have varied impacts on the 10-year maximum mould index. East-facing wall models produced higher maximum mould index values than south-facing models when simulating the:

- Timber-clad wall with direct-fixed cladding (by 3–18 %);
- Fibre-cement-clad wall with direct-fixed cladding (by 9–18 %);
- AAC wall with an unventilated cavity (by 2–6 %); and
- Prefabricated concrete wall (by 5 %).

Conversely, east-facing models produced lower maximum mould index values than south-facing models in simulations of the:

- Timber-clad wall with ventilated cavity (by 12 %);
- Fibre-cement-clad wall with ventilated cavity (by 23 %);
- Masonry veneer wall (by 3–61 %); and

- Cavity masonry wall (by 97 %).

Other wall types either did not produce significant mould index values, or produced very similar mould index values in the east- and south-facing scenarios.

4.1.3 Indoor Humidity Risk Rating

In many cases, the 10-year maximum mould index was reduced significantly by decreasing the Indoor Humidity Risk Rating. Such changes represent an increase in indoor ventilation rate, or decrease in occupant density (see Section 2.5.1 for further explanation).

Exceptions to this trend include all simulations in Climate Zone 1, and simulations of walls that could be described as 'high risk' (i.e. those that produced a mould index value very rapidly, such as most wall types with low-permeance Class 1 membranes in Climate Zones 6–8). Simulations of Climate Zone 1 were insensitive to changes in the Indoor Humidity Risk Rating because air-conditioning was active for the vast majority of the year in that climate, and therefore changes in indoor ventilation rate or occupant density did not impact the indoor boundary conditions significantly. Simulations of 'high risk' cases were insensitive to changes in the Indoor Humidity Risk Rating (H) because even the relatively dry indoor conditions modelled with $H = 3.33$ were humid enough to cause the mould index to reach values close to the maximum possible value for the materials being modelled (typically 3.5).

Apart from the exceptions described above, decreases to the Indoor Humidity Risk Rating tended to widen the range of membrane permeance values that could be used in a given climate without generating a mould index over 3. For example, results indicated a high risk of mould growth in the masonry veneer wall when it was modelled with a Class 1 or Class 2 vapour barrier in Climate Zones 2 and 3 (Figure 4-1), but when the indoor humidity levels were reduced (i.e. when $H = 5$ or $H = 3.33$), that risk was mitigated.

This correlation between Indoor Humidity Risk Rating, and 10-year maximum mould index (Figures 4-1 to 4-18) demonstrates two things:

1. For buildings similar to our 'baseline' scenario, i.e. with high occupant density and low ventilation rates, the provision of additional indoor ventilation can be very effective at mitigating the risk of interstitial mould growth in walls; and
2. Within the buildings stock, those buildings that are not similar to our 'baseline' scenario, i.e. those with low occupant densities and/or adequate indoor ventilation, are likely to be at lower risk of developing interstitial mould growth in walls than is indicated by the 'baseline' results.

4.1.4 Cavity Ventilation

In all climates except for Climate Zone 1, the addition of a ventilated cavity to a wall reduced the range of cases that produced 10-year maximum mould index values exceeding 3. Such reduction in mould risk is caused by the following effects:

1. Removal of moisture from the outdoor surface of the membrane via convection; and
2. Additional thermal insulation (see Sections 3.3.2 and 8) between the location in the wall at greatest risk of mould growth (i.e. insulation/membrane interface) and the outdoor environment, thereby producing higher temperatures and lower relative humidities at that location during cold periods.

The magnitude of mould risk reduction provided by cavity ventilation in Climate Zones 2–8 is evident in Figures 4-6 to 4-17. In many cases, the addition of a ventilated cavity shifted the 'point of failure', in terms of the lowest membrane permeance value that did not produce a mould index value over 3, down approximately one membrane class. For example, a significant risk of mould growth was predicted for the fibre-cement-clad wall in Climate Zone 5 in most cases modelled with Class 1, 2 or 3 membranes (Figure 4-9), whereas the addition of a ventilated cavity reduced the range of cases meeting the mould index failure criterion to approximately align with Class 1 and 2 membranes only (Figure 4-10).

In Climate Zone 1, vapour was driven from outdoors inwards for the majority of the time, and the location of highest mould growth risk in the walls was at the insulation/plasterboard interface. Therefore, in Climate Zone 1, the second effect listed above was of no benefit and the first effect listed above could actually increase the risk of mould growth since cavity ventilation air flows could enhance vapour transport from outdoors to the outdoor surface of the membrane. Results from this study demonstrated a slight increase in the 10-year maximum mould index in some walls with highly vapour-permeable (Class 4) membranes in Climate Zone 1. However, cavity ventilation did not cause the mould index in any of these walls to exceed the threshold value of 3 in the cases investigated here.

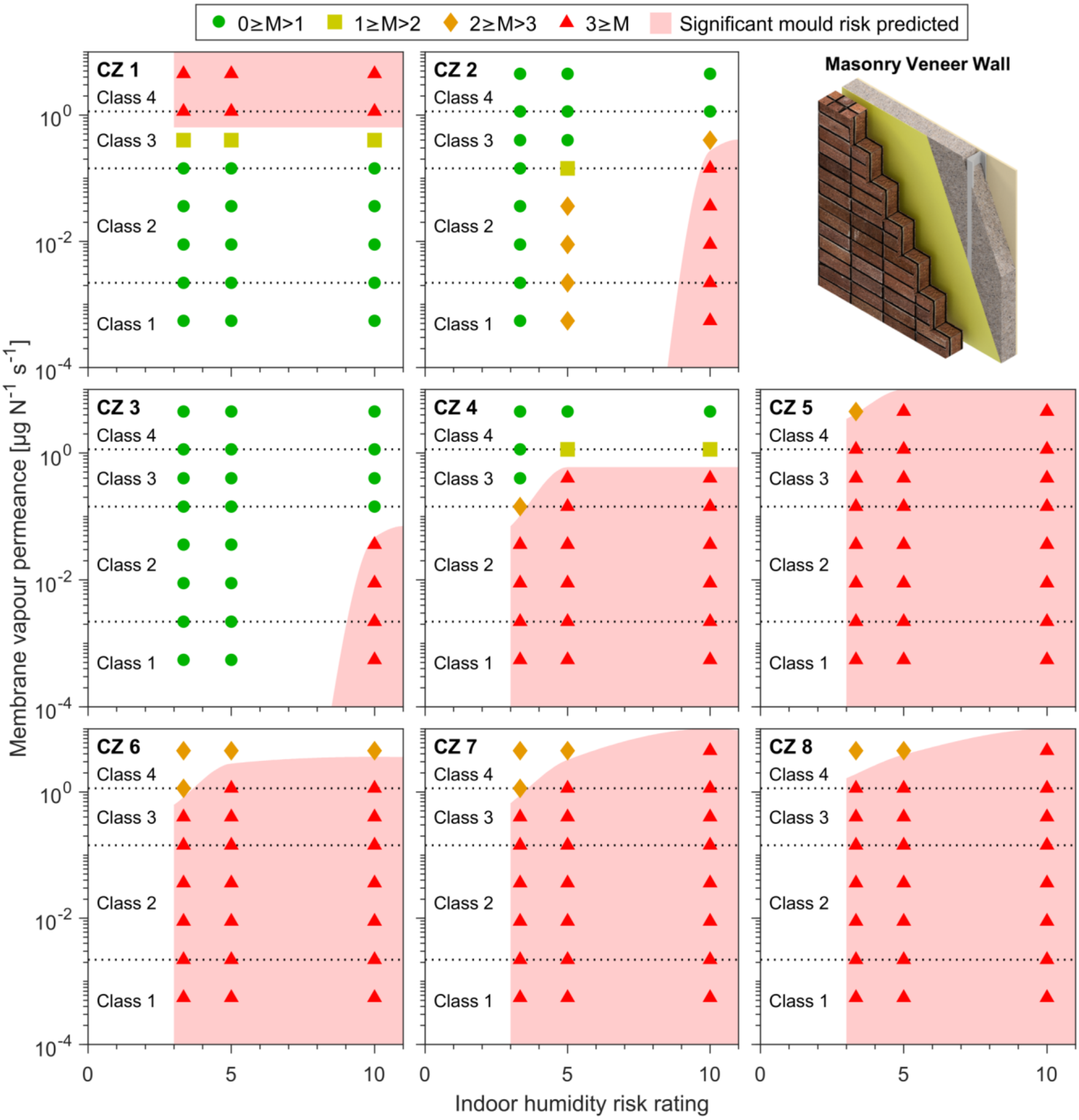


Figure 4-1: Maximum 10-year mould index (M) simulated in masonry veneer walls.

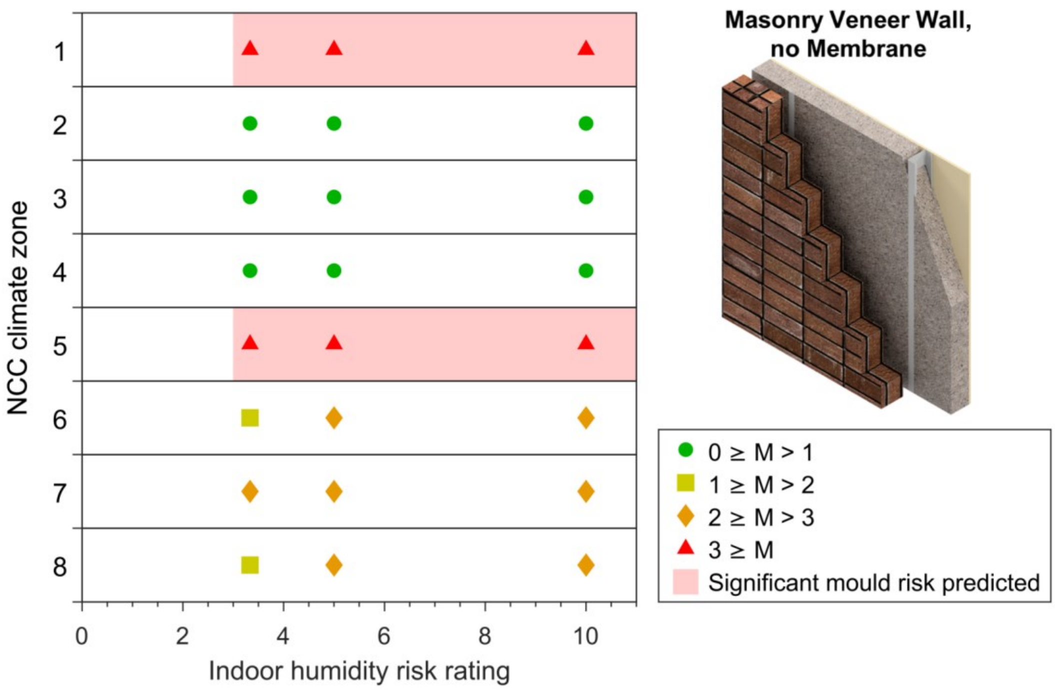


Figure 4-2: Maximum 10-year mould index (M) simulated in masonry veneer walls with no membrane.

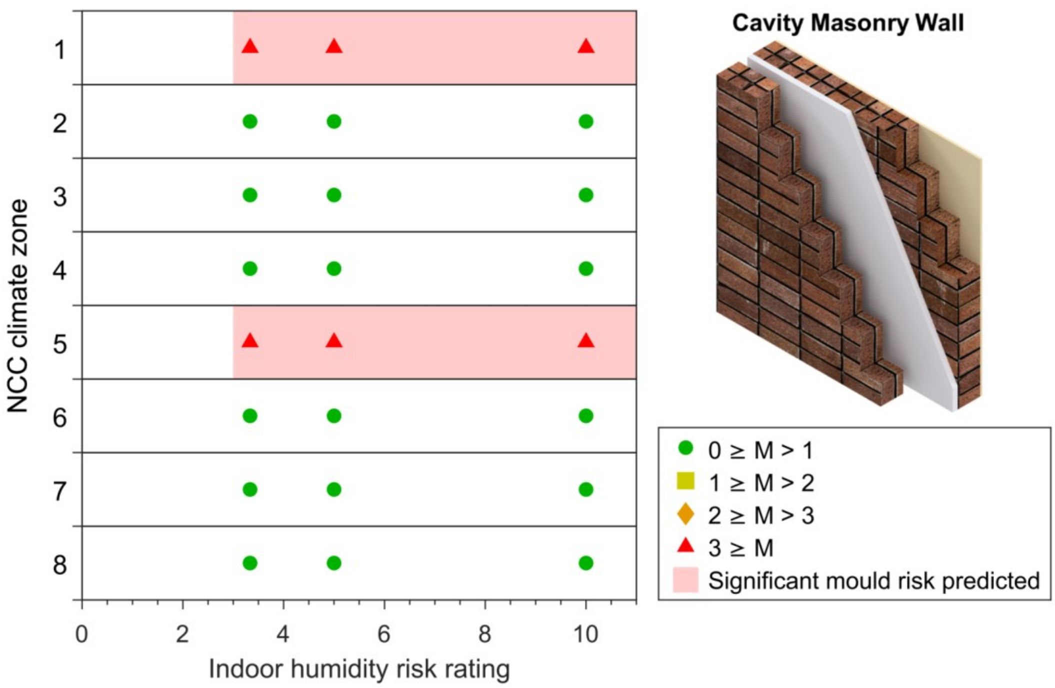


Figure 4-3: Maximum 10-year mould index (M) simulated in cavity masonry walls.

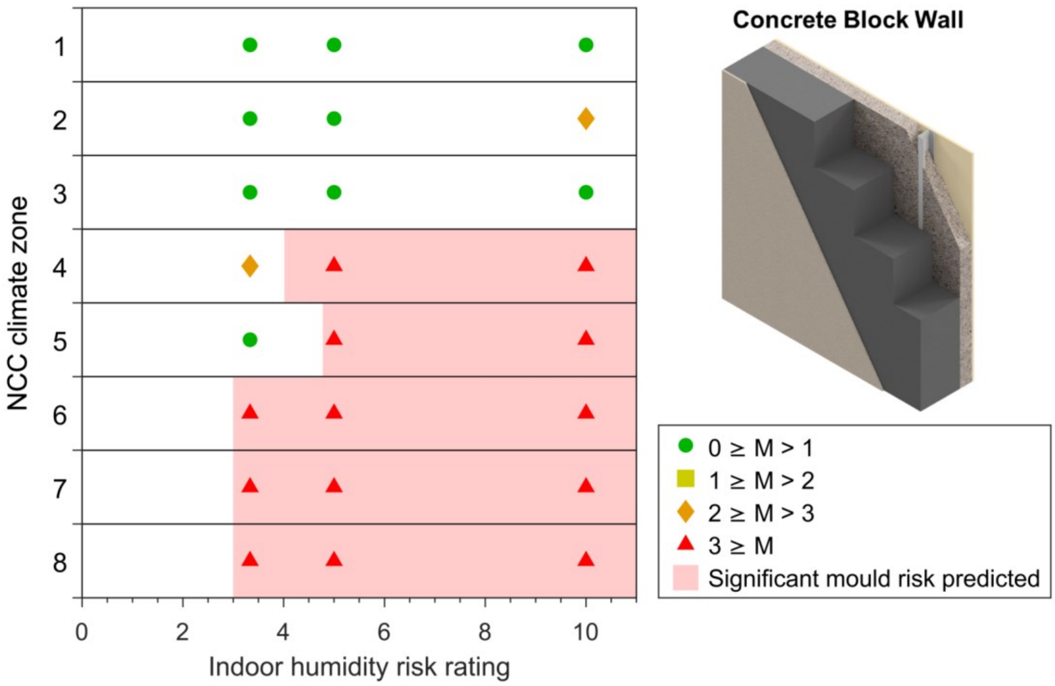


Figure 4-4: Maximum 10-year mould index (M) simulated in concrete block walls.

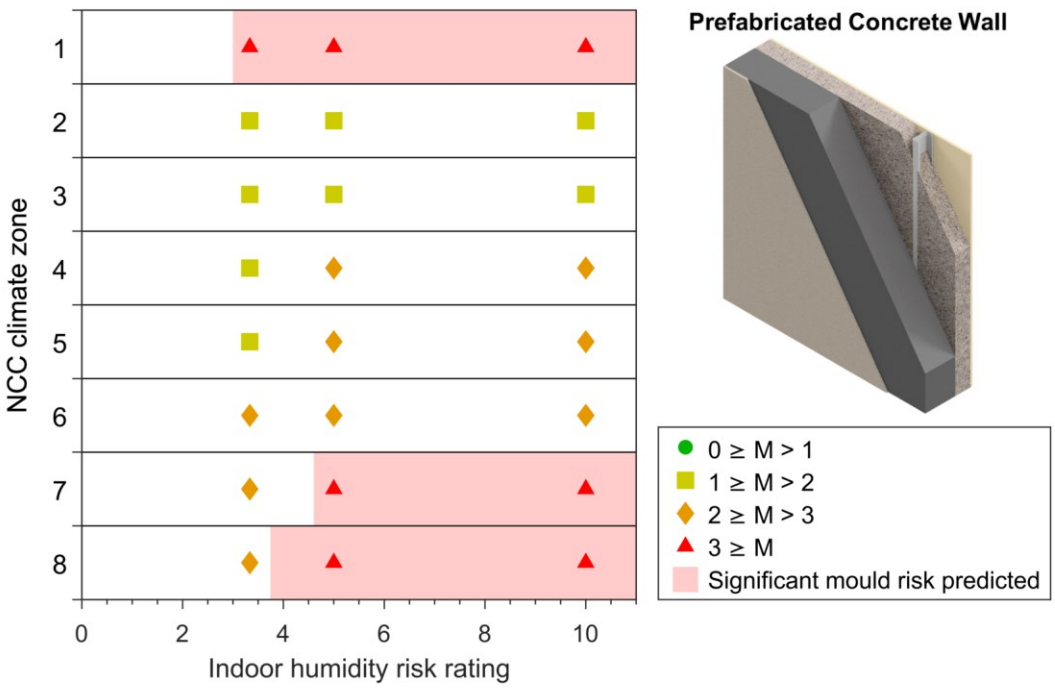


Figure 4-5: Maximum 10-year mould index (M) simulated in prefabricated concrete walls.

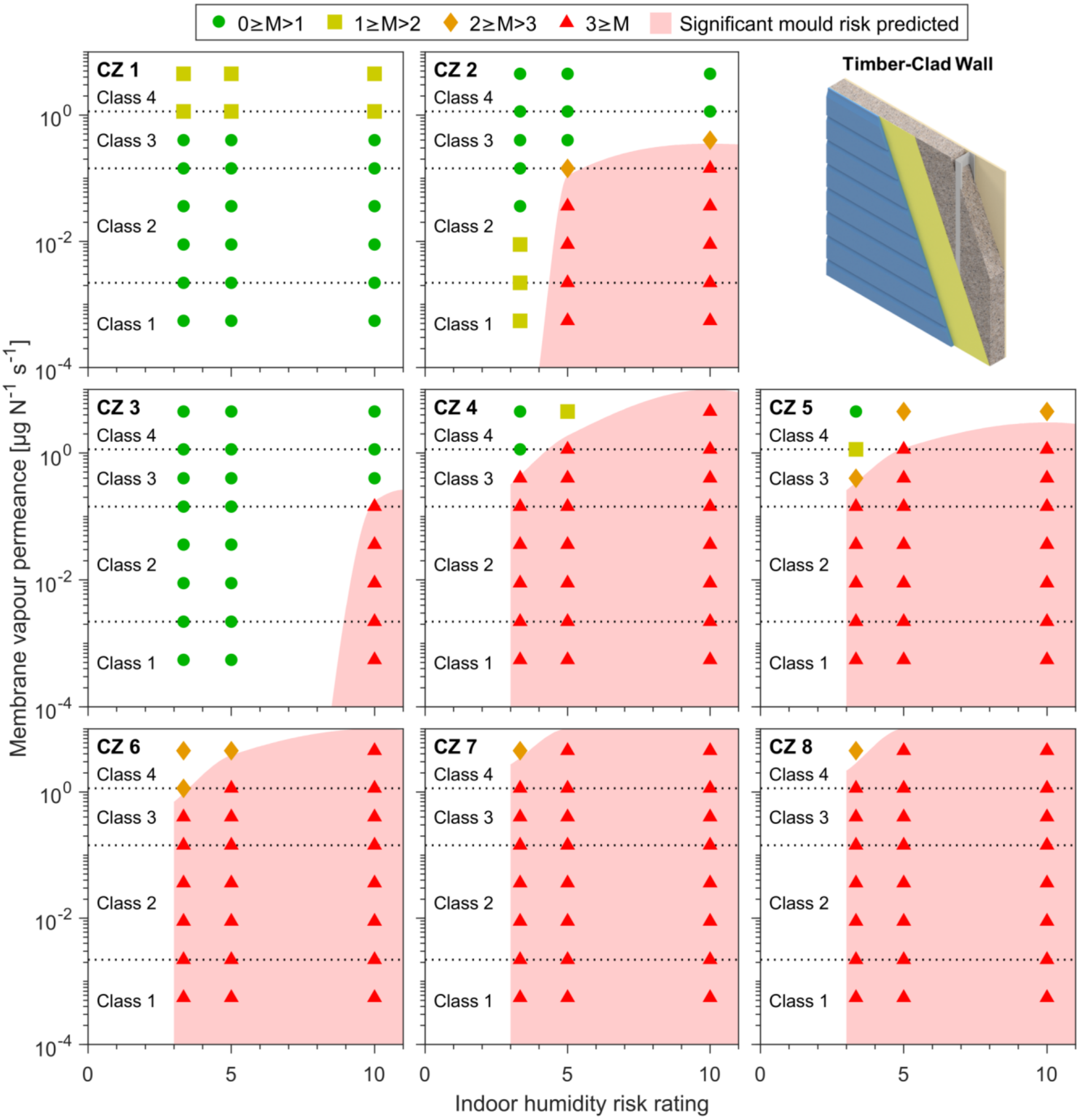


Figure 4-6: Maximum 10-year mould index (M) simulated in timber-clad walls.

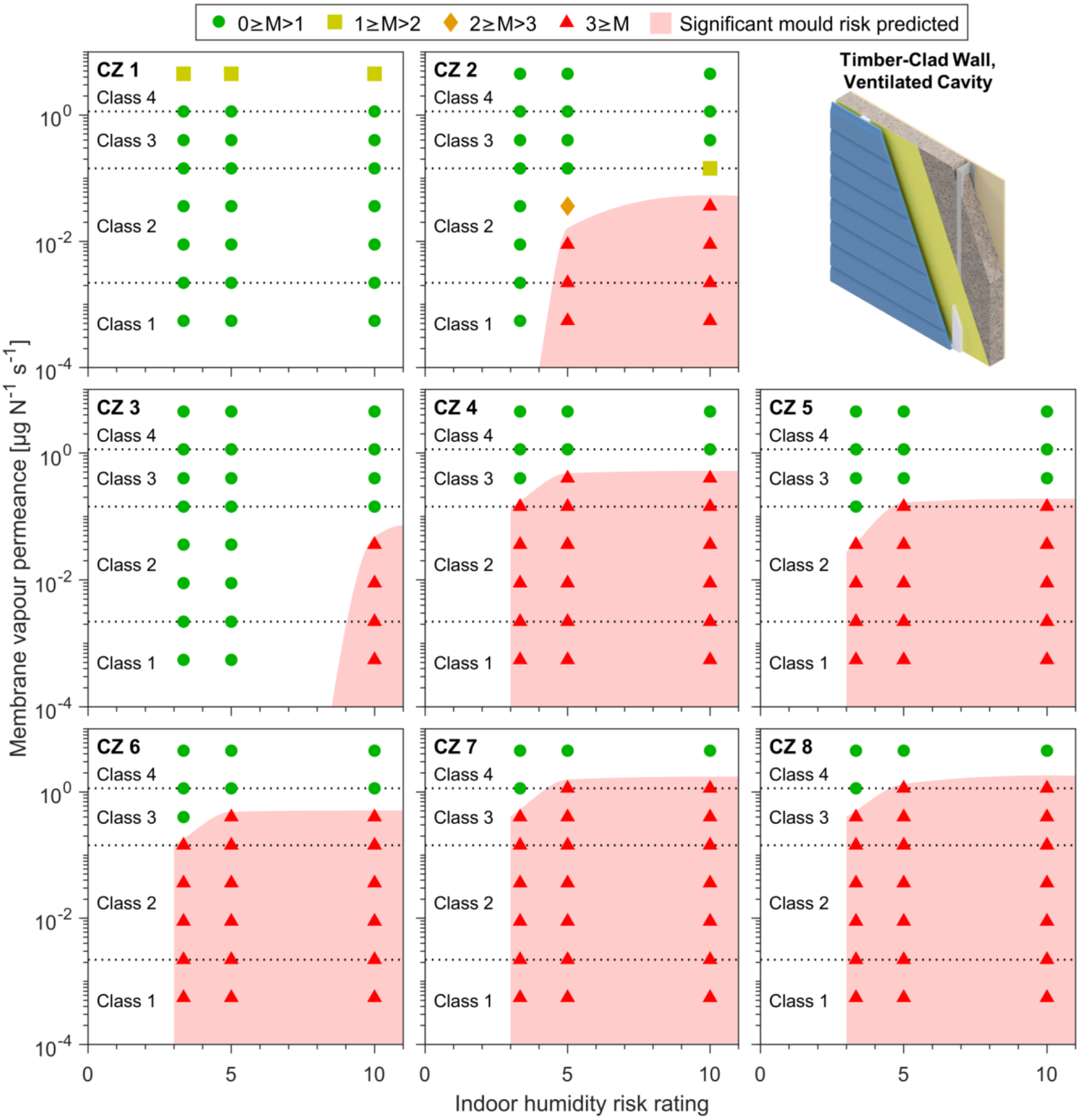


Figure 4-7: Maximum 10-year mould index (M) simulated in timber-clad walls with ventilated cavities.

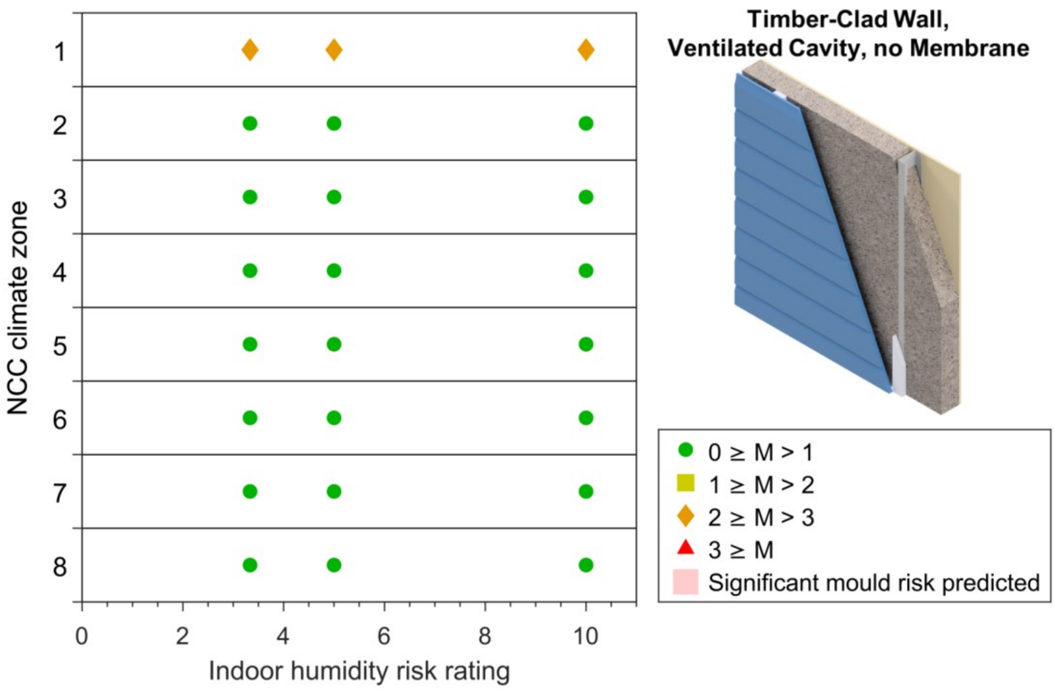


Figure 4-8: Maximum 10-year mould index (M) simulated in timber-clad walls with ventilated cavities and no pliable membrane.

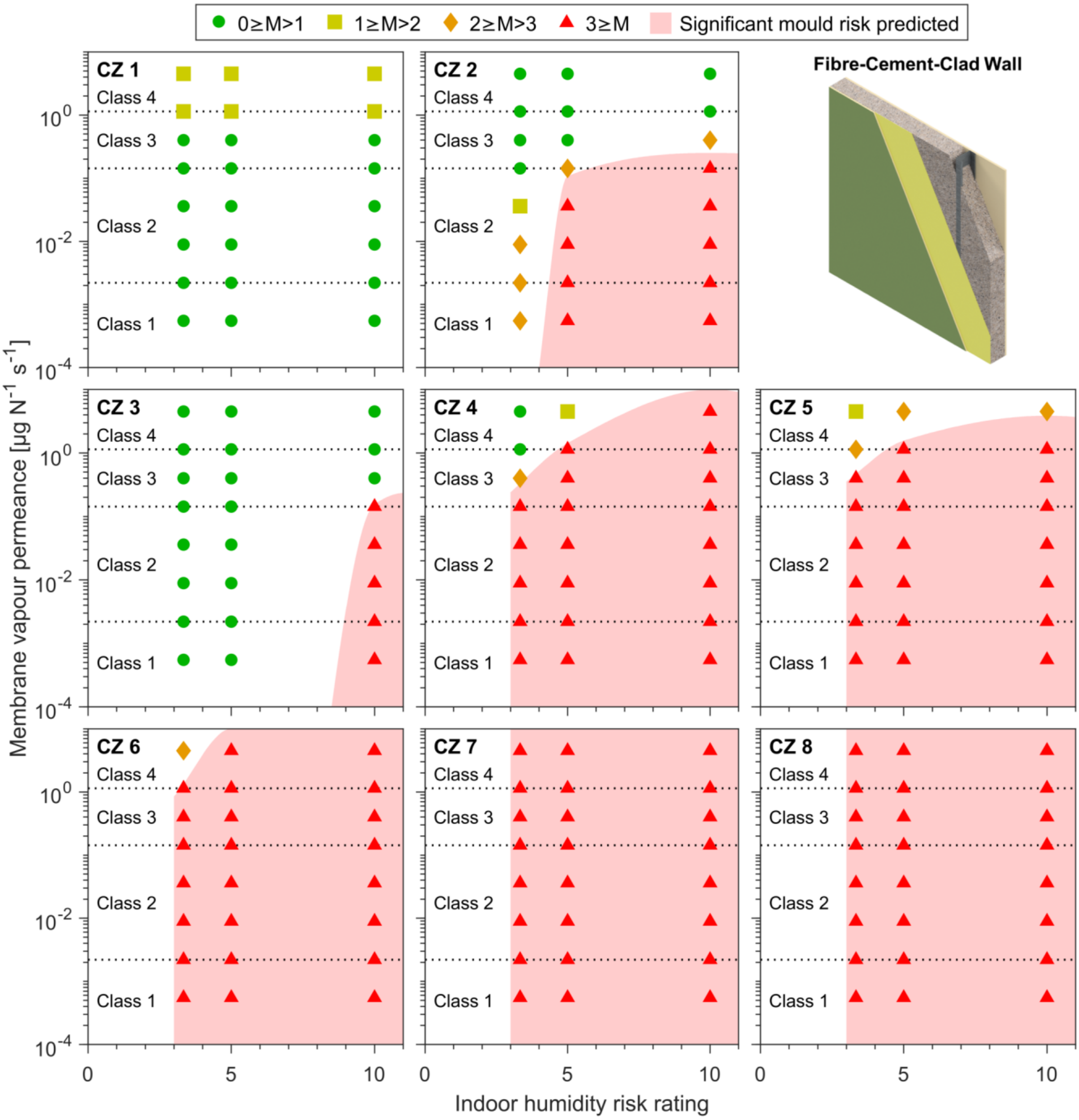


Figure 4-9: Maximum 10-year mould index (M) simulated in fibre-cement-clad walls.

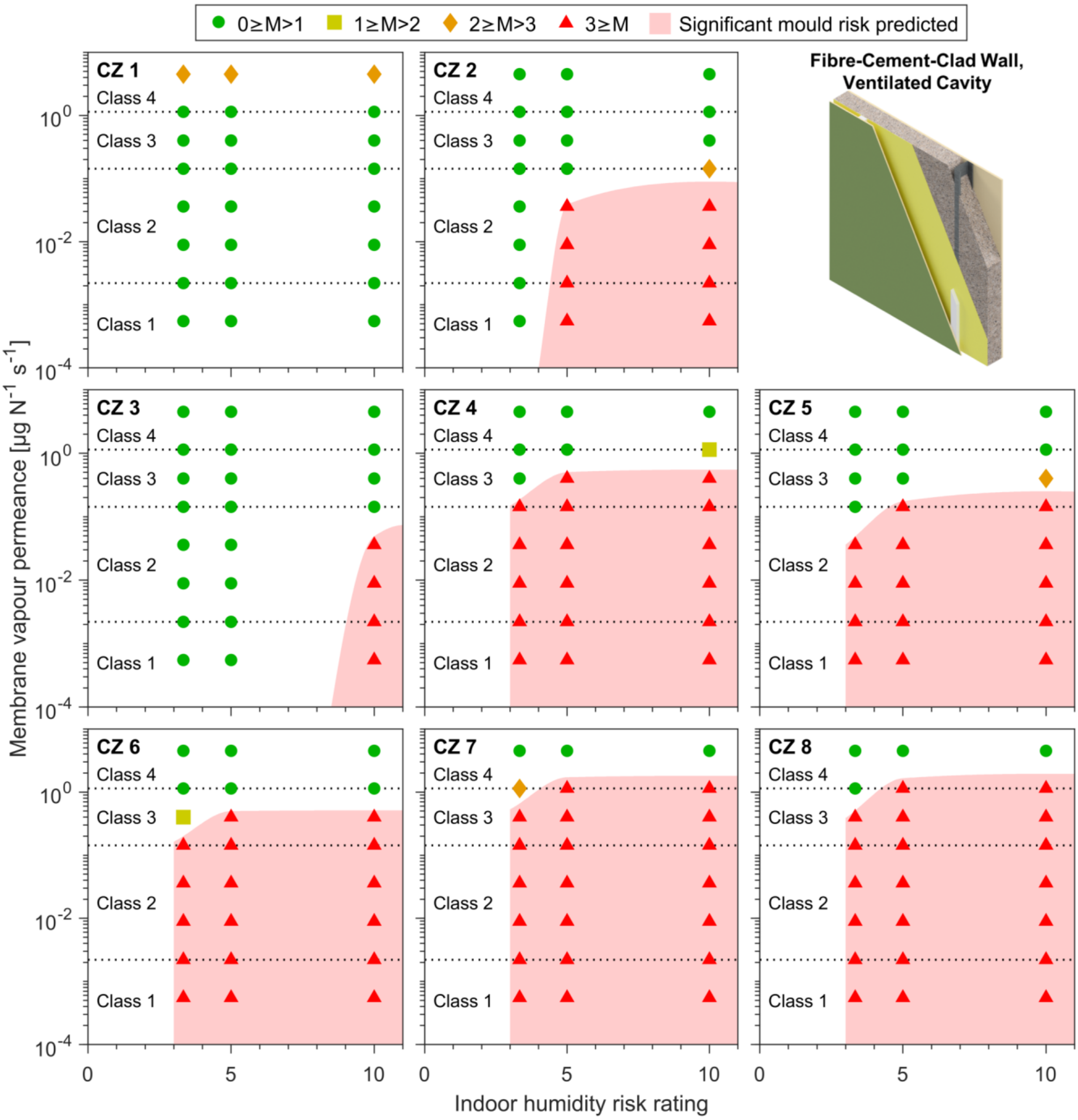


Figure 4-10: Maximum 10-year mould index (M) simulated in fibre-cement-clad walls with ventilated cavities.

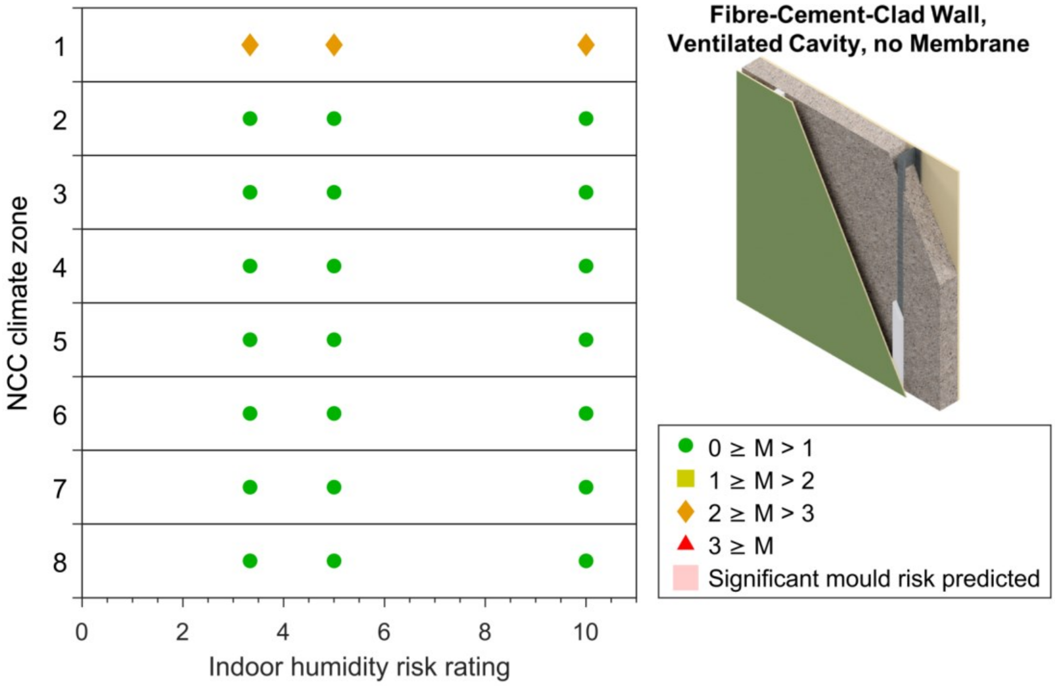


Figure 4-11: Maximum 10-year mould index (M) simulated in fibre-cement-clad walls with ventilated cavities and no pliable membrane.

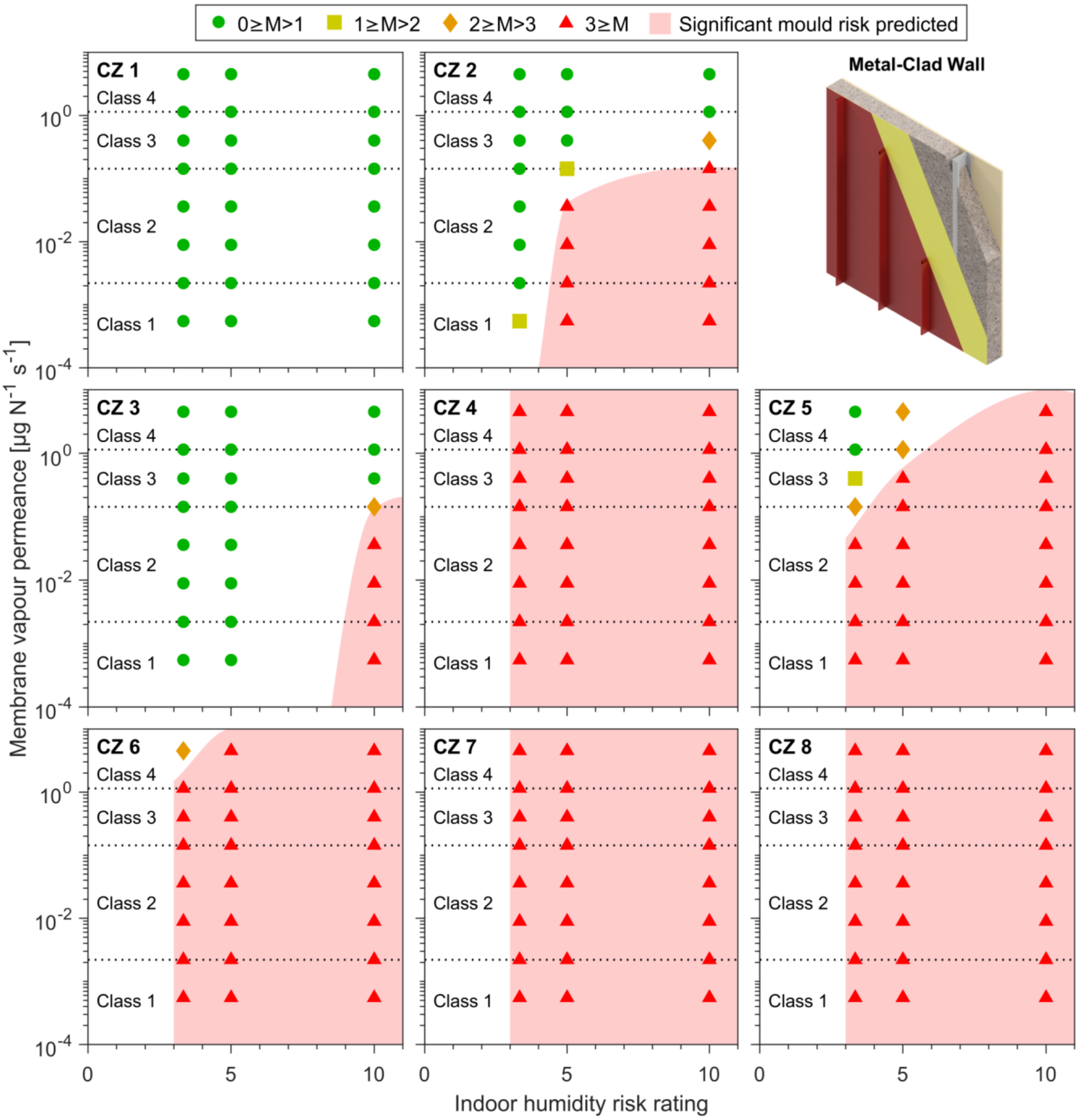


Figure 4-12: Maximum 10-year mould index (M) simulated in metal-clad walls.

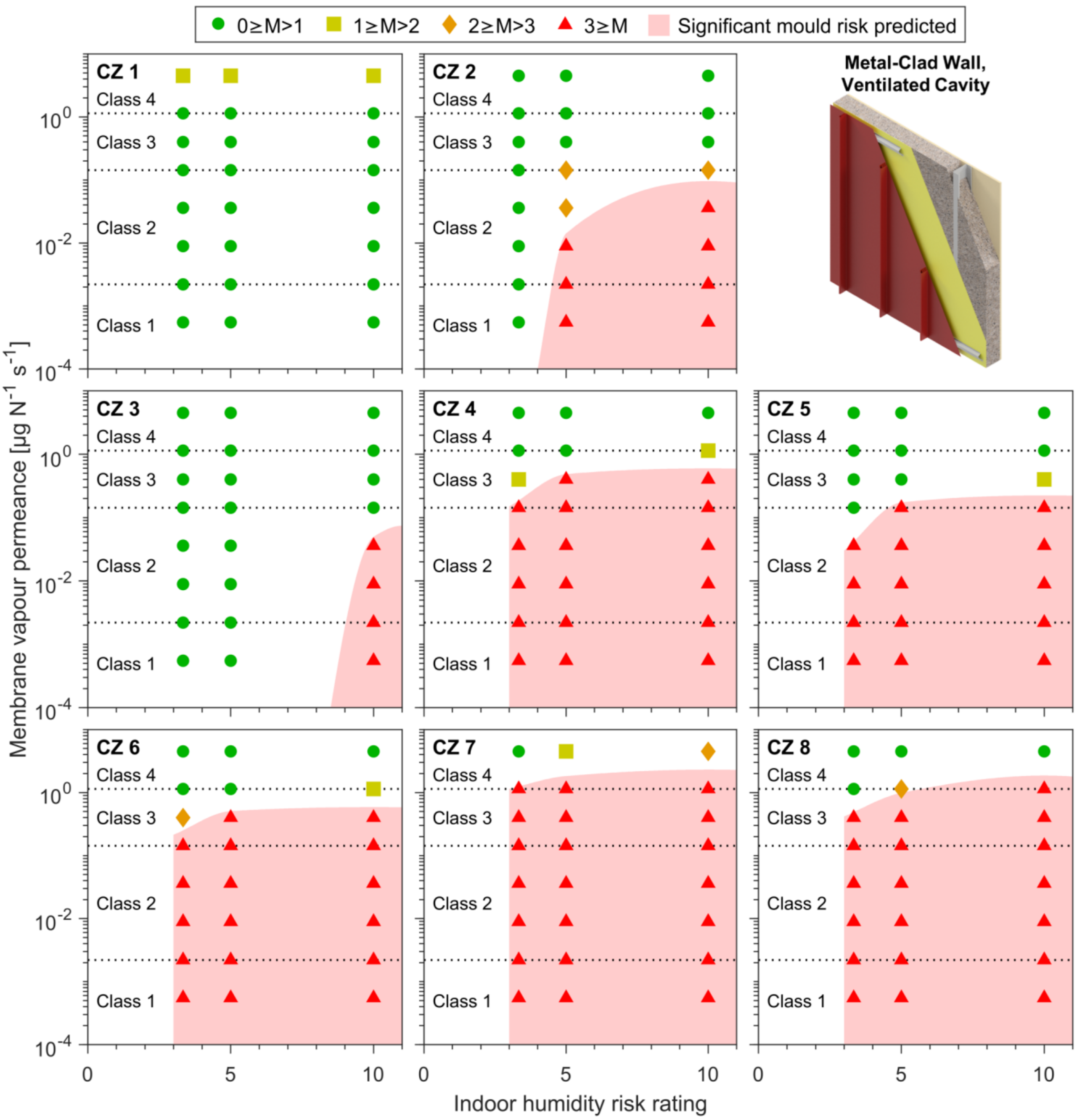


Figure 4-13: Maximum 10-year mould index (M) simulated in metal-clad walls with ventilated cavities.

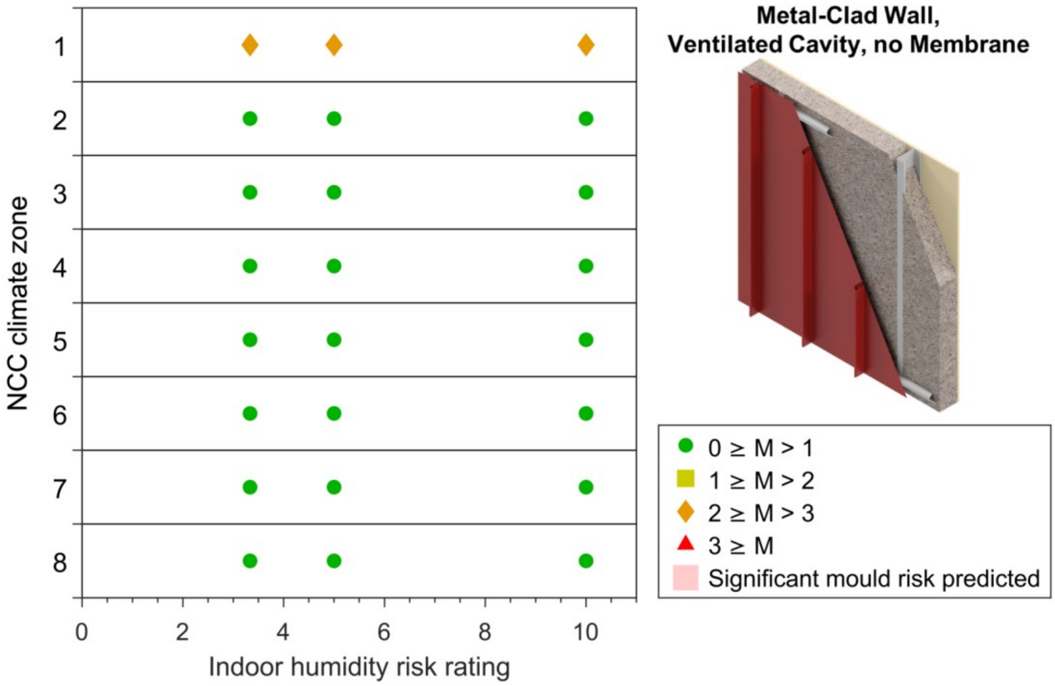


Figure 4-14: Maximum 10-year mould index (M) simulated in metal-clad walls with ventilated cavities and no pliable membrane.

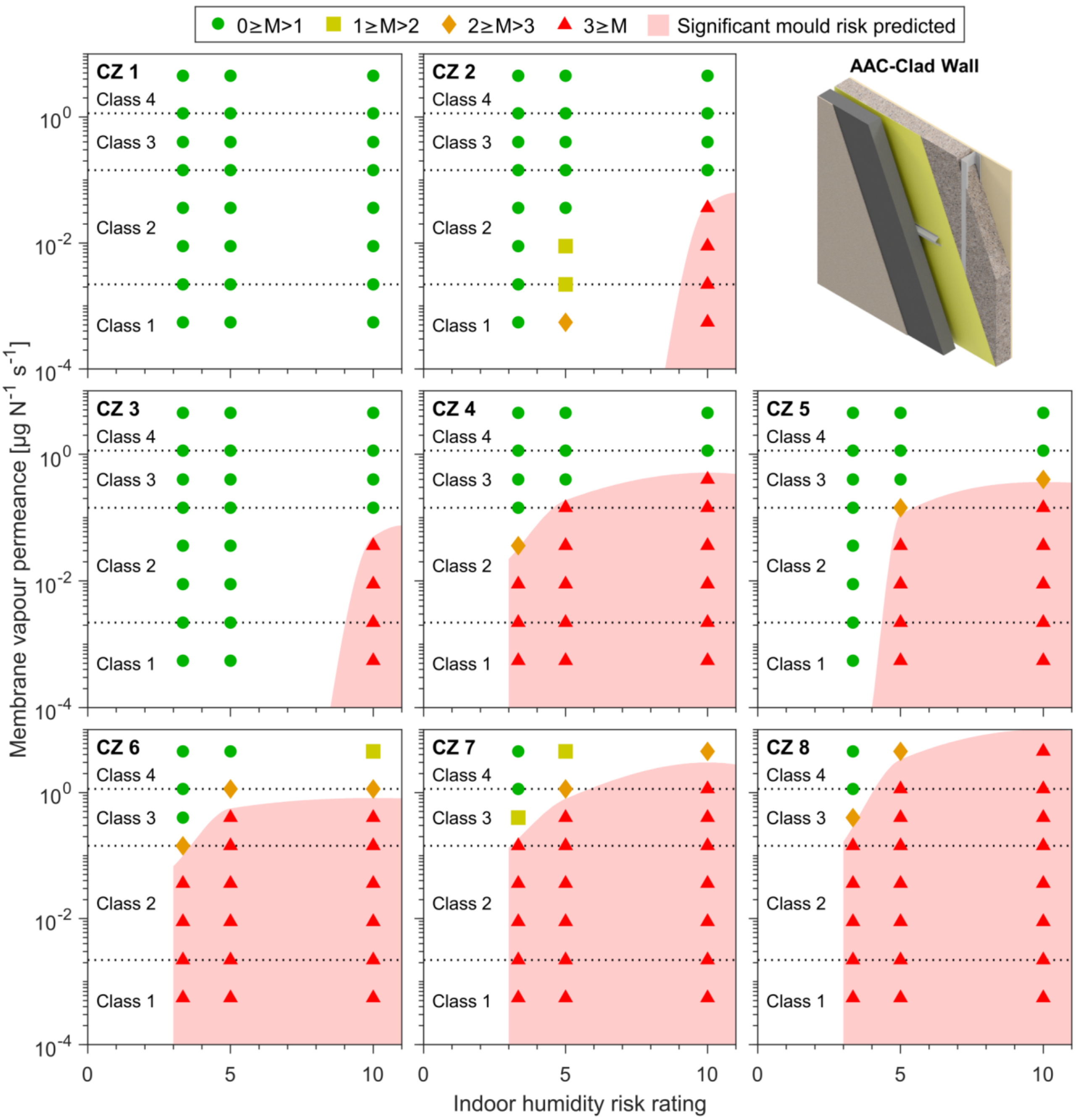


Figure 4-15: Maximum 10-year mould index (M) simulated in walls with autoclaved aerated concrete (AAC).

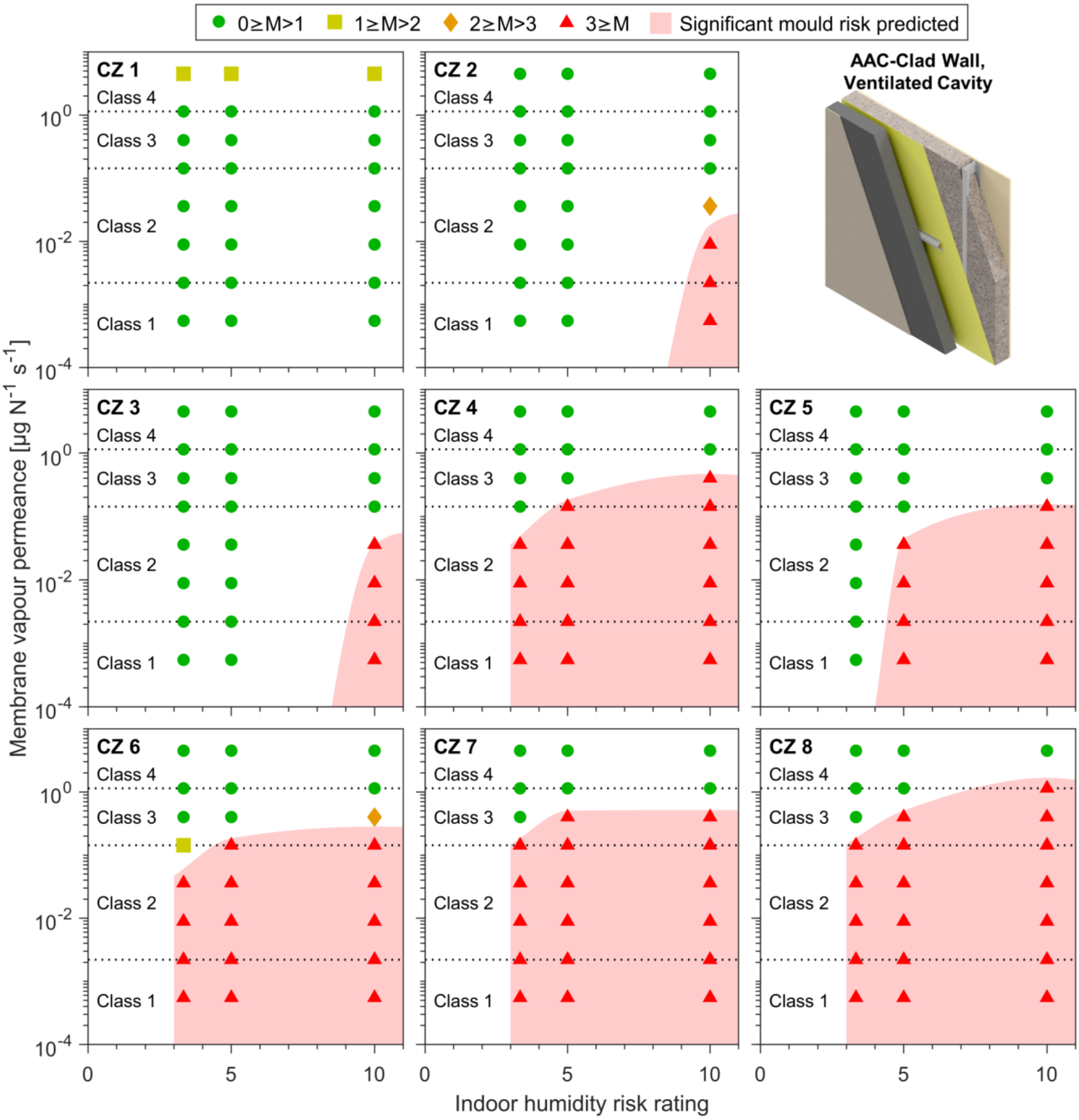


Figure 4-16: Maximum 10-year mould index (M) simulated in walls clad with autoclaved aerated concrete (AAC), with ventilated cavities.

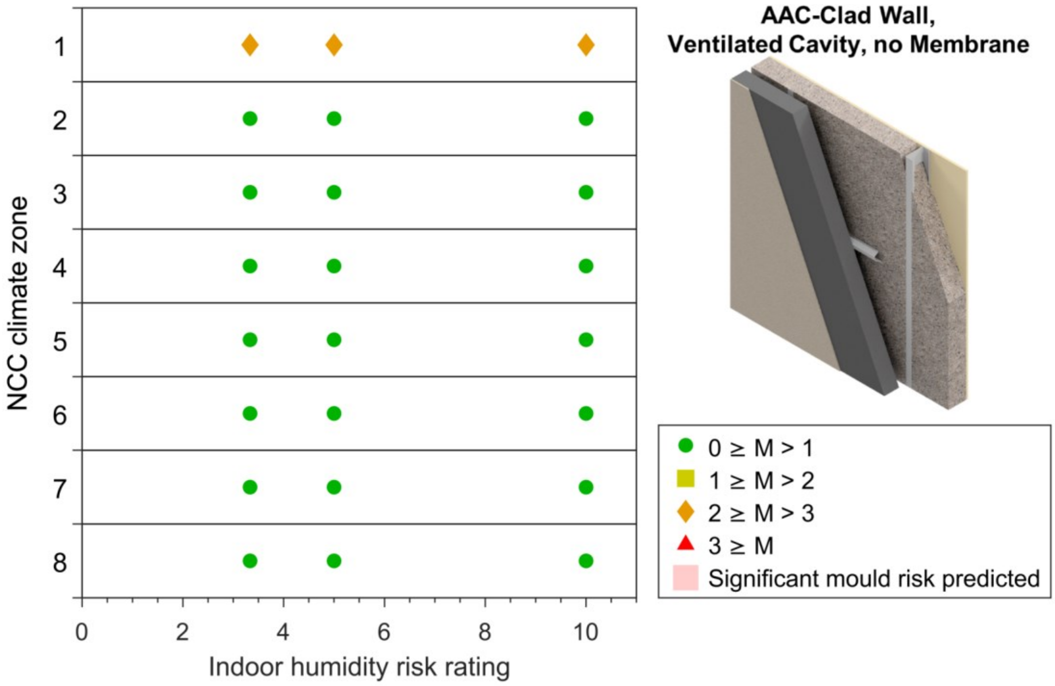


Figure 4-17: Maximum 10-year mould index (M) simulated in walls clad with autoclaved aerated concrete (AAC), with ventilated cavities and no membrane.

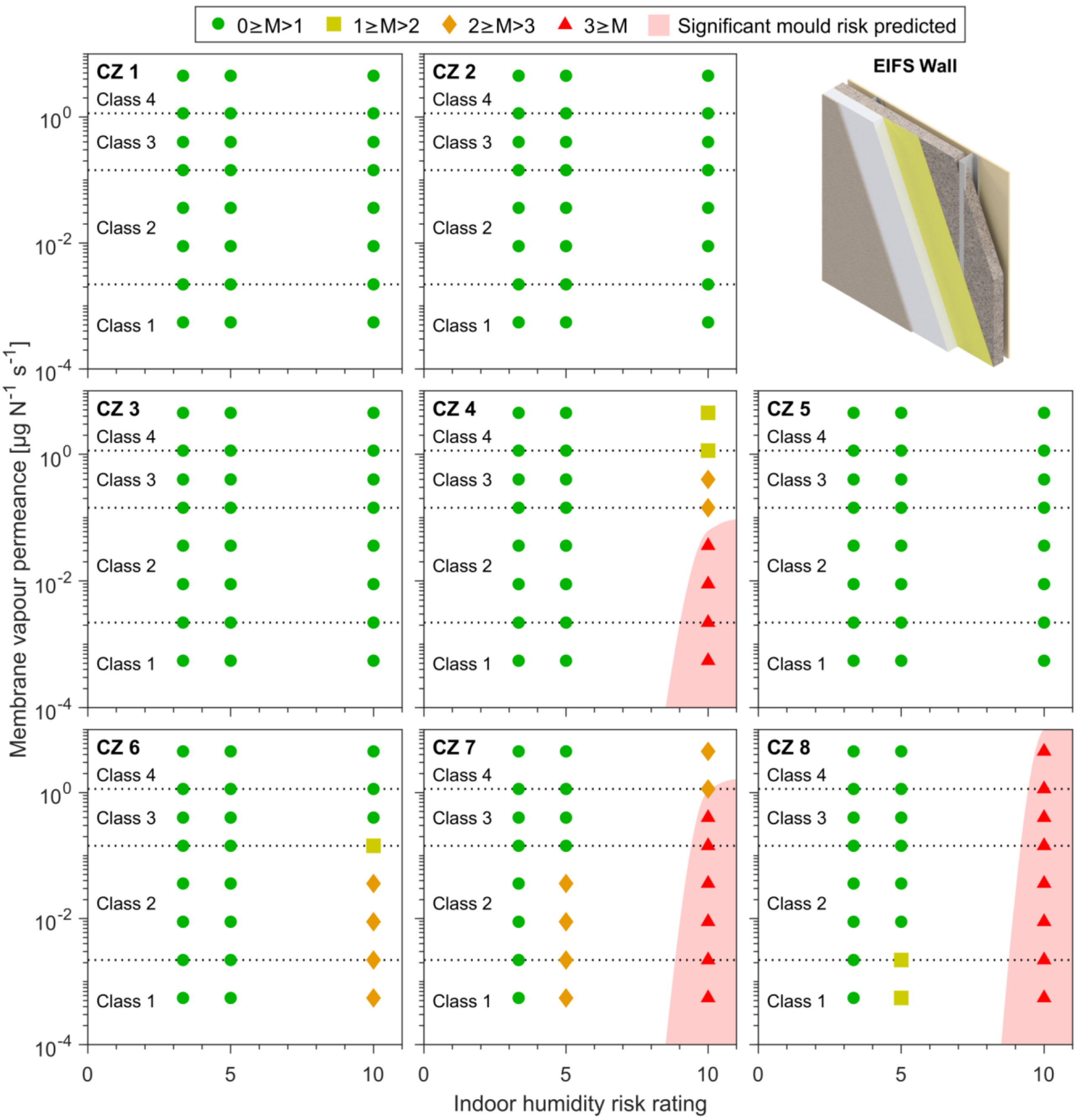


Figure 4-18: Maximum 10-year mould index (M) simulated in walls clad with an external insulation finishing system (EIFS).

4.2 ROOFS

Figures 4-19 to 4-24 present the maximum mould index reached within the tiled and metal-clad roofs, with and without ventilated cavities and with and without membranes, during 10-years of simulated operation. Following the same approach applied to data from wall simulations, the roof data have been graphed with Indoor Humidity Risk Rating on the horizontal axis, and membrane permeance on the vertical axis (in cases where the construction included a membrane), with separate results presented for each climate zone.

4.2.1 Location of Highest Mould Index within the Roof

The location with the highest risk of mould growth within the roof constructions followed the same general trend as it did in wall constructions: in Climate Zone 1, the highest mould index value arose at the interface between the plasterboard and insulation, and in all other climate zones, the highest mould index value arose on the outdoor side of the insulation.

However, the both roof constructions included a cavity between the membrane and insulation, which did not exist in the wall cavities. In cases where this lower cavity was not ventilated, the maximum mould index typically arose on the indoor side of the cavity (i.e. on the top surface of the insulation), whereas in cases with cavity ventilation the maximum mould index typically arose on the outdoor side of the cavity (i.e. on the underside of the membrane).

4.2.2 Roof Orientation

The orientation of the two roof constructions in Climate Zone 1 (i.e. either east- or south-facing) did not have a large effect on the magnitude of the maximum mould index. Among the simulations of the tiled and metal-clad roofs that produced mould index values larger than one, the east-facing cases typically produced maximum mould index values 8 % lower, and 4 % higher, respectively, than those from corresponding south-facing cases.

4.2.3 Indoor Humidity Risk Rating

As was the case for walls, decreasing the Indoor Humidity Risk Rating from the ‘baseline’ value of 10 to 5 or 3.33 reduced the maximum mould index arising within both types of roof, except for in Climate Zone 1 and in particularly ‘high risk’ cases.

The indoor space was modelled as if it were air conditioned for the vast majority of the time in simulations of Climate Zone 1, which prevented changes in the Indoor Humidity Risk Rating from having a substantial impact on results.

Cases with a particularly high mould risk were often very insensitive to changes in the Indoor Humidity Risk Rating because of non-linearities in the 10-year maximum mould index when used as a performance metric. Incremental modifications to reduce the risk in such cases tend to have very little effect on the maximum mould index value until a certain point, after which subsequent changes can reduce the maximum mould index substantially. Therefore, in cases where all three Indoor Humidity Risk Ratings produced very high (i.e. >3) mould index values, these results indicate that reduction of the Indoor Humidity Risk Rating (e.g. by increasing indoor ventilation rates) is unlikely to be sufficient to mitigate the mould risk—such interventions could still be effective if combined with other measures.

4.2.4 Cavity Ventilation

The introduction of cavity ventilation to the cavity formed between the membrane and insulation was extremely effective in mitigating the simulated risk of mould growth in the majority of roof cases investigated. A comparison of Figure 4-19 with Figure 4-21, and of Figure 4-22 with Figure 4-24, reveals that such ventilation reduced the maximum mould index below three in all cases where it had otherwise exceeded three.

While the introduction of such cavity ventilation to roof models eliminated all mould index values exceeding the threshold value of three, it also increased the maximum mould index in several cases, including all cases in Climate Zone 1, and cases with vapour-permeable membranes in Climate Zones 5 and 7 (and 2 in the case of the tiled roof). The increased mould index values in Climate Zone 1 arose for the same reason they had in simulations of walls when cavity ventilation was added, i.e. the ventilation enhanced vapour transport between the outdoor environment and insulation within the wall, which tended to increase the simulated level of mould risk in Climate Zone 1 because the primary vapour drive was from outdoors inwards.

In Climate Zones 2, 5 and 7, the increased mould index values caused by cavity ventilation appear to have been a product of outdoor boundary conditions. The relative humidity at the outdoor surface of the insulation tended to be dominated by a seasonal variation in roofs without cavity ventilation, with higher relative humidity during winter and lower relative humidity during the summer, whereas the relative humidity at this location in roofs with cavity ventilation was much more dominated by diurnal cycles, with higher relative humidity overnight. In unventilated cases where the seasonal relative humidity variations did not exceed the threshold relative humidity for mould index increase (85 %) for a long period, the mould index did not reach large values. However, once cavity ventilation was introduced, if the outdoor boundary conditions included many humid nights, the diurnal fluctuations in relative humidity within the roof structure could exceed the threshold value frequently enough to raise the mould index over time. This nuanced interaction between roof structure, outdoor environment, and mould index model, is an example of the type of result that is likely to be highly sensitive to modelling assumptions such as the choice of boundary conditions (including climate data) and material properties.

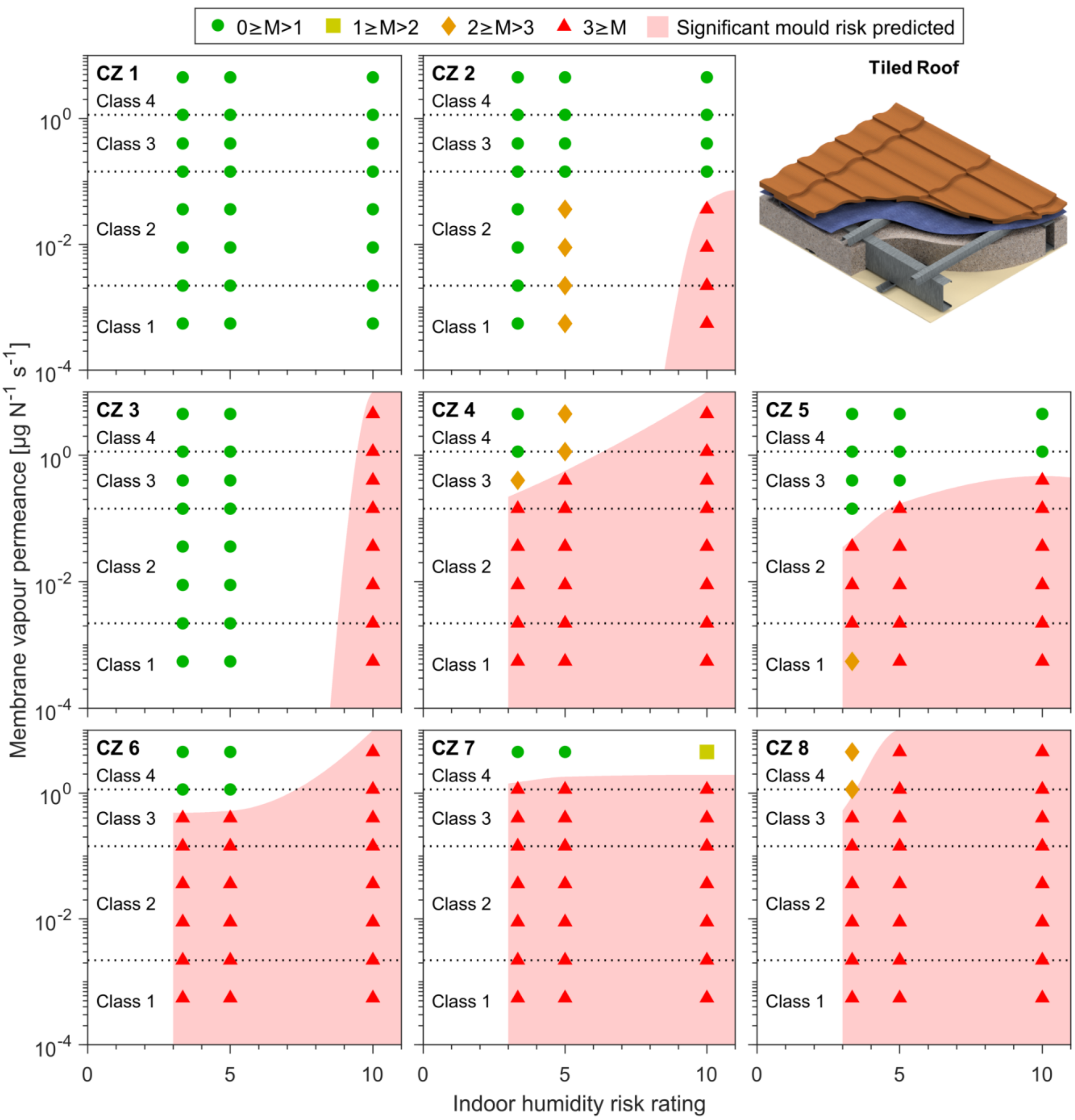


Figure 4-19: Maximum 10-year mould index (M) simulated in tiled roofs.

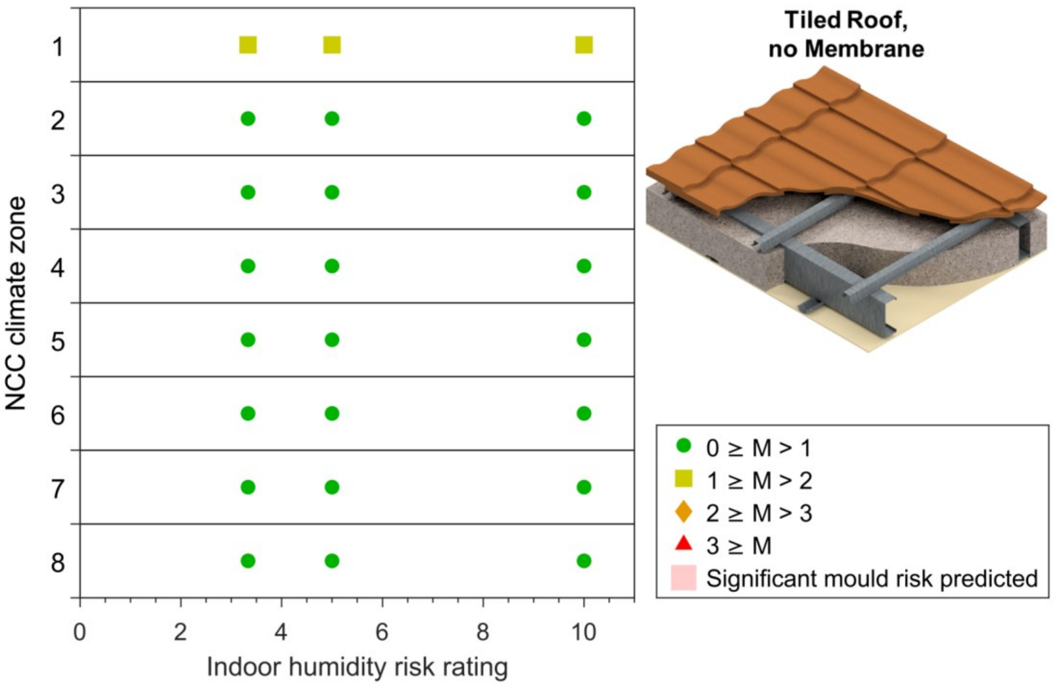


Figure 4-20: Maximum 10-year mould index (M) simulated in tiled roofs with no membrane.

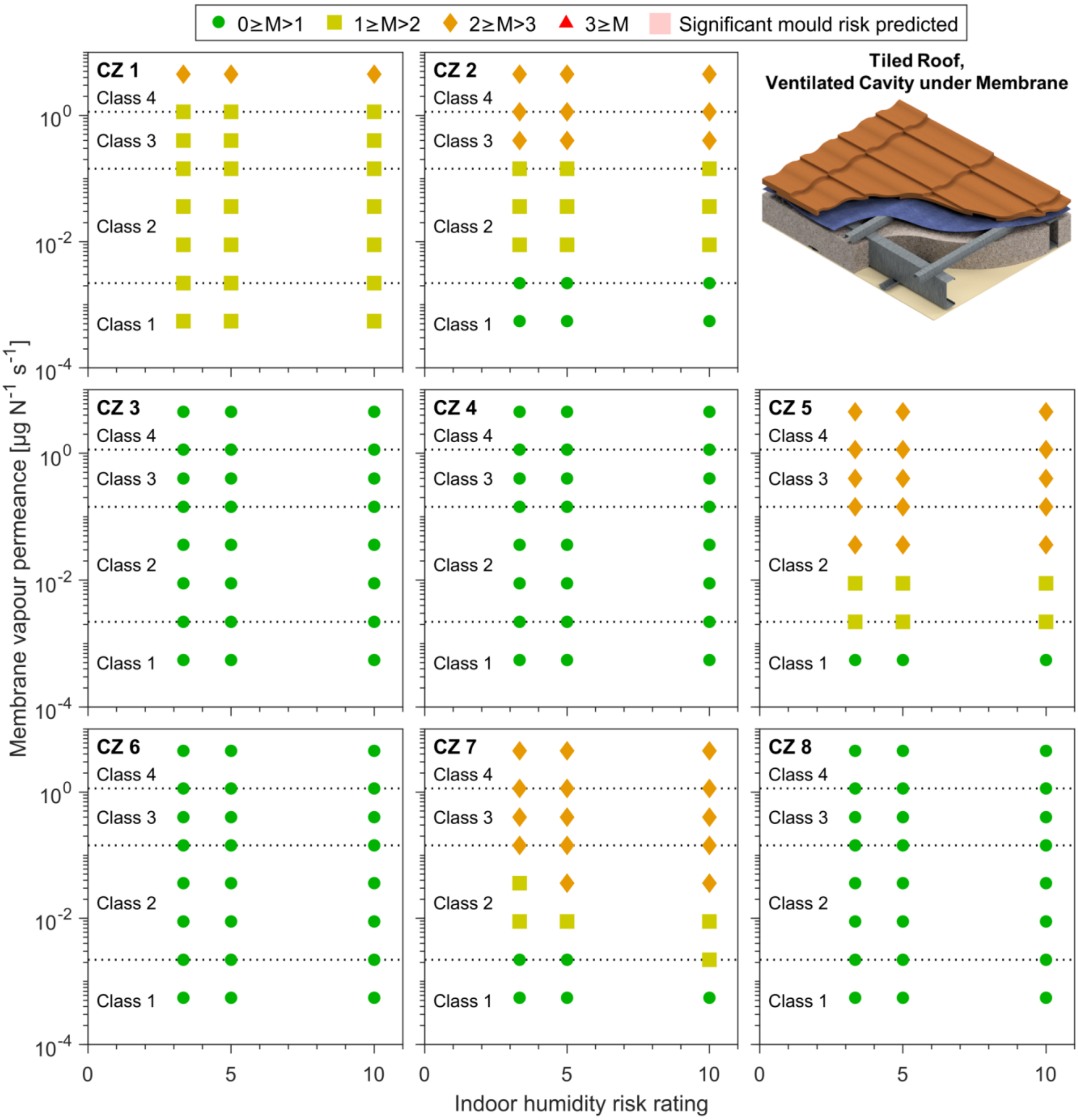


Figure 4-21: Maximum 10-year mould index (M) simulated in tiled roofs with ventilation under the membrane.

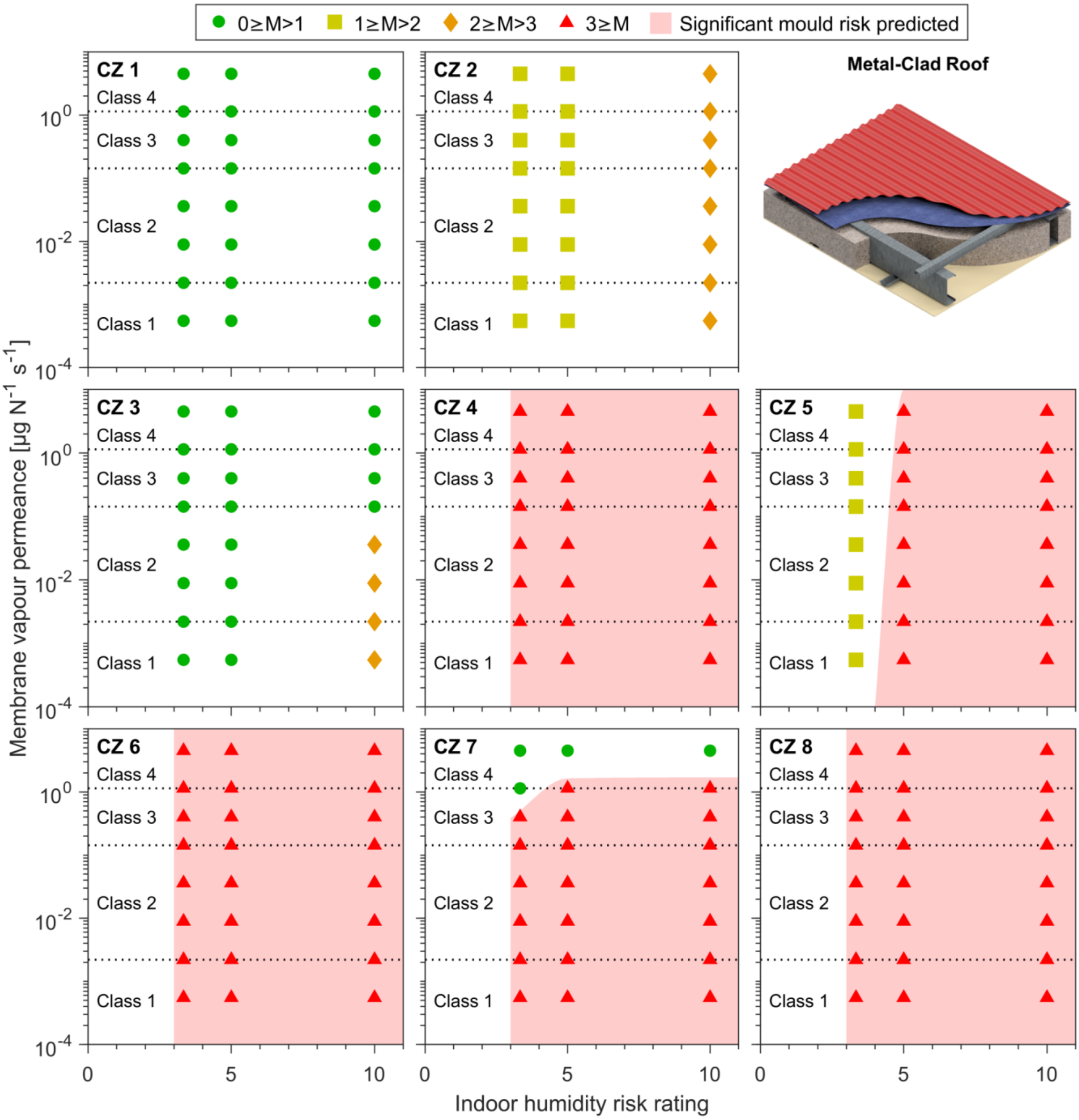


Figure 4-22: Maximum 10-year mould index (M) simulated in metal-clad roofs.

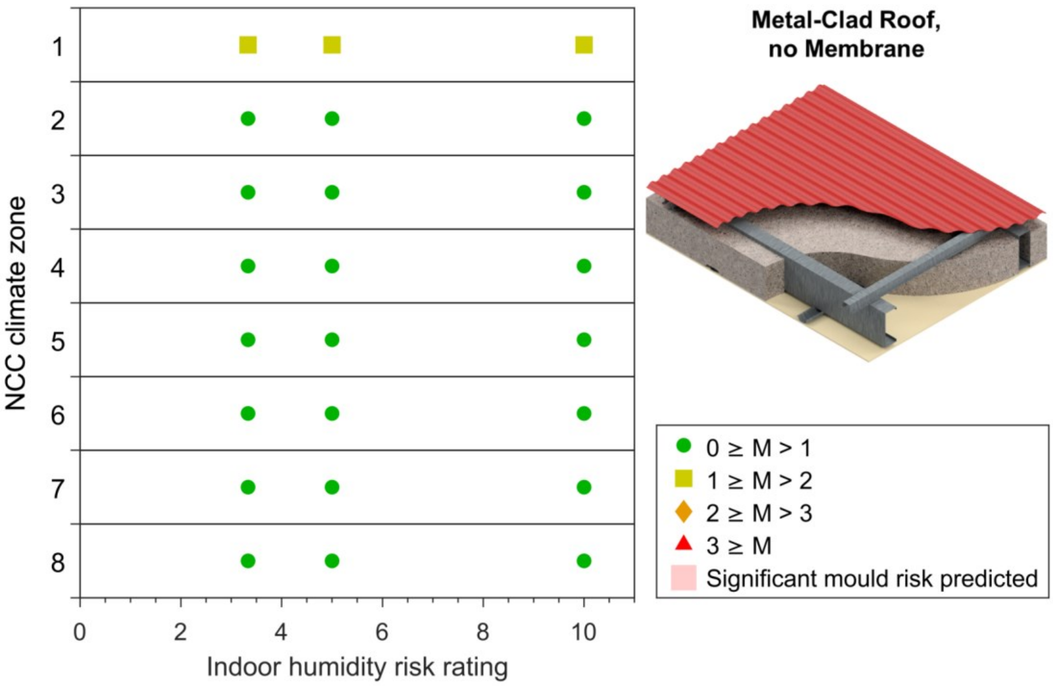


Figure 4-23: Maximum 10-year mould index (M) simulated in metal-clad roofs with no membrane.

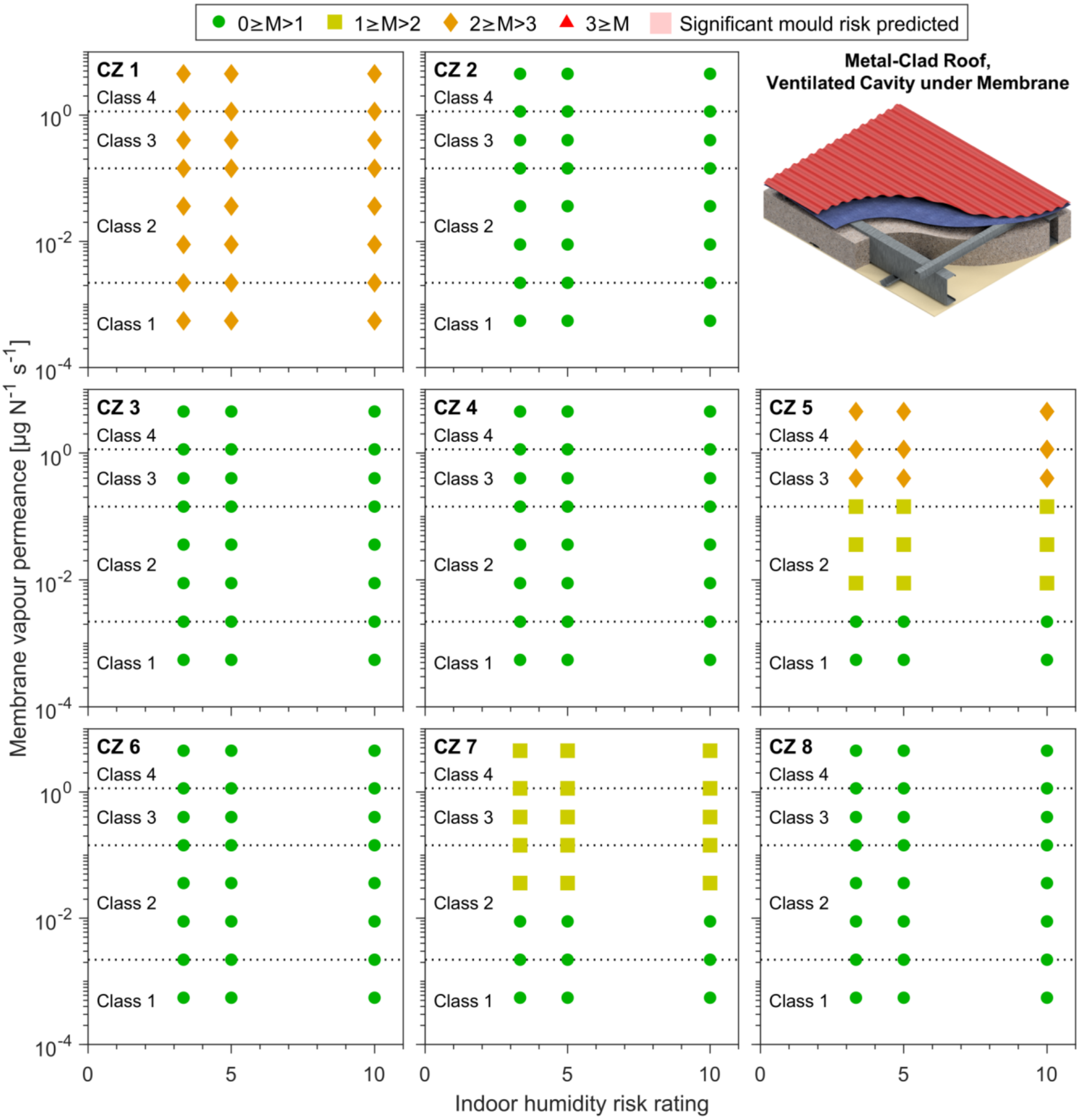


Figure 4-24: Maximum 10-year mould index (M) simulated in metal-clad roofs with ventilation under the membrane.

4.3 WINDOWS

The temperature distributions generated through steady, two-dimensional finite-element thermal simulations of the three window sills are illustrated in Figure 4-25, and results from the transient condensation simulations of the three glazing systems and three window sills are presented in Figures 4-26 and 4-27, respectively.

The 'condensation index' of the glazing systems and frame components are presented in Table 4-1. These values are equivalent to the condensation index defined in NFRC procedures [6,7], except that under NFRC procedures the condensation index is calculated for a complete window system by taking the lowest value of centre-of-glazing, edge-of-glazing, and frame condensation index values. In this study, the frame and centre-of-glazing have been treated separately and assigned their own condensation index values.

The condensation index represents the dimensionless temperature of the coldest point on the indoor surface of the window component, multiplied by 100. It ranges from 0 to 100, where a value of 0 would indicate that the coldest point on the indoor surface of the component is at a temperature equal to the outdoor temperature under a standard set of steady conditions, and a value of 100 would indicate that the entire indoor surface is at the indoor temperature under the same steady conditions. Thus, it is not possible for a condensation index value to equal 0 or 100, but higher numbers indicate a indoor surface temperatures closer to the indoor conditions and therefore a lower risk of condensation during cold periods.

Table 4-1: The dimensionless indoor surface temperature, i.e. 'condensation index', determined for each of the glazing systems and window frame components investigated.

Window component	Condensation index
Single glazed (6 mm clear glass)	23.3
Double glazed (6 mm clear glass; 12 mm air-filled cavity; 6 mm clear glass)	63.3
Double glazed, low-e (6 mm clear glass; 12 mm low-emittance, argon-filled cavity (e_1=0.84, e_2=0.08); 6 mm clear glass)	79.5
Aluminium sill	18.7
Thermally-broken aluminium sill	56.2
uPVC sill with steel core	77.2

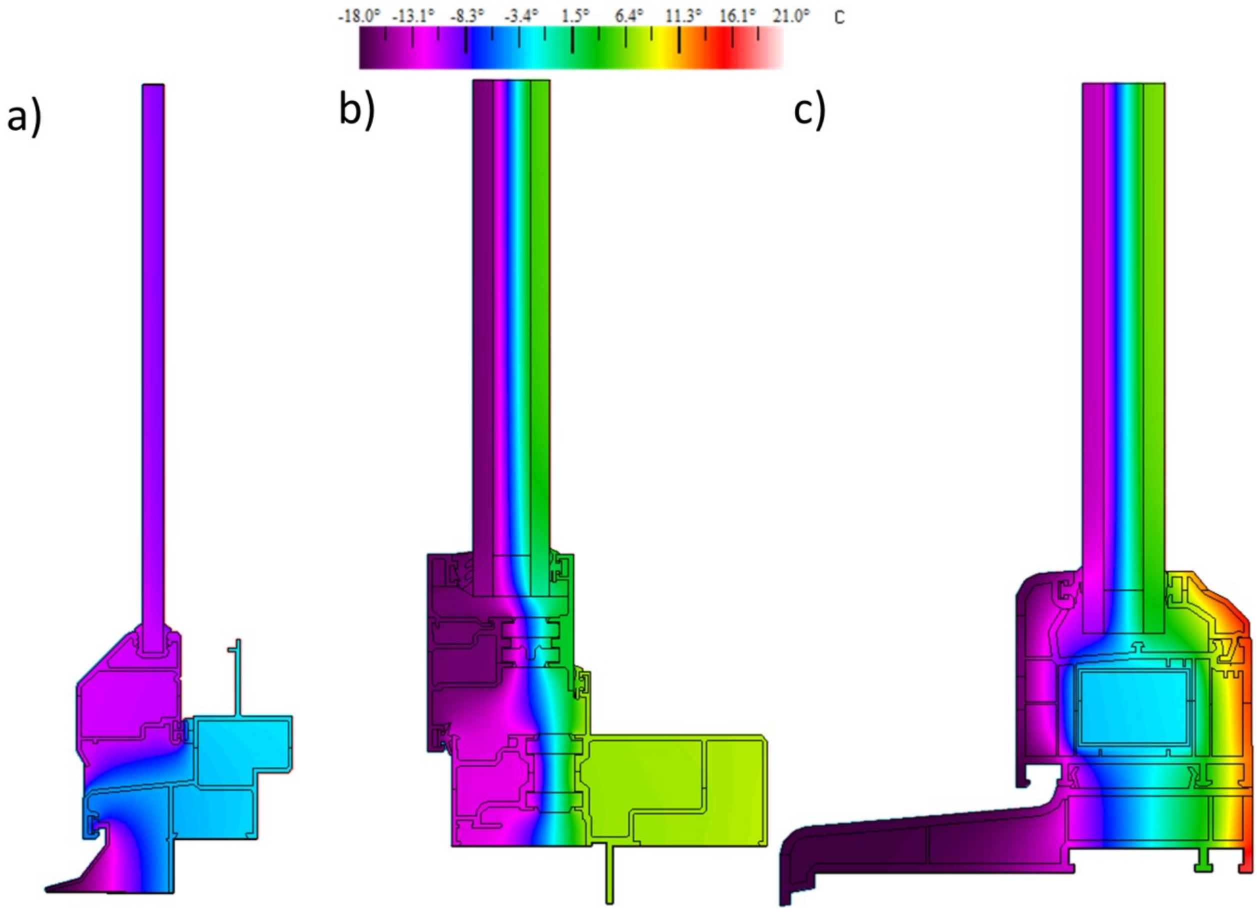


Figure 4-25: Temperature distributions simulated in the three window frames: a) aluminium sill, b) thermally broken aluminium sill, and c) uPVC sill. Images are not drawn to the same scale.

The simulation results presented in Figures 4-26 and 4-27 represent the proportion of time during which condensate runoff was predicted to occur on the indoor surface of each window component.

Simulations of the 'low-performance' components, i.e. aluminium sill and single glazing, predicted condensate runoff to occur very frequently (from 2 % to 76 % of the time) in all cases involving Climate Zones 2–8 and Indoor Humidity Risk Ratings exceeding 1.67. Condensate runoff on the outdoor surfaces of these 'low-performance' components is likely in Climate Zone 1, but has not been reported here since such outdoor condensation does not necessarily cause mould or durability issues in the building envelope or indoor environment.

Simulations of the 'medium-performance' components produced mixed results. Condensate runoff occurred frequently (from 0.5 % to 35 % of the time) in simulations of the double glazing when the Indoor Humidity Risk Rating exceeded 5 and the outdoor climate represented Climate Zones 2–8. However, in all other cases no condensate runoff was predicted, indicating that measures to manage indoor humidity, such as ventilation, could effectively mitigate the risk of condensate runoff from double glazing in all climate zones. Condensate runoff from the thermally-broken aluminium sill was only predicted in four climate zones and under severe indoor humidity conditions, with runoff predicted 0.1 % to 3.5 % of the time in Climate Zones 7 and 8 when the Indoor Humidity Risk Rating exceeded 6.67, and 0.3 % to 0.9 % of the time in Climate Zones 2 and 4 when the Indoor Humidity Risk Rating exceeded 8.33.

The 'high-performance' components (i.e. uPVC sill and argon-filled double glazing with low-e coating) were not predicted to cause condensate runoff in any of the simulated cases.

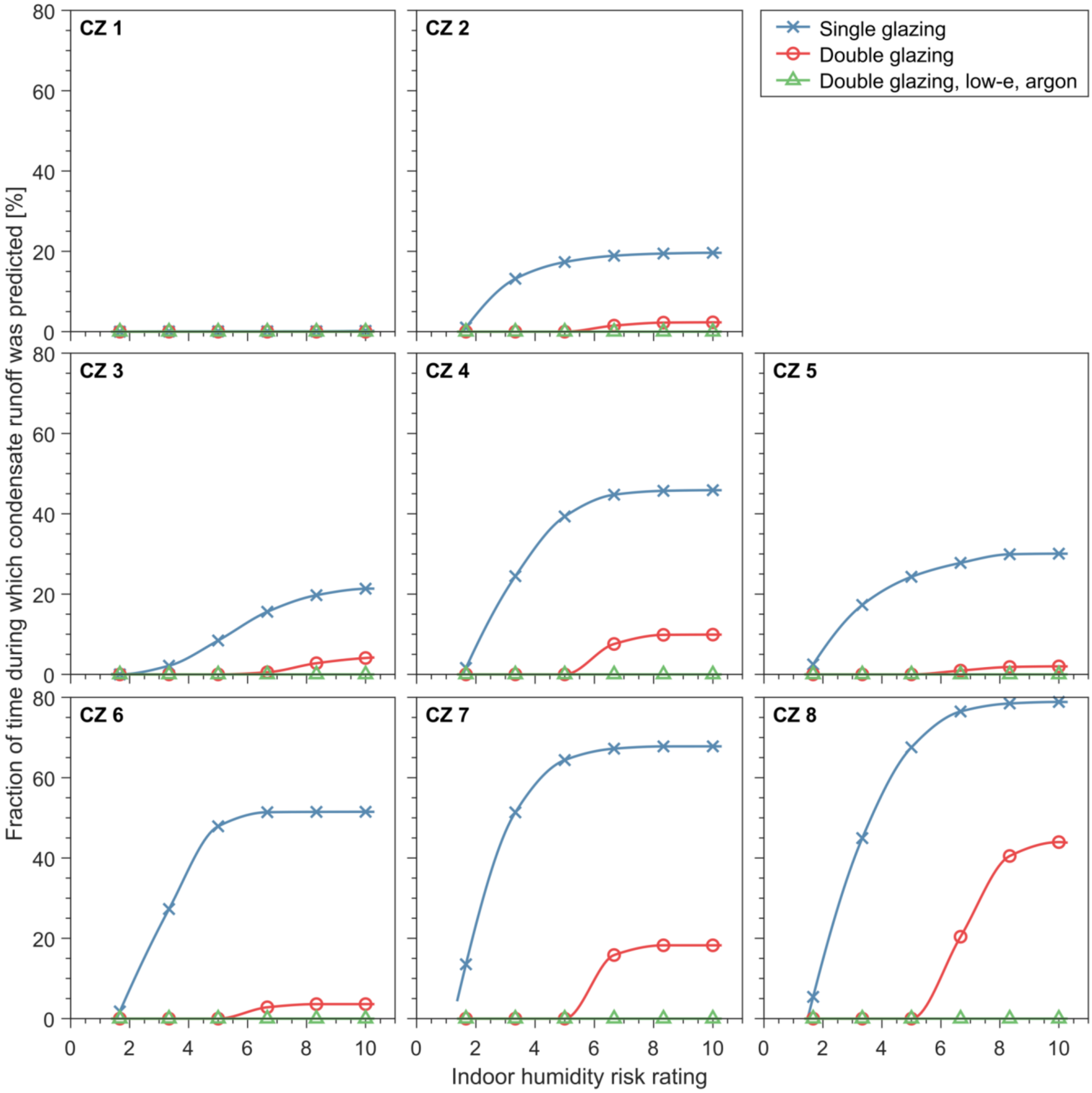


Figure 4-26: Proportion of time during which condensate runoff was predicted to occur on the indoor surface of three glazing systems.

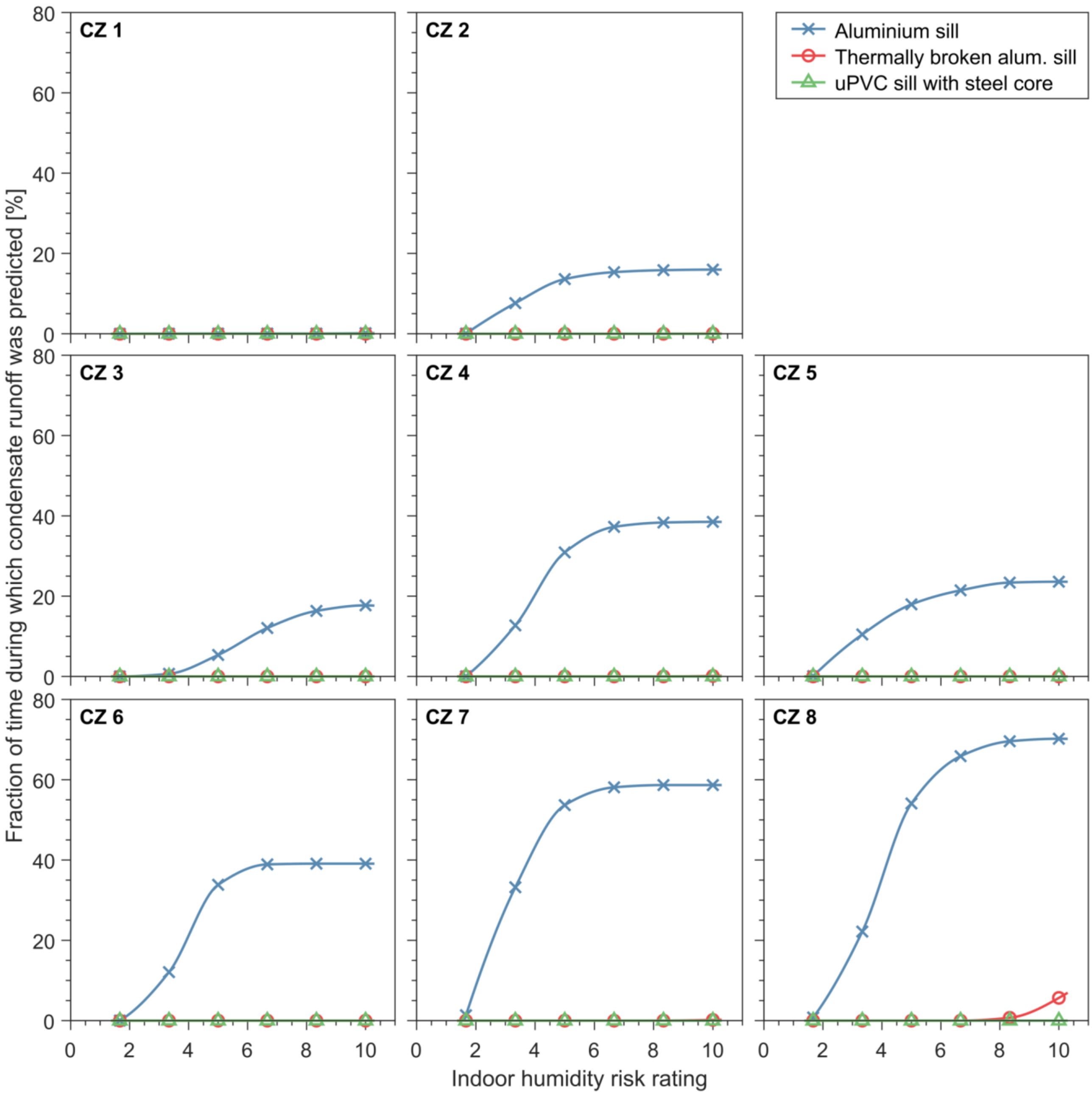


Figure 4-27: Proportion of time during which condensate runoff was predicted to occur on the indoor surface of three window frame components.

The frequency of condensate runoff simulated on the 'low-performance' window components (Figures 4-26 and 4-27) may seem to be unrealistically high, but when subjected to further analysis these values appear to be correct and are the result of the extremely severe boundary conditions applied in this study. A simple method to test the validity of these results is to compare the indoor dry bulb temperature and dew point temperature with the condensation index of the window component (Table 4-1), and the distribution of outdoor air temperatures from each climate file (Appendix B). The indoor dry bulb and dew point temperatures were 21.1 °C and approximately

15.4 °C for the majority of the time that air conditioning was not active in cases with an Indoor Humidity Risk Rating of 10 (see Sections 2.5 and 6). Taking the aluminium sill as an example, with condensation index of 18.7, condensation could be expected to occur whenever the outdoor temperature was below 14.1 °C. Inspection of the climate data (Appendix B) reveals that the proportion of time the outdoor air temperature was at such low temperatures in each climate zone is of similar order of magnitude to the corresponding simulation results in Figure 4-27. While this comparison is approximate, since the simulations included solar heat gains, explicit calculations of radiant heat exchange with the sky and ground, latent heat release/absorption, etc., whereas this simple calculation does not, the comparison is valuable as a test of feasibility.

5 Sensitivity to Outdoor Climate

5.1 BACKGROUND

Previous projects used as the basis for condensation provisions in the NCC have focused on a relatively small set of locations (and therefore climates) in Australia. This gave rise to questions as to whether each selected location could be assumed to accurately represent other locations within the same NCC Climate Zone. For example, it was questioned whether simulations run with climate data from eastern Sydney (in NCC Climate Zone 5) could provide results that are relevant to Adelaide (also in NCC Climate Zone 5). Moreover, even if the simulated level of mould risk throughout each NCC climate zone was relatively uniform, it was not clear whether the simulated locations represented 'worst-case' or 'typical' conditions within those climate zones.

To address these questions, it was suggested that this study should include simulations in all 69 NatHERS climate zones. The limited time available to complete the project did not allow such a broad set of climates to be included in the entire simulation study, so a climate sensitivity study was undertaken to assess the variance in simulated mould risk within each NCC climate zone and select eight representative locations to simulate in the primary simulation study.

It was also decided that the population in each NatHERS climate zone should be taken into account when selecting locations to simulate through the remainder of the project. For this purpose, population data were assembled based on the 'place of normal residence' reported by participants in the 2021 Australian Bureau of Statistics census.

5.2 AIMS

The aims of the climate sensitivity study were to:

1. Quantify the variance in simulated mould risk across the 69 NatHERS climate zones using models of two wall types;
2. Assess the degree of correlation between the existing eight NCC climate zones and the level of simulated mould risk; and
3. Select eight locations within Australia for simulation in the remainder of the Condensation Mitigation Modelling project.

5.3 RESULTS

Figure 5-1 and Figure 5-2 present the maximum mould index reached during a 10 year simulation in each of the 69 NatHERS climate zones, for the masonry veneer and fibre-cement-clad walls, respectively.

It is important to note the non-linearity of the 10-year maximum mould index when using it as a performance metric. For a given construction, there is typically a very wide range of conditions which would produce a 10-year maximum mould index value very close to zero, and another broad set of conditions that would produce a value close to the maximum that is possible (which is 3.5 in the cases presented here). In the relatively narrow range of conditions between those two extremes, the 10-year maximum mould index is typically very sensitive to changes in the simulated conditions and assumptions.

For the present exercise, it should be borne in mind that differences in the mould index that appear large do not necessarily indicate a large difference in the climatic conditions. A holistic comparison including results from both wall types, and with all three membranes, is likely to provide a more reliable indication of the severity of the simulated climatic conditions.

The results presented in Figure 5-1 and Figure 5-2 demonstrate that, in a broad sense, the existing eight NCC climate zones correlate reasonably well with the level of simulated mould risk. The mean 10-year maximum mould index simulated in Climate Zones 1–8 was 0.23, 0.98, 0.35, 2.04, 2.39, 2.92, 3.22 and 3.49, respectively.

Results within each NCC climate zone were found to be relatively uniform, although with some variance, as could be expected. When the six results from each location are added together (to produce a single mould risk rating between 0 and 21 for each location), the standard deviation in those values equals 6 %, 29 %, 16 %, 17 %, 14 %, 2 %, 7 % and 0.25 % of the total possible range (i.e. 21) within NCC Climate Zones 1–8, respectively.

Simulations of NCC Climate Zones 1, 6 and 7 produced results that were especially uniform, with only a small number of locations deviating significantly from the others. The apparently large differences between these few outlying cases is a result of the non-linearity of the 10-year maximum mould index.

Results from NCC Climate Zone 2 varied the most, with simulations of NatHERS Climate Zones 9 and 11 suggesting significant mould growth in 3 and 4 cases, respectively, while simulations of the other four locations did not produce any mould index values over the failure threshold of 3.

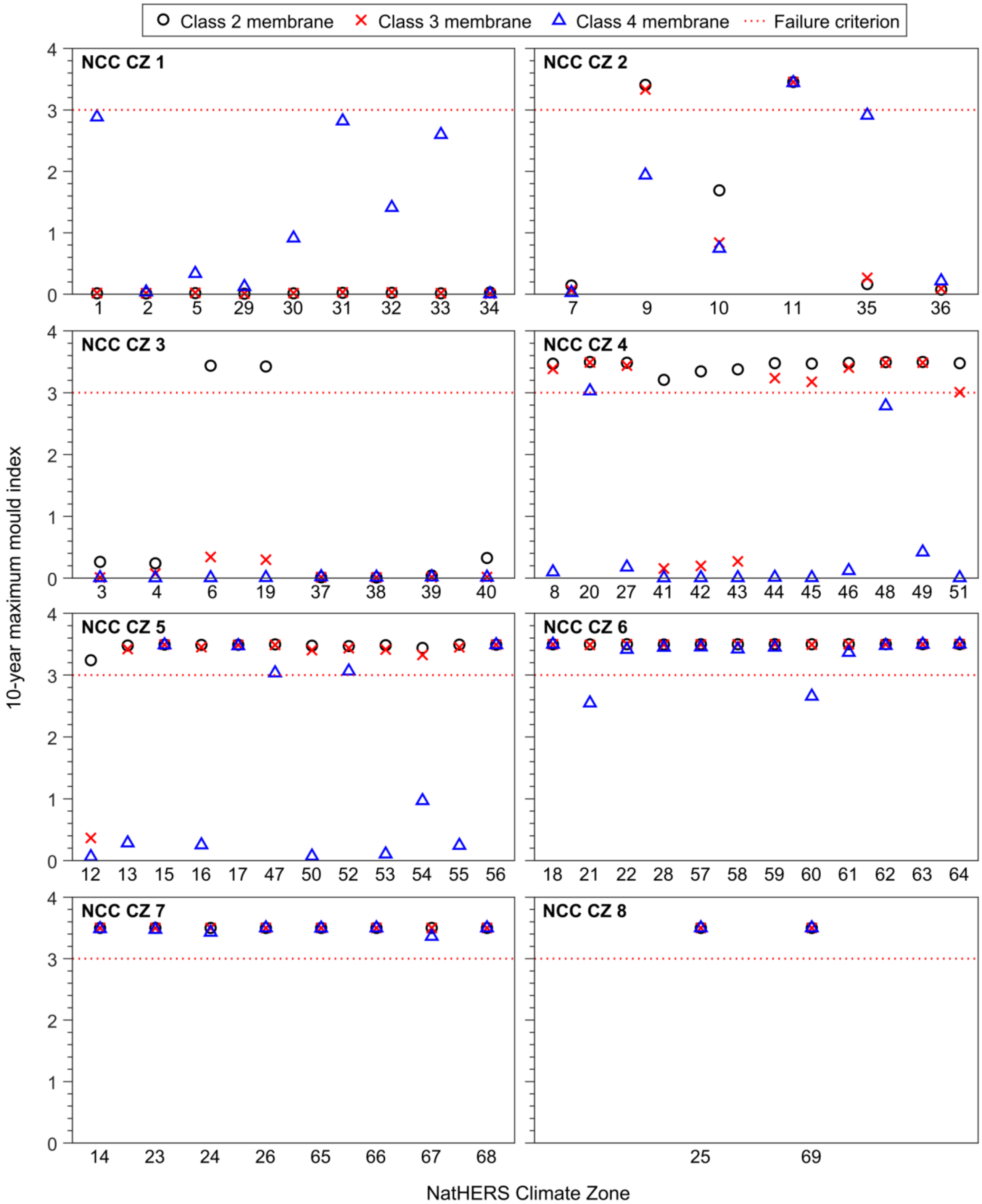


Figure 5-1: Results from WUFI simulations of the masonry veneer wall in all 69 NatHERS climate zones, with three different pliable membranes.

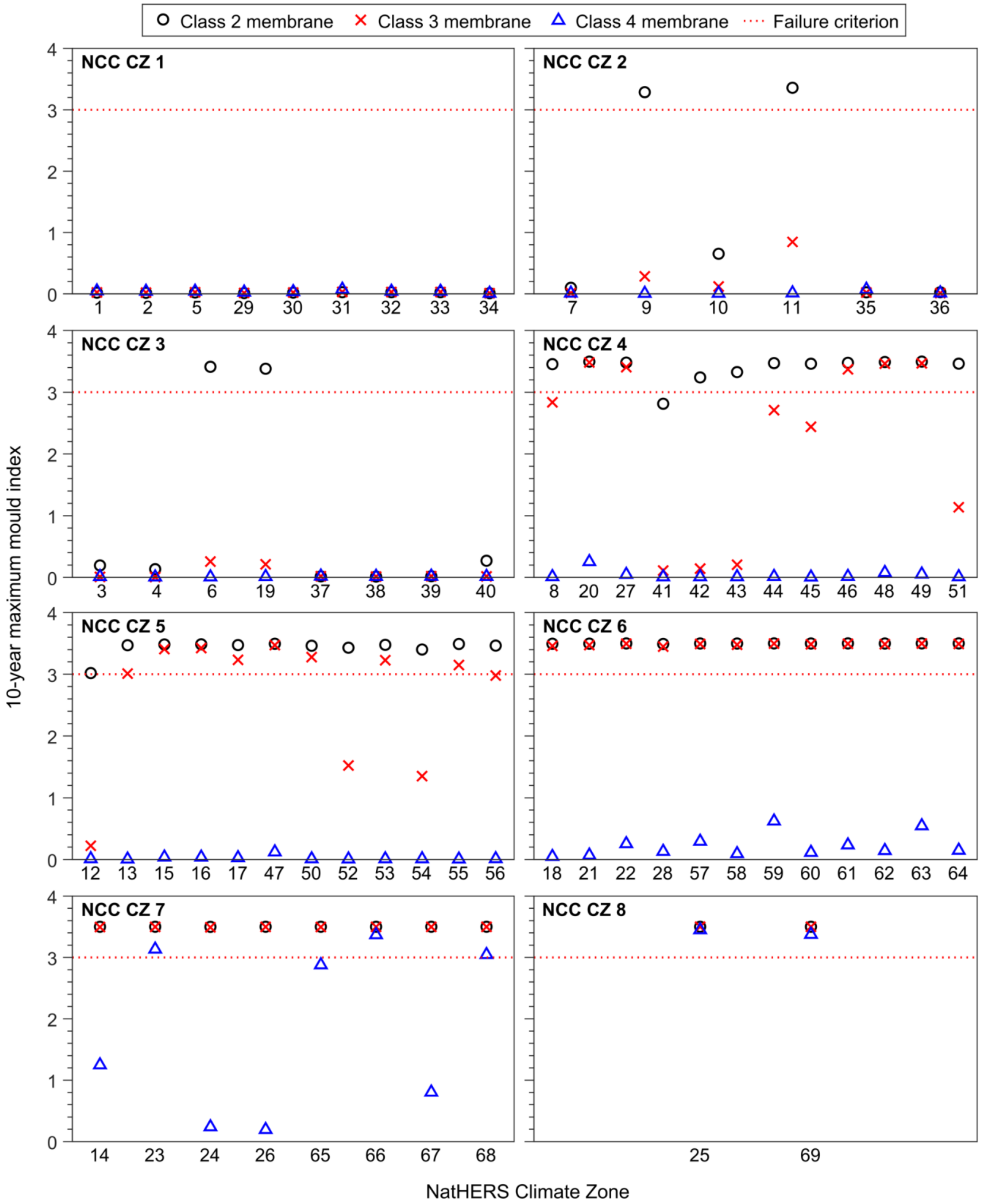


Figure 5-2: Results from WUFI simulations of the fibre-cement-clad wall in all 69 NatHERS climate zones, with three different pliable membranes.

A moderate degree of variation can be seen in results from NCC Climate Zones 3, 4 and 5, which is also likely to be impacted by the non-linearity of the 10-year maximum mould index. For example, results from all locations in NCC Climate Zone 3 are very similar except for those obtained with Class 2 membranes in NatHERS climate zones 6 and 19. This indicates that the climate data from those two locations is more severe (in terms of mould risk) than data from the other locations, but the magnitude of difference in results from these few cases is not a reliable indicator of the magnitude of difference in climatic conditions—a combined analysis of results from both wall types and all three membranes in each location is a more reliable indicator of the severity of conditions.

5.4 CONCLUSION

Based on these results and in consultation with the ABCB Office and Condensation TRG, it was decided to:

1. Use the existing NCC climate zones for the primary simulation study; and
2. Simulate the representative locations summarised in Table 5-1, and shown on a map in Figure 5-3 to represent each of the eight climate zones.

This selection was generated by the following procedure (also presented in Table 5-2):

a) Sorting the investigated locations within each NCC climate zone in order of increasing mould risk, based on the sum of 10-year maximum mould index values simulated for the two wall types with three different membranes (i.e. a single value ranging from zero to 21); and
b) Selecting the locations that span the 90th percentile of population within each of those sorted lists.

This approach targets the locations within each climate zone that present the highest simulated risk of mould growth, while avoiding any outlying locations that are home to a small proportion of the population (and are therefore arguably not suitable choices to represent the entire climate zone).

Table 5-1: Summary of the locations used to represent each climate zone.

NCC climate zone	NatHERS climate zone	Location
1	1	Darwin
2	9	Amberley
3	19	Charleville
4	20	Wagga Wagga
5	15	Williamtown
6	62	Moorabbin
7	66	Ballarat
8	25	Cabramurra

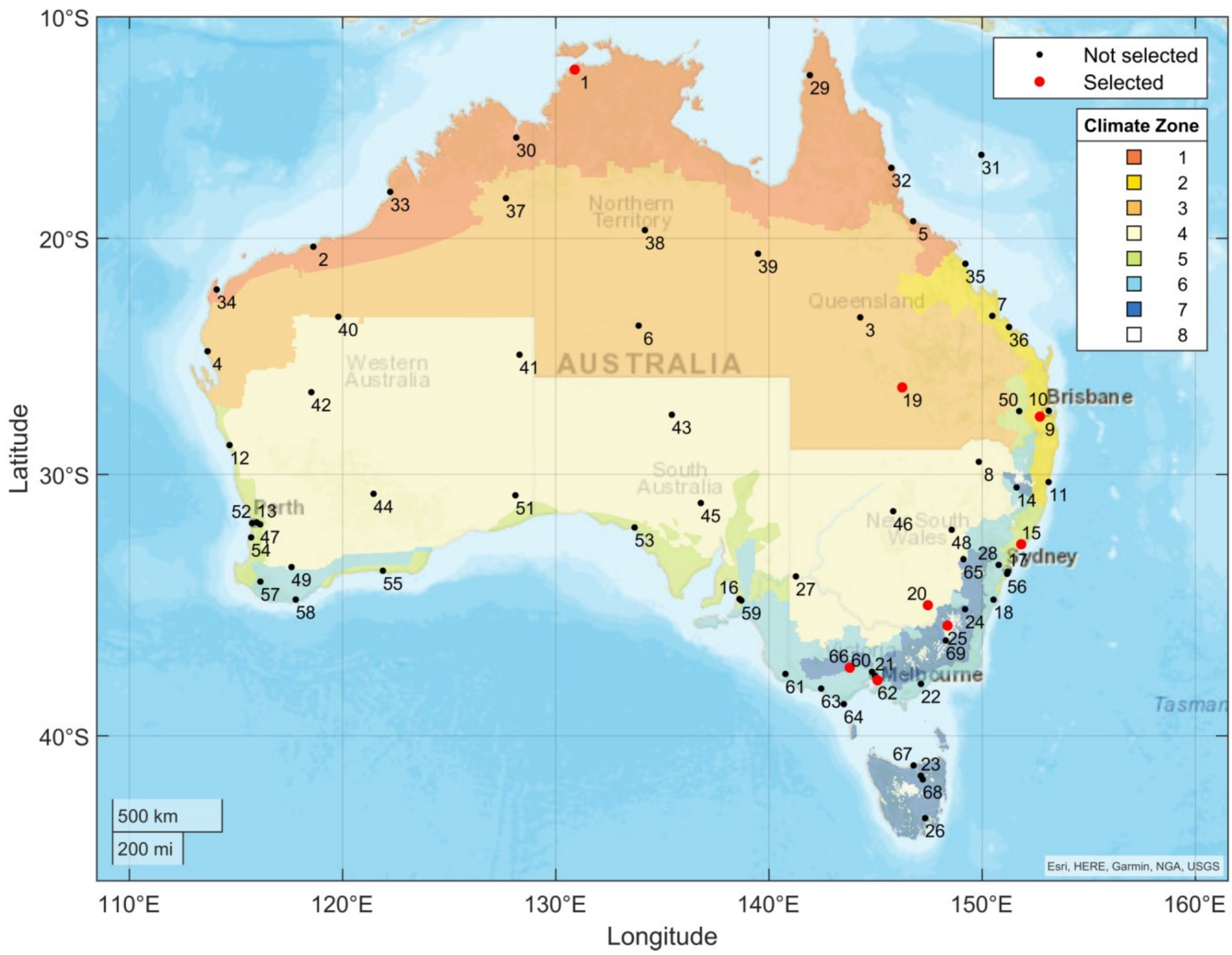


Figure 5-3: Locations used to represent each of the 69 NatHERS climate zones. Climate zones included in the primary simulation study are indicated by larger red dots.

Table 5-2: Results used to select a NatHERS climate zone to represent each NCC climate zone, listed in order of increasing simulated mould risk within each NCC climate zone. Rows shown in bold with shading detail the climates selected for inclusion in the remainder of the project.

NCC climate zone	NatHERS climate zone	Sum of simulated 10-year maximum mould index values	Fraction of total NCC climate zone population [%]
1	34	0.07	0.41
	2	0.14	5.64
	29	0.19	2.63
	5	0.46	31.07
	30	1.02	2.49
	32	1.56	34.50
	33	2.72	1.38
	31	3.00	1.48
	1	**3.00**	**20.39**
2	7	0.35	2.78
	36	0.43	5.96
	35	3.46	3.14
	10	4.06	63.93
	9	**12.26**	**19.59**
	11	14.57	4.60
3	38	0.08	6.01
	37	0.11	13.50
	39	0.14	10.07
	4	0.46	2.48
	3	0.50	21.11
	40	0.66	6.12
	19	**7.34**	**31.07**
	6	7.46	9.64
4	41	6.30	0.25
	42	6.94	0.98
	43	7.20	0.84
	51	11.10	0.02
	45	12.56	2.41
	44	12.92	9.79
	8	13.26	6.79
	46	13.87	3.87
	27	14.03	34.41
	49	14.42	2.83
	48	16.79	12.83
	20	**17.24**	**24.96**
5	12	6.92	0.57
	54	12.49	3.42
	13	13.67	17.60
	50	13.70	2.93
	53	13.71	0.35
	55	13.83	0.10
	16	14.14	17.50
	52	14.93	4.46

NCC climate zone	NatHERS climate zone	Sum of simulated 10-year maximum mould index values	Fraction of total NCC climate zone population [%]
	56	16.93	38.48
	47	17.11	2.28
	17	17.18	1.36
	15	**17.40**	**10.97**
6	21	16.57	7.26
	60	16.75	22.66
	58	17.48	0.80
	18	17.49	3.72
	28	17.50	24.49
	61	17.59	1.03
	62	**17.60**	**32.19**
	64	17.64	1.87
	22	17.66	2.90
	57	17.73	0.20
	63	18.04	1.34
	59	18.07	1.56
7	24	17.65	32.88
	26	17.69	11.96
	67	18.16	3.71
	14	18.73	5.24
	65	20.37	9.40
	68	20.54	3.07
	23	20.61	4.23
	66	**20.87**	**29.50**
8	69	20.87	41.21
	25	**20.95**	**58.79**

6 Sensitivity to Indoor Climate

6.1 BACKGROUND

During the Condensation TRG review of the return brief, a potential issue was raised relating to the indoor humidity boundary conditions. When the standard AIRAH DA07 'intermediate' method is applied to relatively severe cases (such as the 'baseline' case in this study with Indoor Humidity Risk Rating of 10), the 70 % relative humidity cap that is part of that method is active for the majority of time that air conditioning is not active, resulting in quite unrealistic indoor boundary conditions, and reversing the indoor-outdoor vapour pressure gradient at times.

For example, Figure 6-1 illustrates the indoor humidity boundary conditions that would be generated for simulations of Melbourne. When air conditioning is active, the indoor relative humidity is fixed to a value close to 35 %, and at almost all other times it is limited to 70 % by the cap.

Potential problems with such indoor boundary conditions include the following:

a) They do not accurately represent typical conditions inside Australian residential buildings, where active systems to limit humidity below a certain value are very rarely installed.

b) The 70 % relative humidity cap can at times force the indoor vapour pressure excess below zero (i.e. force the vapour pressure indoors lower than outdoors), which is not realistic except in buildings with mechanical dehumidification.

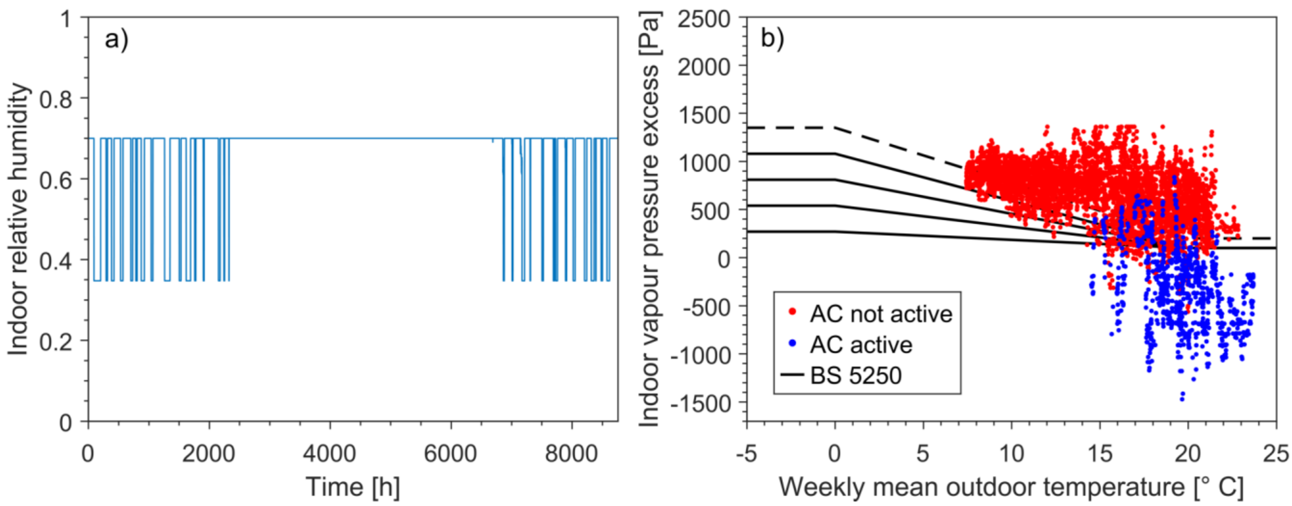


Figure 6-1: Indoor humidity boundary conditions determined for Melbourne following the AIRAH DA07 intermediate method with the standard 70 % relative humidity cap: a) relative humidity time series, b) indoor vapour pressure excess at each timestep compared to the indoor climate classes defined in BS 5250. Input assumptions include a floor area of 90 m^2, ceiling height of 2.4 m, infiltration rate of 0.2 ACH, and 3 bedrooms (4 occupants).

A possible solution is to lift the 70 % relative humidity cap to 90 % or 95 %, as illustrated in Figure 6-2. However, this produces indoor humidity levels far higher than typical measured values that we are aware of, or the ‘indoor humidity classes’ defined in BS 5250 [5], ISO 13788 and CIBSE Guide A [92] (see Figure 6-2b and Figure 6-3) . Within the AIRAH DA07 protocol, the 70 % relative humidity cap counterbalances several other simplistic assumptions. For example, the assumption that windows and doors are never opened.

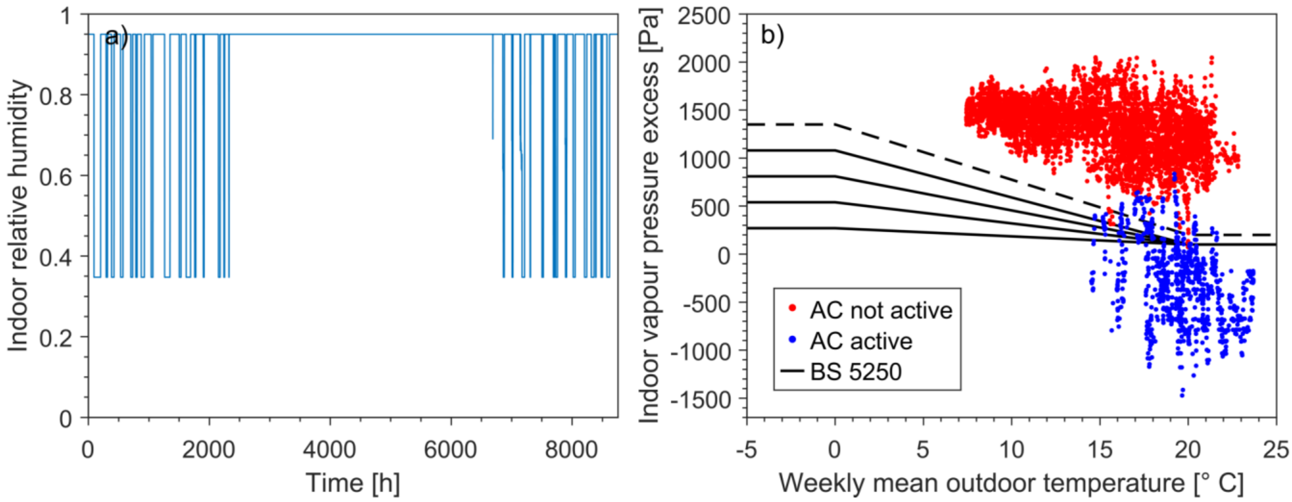
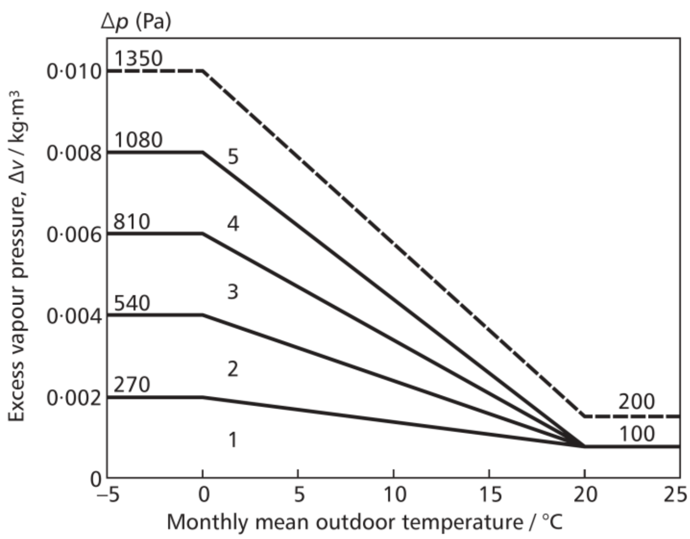


Figure 6-2: Indoor humidity boundary conditions determined for Melbourne following the AIRAH DA07 intermediate method with a 95 % relative humidity cap. Input assumptions are the same as in Figure 6-1.

The indoor humidity classes defined in BS 5250, ISO 13788 and CIBSE Guide A (Figure 6-3) offer an alternative model for indoor humidity boundary conditions, and are based on measured values from real buildings.



Class	BS 5250	ISO 13788, CIBSE Guide A
1	Storage areas	Storage areas
2	Offices, shops	Offices, dwellings with normal occupancy and ventilation
3	Dwellings with low occupancy	Buildings with unknown occupancy
4	Dwellings with high occupancy, sports halls, kitchens, canteens, buildings heated with unflued gas heaters	Sports halls, kitchens, canteens
5	Special buildings, e.g. laundry, brewery, swimming pool	Special buildings, e.g. laundry, brewery, swimming pool

Figure 6-3: Indoor humidity classes, as defined in BS 5250, ISO 13788 and CIBSE Guide A. The graph is reproduced from CIBSE Guide A.

However, direct use of the existing indoor humidity classes would not allow boundary conditions to be developed to represent specific values of parameters such as building volume, number of occupants, or ventilation rates. Therefore, such an approach to define indoor boundary conditions was not suitable for use in this study, since it would not allow quantified changes in the building ventilation rate to be tested.

A hybrid approach is possible, in which the AIRAH DA07 intermediate method is first applied to calculate the indoor vapour pressure excess, and that value is then used to determine where the specific case should lie within the BS 5250 indoor humidity classes. The steps involved in this method are as follows:

1. Calculate the indoor temperature according to AIRAH DA07.
2. Calculate the indoor vapour pressure (p_i), given by Equations *1* and *2*.
3. Calculate indoor humidity boundary conditions as follows:
    a. Whenever air conditioning is active, use the separate model defined in AIRAH DA07.
    b. When air conditioning is not active:
        i. When the weekly mean outdoor air temperature is lower than 0 °C, set the indoor vapour pressure equal to p_i.
        ii. When the weekly mean outdoor air temperature is higher than 20 °C, set the indoor vapour pressure 100 Pa higher than the weekly mean outdoor vapour pressure.
        iii. When the weekly mean outdoor air temperature lies between 0 and 20 °C, apply linear interpolation between the indoor vapour pressure values determined for 0 and 20 °C following steps i and ii above.
    c. Cap the indoor relative humidity at 95 %.

This hybrid method produces indoor humidity conditions that are aligned relatively closely with measured data [91] and the 'indoor humidity classes' of BS 5250 [5], but are also based on a specific set of assumed building volume, number of bedrooms, and ventilation rate. Figure 6-4 presents indoor humidity conditions generated using the hybrid method for the case with Indoor Humidity Risk Rating of 10 (i.e. the same case presented in Figure 6-1 and Figure 6-2), as well as a case with Indoor Humidity Risk Rating of 3.33. In this example, the data appear to align relatively closely with the appropriate indoor humidity classes (Figure 6-4b and Figure 6-4d), and the time series of relative humidity data (Figure 6-4a and Figure 6-4c) appear more realistic than those produced using the standard AIRAH DA07 intermediate method.

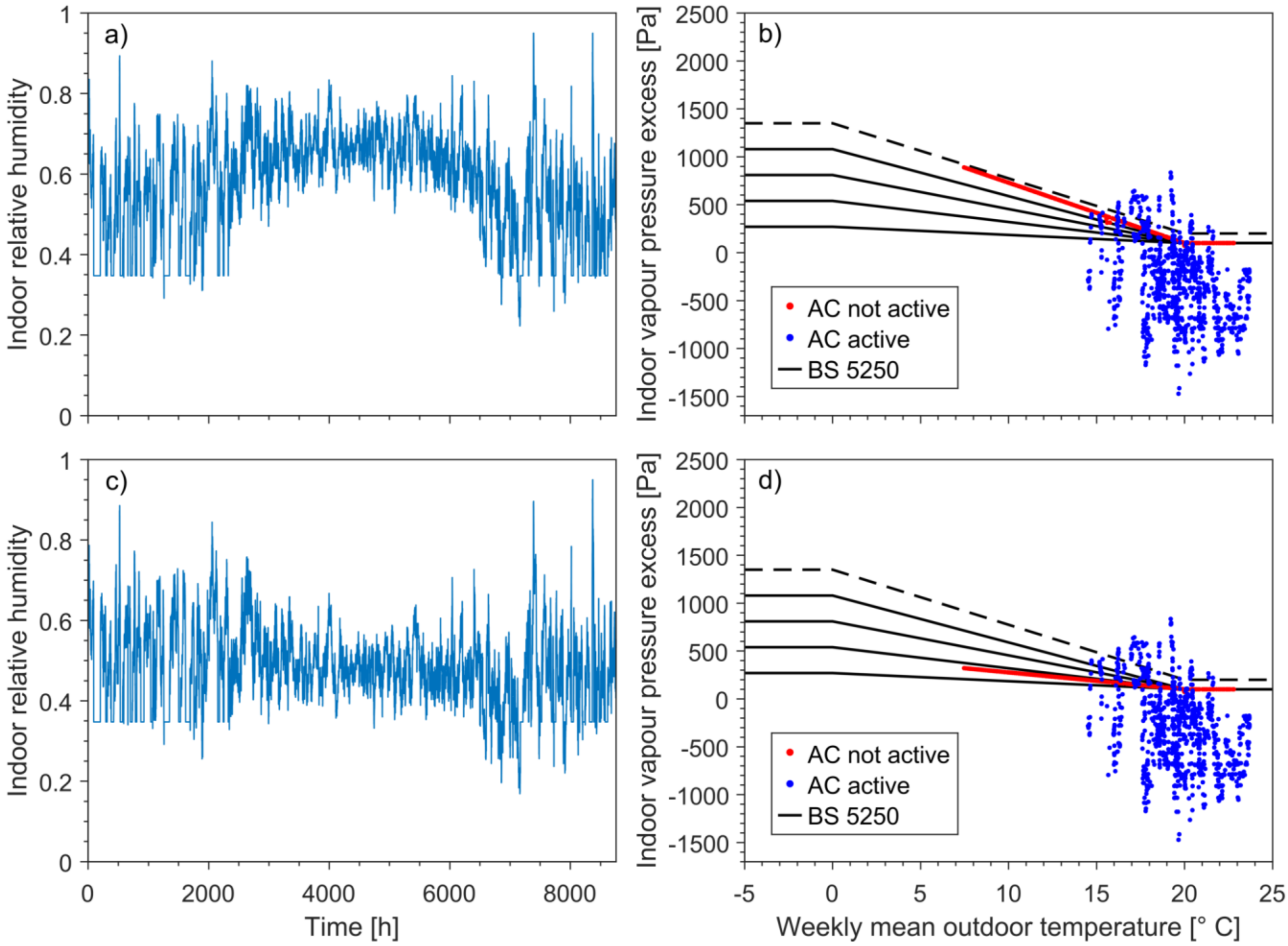


Figure 6-4: Indoor humidity boundary conditions determined for Melbourne following the hybrid method described in this report: a,c) relative humidity time series, b,d) indoor vapour pressure excess at each timestep compared to the indoor climate classes defined in BS 5250. Input assumptions in a and b are the same as in Figure 6-1 and 2; in c and d the infiltration rate has been increased from 0.2 to 0.6 ACH.

6.2 AIMS

The aims of the indoor boundary condition sensitivity study were to:

1. Investigate the impact of the standard AIRAH DA07 intermediate method (with 70 % relative humidity cap) on boundary conditions that would be simulated in the 69 NatHERS climate zones.
2. Quantify differences between mould index values simulated using this standard method and those simulated using the hybrid method described in Section 6.1.
3. In consultation with the ABCB Office and Condensation TRG, select a method to produce indoor boundary conditions for the primary simulation study.

6.3 IMPACT ON INDOOR BOUNDARY CONDITIONS

Figure 6-5 provides an overview of indoor humidity conditions generated when applying the standard AIRAH DA07 intermediate method (with 70 % relative humidity cap) to each of the 69 NatHERS climate zones.

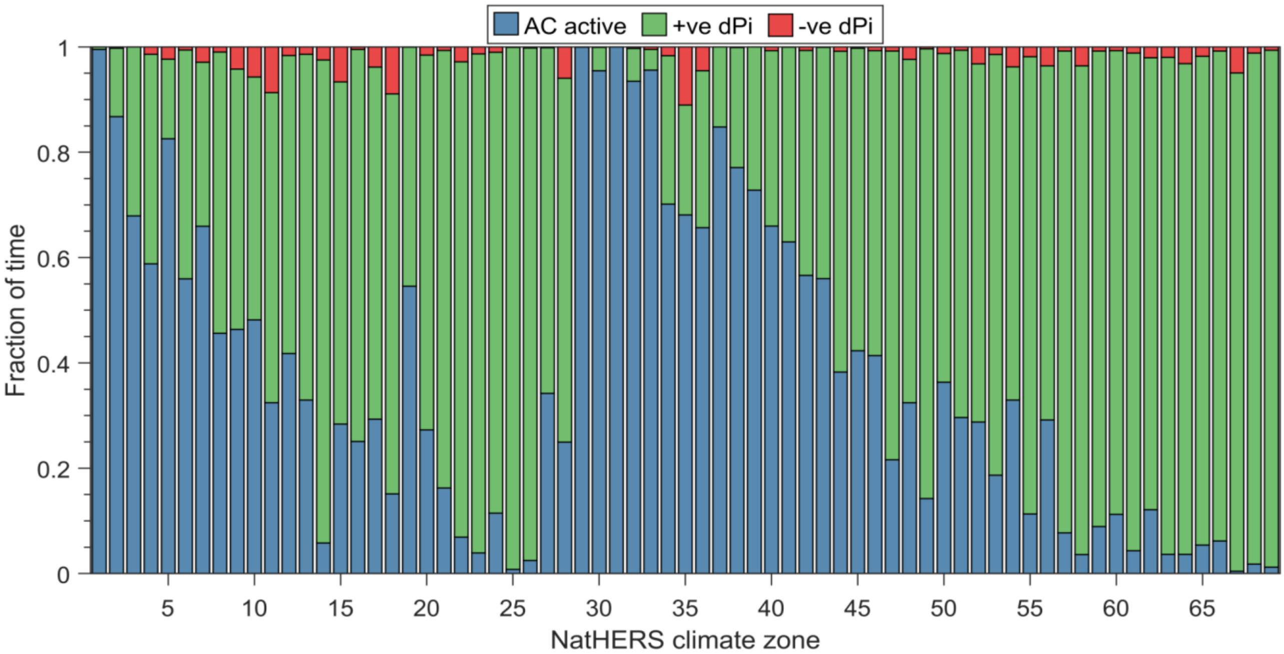


Figure 6-5: Distribution of indoor humidity conditions generated using the standard AIRAH DA07 method (with 70 % relative humidity cap) for the 69 NatHERS climate zones. Each bar represents the distribution of hours through the course of a year in which either: air-conditioning (AC) is active, AC is not active and dp_i is positive (i.e. driving diffusion from indoors outwards), and AC is not active and dp_i is negative.

The proportion of time in which the indoor vapour pressure excess is negative (i.e. indoor vapour pressure is lower than outdoor vapour pressure), and air conditioning is not active, is represented by the red bars. This occurred most frequently in Climate Zone 35, where it occurred 11 % of the time, and in Climate Zones 18 and 11, where it occurred 9 % of the time. On average across the 69 climate zones, it occurred 2 % of the time. While these values appear significant in some climate zones and potentially insignificant in others, it should be noted that they are the 'tip of the iceberg', so to speak, in terms of the impact of the 70 % relative humidity cap—they only include times at which the indoor vapour pressure excess was reduced to such a degree that it became negative.

Based on this analysis, 8 climate zones were selected for further investigation (Figure 6-6). They included four locations with relatively high frequency of negative indoor vapour pressure excess and different levels of air-conditioning usage (Climate Zones 35, 11, 18 and 67), and four locations representing different inland climates, for comparison (Climate Zones 6, 14, 66 and 23). Note that this analysis was undertaken before the climate sensitivity study (Section 5), so the climates selected here do not match those simulated in the rest of this report.

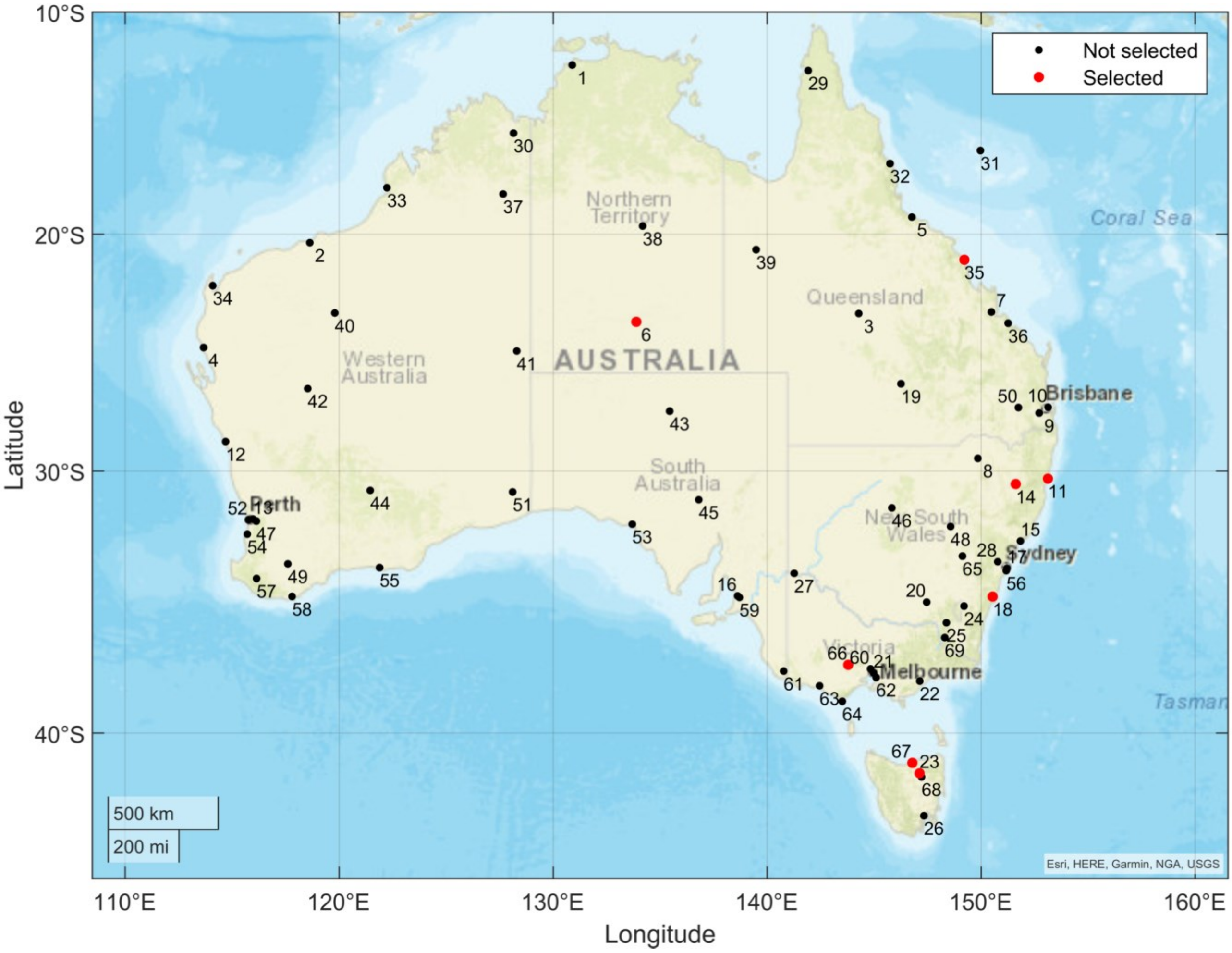


Figure 6-6: Locations used to represent each of the 69 NatHERS climate zones. Climate zones selected for inclusion in the indoor boundary condition sensitivity study are shown in red.

Figure 6-7 presents the distribution of indoor relative humidity values generated for each of the 8 selected climate zones using the three methods described in Section 6.1.

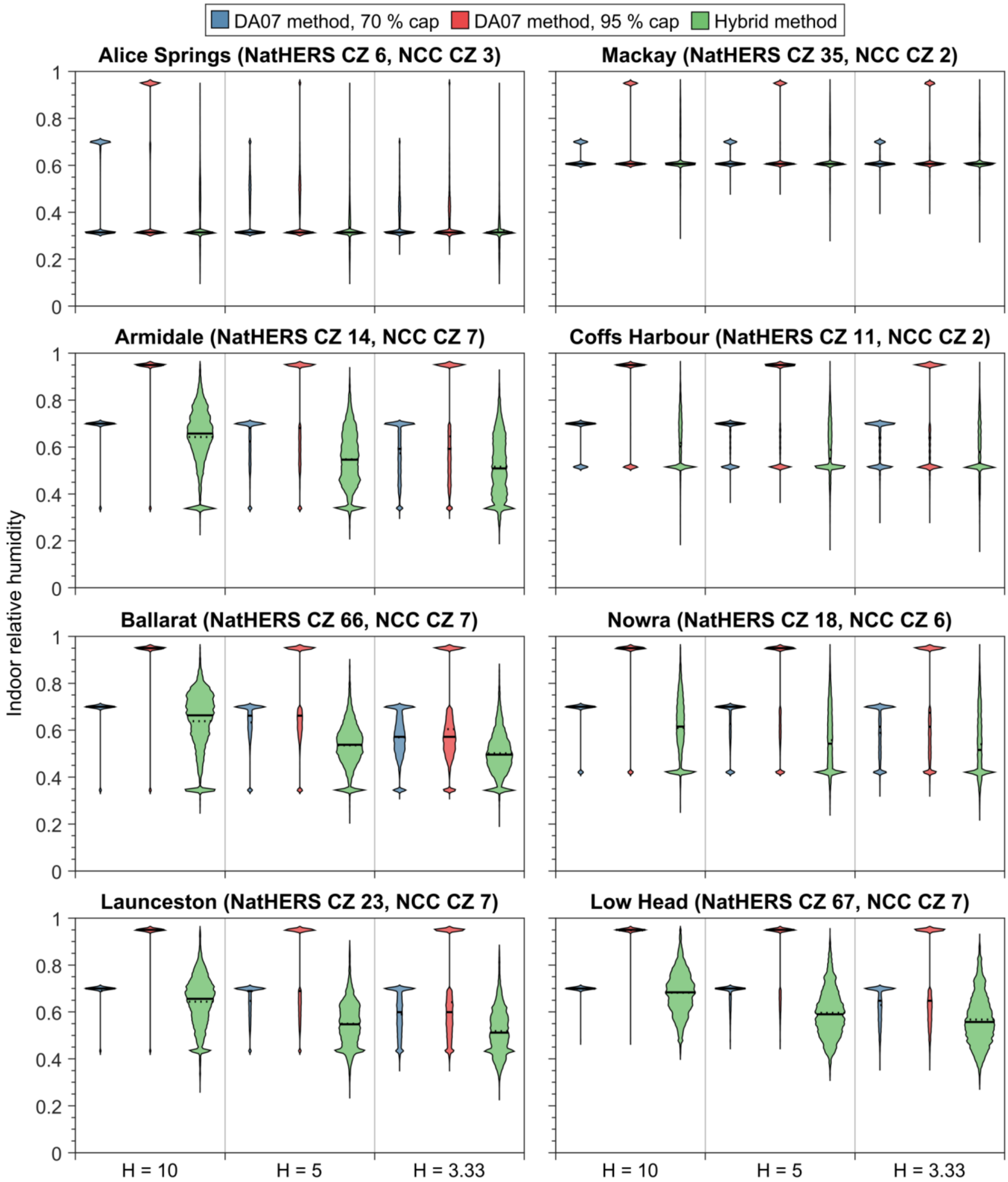


Figure 6-7: Distributions of indoor relative humidity during one year, determined for the 8 selected locations and three Indoor Humidity Risk Ratings (H = {10, 5, 3.33}), using each of the investigated methods.

It is clear in Figure 6-7 that regardless of whether the relative humidity cap is set to 70 % or 95 % within the AIRAH DA07 intermediate method, the indoor relative humidity was set at the limiting value for a relatively high proportion of time. This is true for cases with all three Indoor Humidity

Risk Ratings investigated. In contrast, the hybrid method produces indoor relative humidity values with a broader distribution when air conditioning is not active.

The impact of increased ventilation is visible in most of the relative humidity distributions in Figure 6-7; reductions in the Indoor Humidity Risk Rating produce lower indoor relative humidity values. However, the effects of ventilation are less noticeable in climates that demand frequent air conditioning, since the assumed ventilation rate does not impact the indoor relative humidity boundary condition when air conditioning is active within any of the methods.

6.4 IMPACT ON HYGROTHERMAL SIMULATION RESULTS

Simulations were run of the masonry veneer and fibre-cement-clad walls described in Section 2.2 in each of the 8 selected climate zones, and with three different membrane vapour permeance values (0.0022, 0.1429 and 1.1403 µg N^{-1} s^{-1}). These simulations were run twice: once with the standard AIRAH DA07 intermediate method (with 70 % relative humidity cap), and once with the hybrid method described in Section 6.1. Mould index values produced by the simulations of the masonry veneer and fibre-cement-clad walls are presented in Figure 6-8 and Figure 6-9, respectively.

Simulations run with the different indoor humidity conditions typically produced similar mould index results. However, differences between results from the two approaches were large enough to cause a change in whether the mould index exceeded 3 within the 10 simulated years in 5 of the 48 simulated cases. Therefore, the choice of approach can have a significant impact on the results of a study such as this.

In the cases simulated, the hybrid method typically produced lower mould index values than the standard intermediate method. However, this trend was reversed in some cases (e.g. see results for the masonry veneer wall in Climate Zone 35 and the fibre-cement-clad wall in Climate Zone 66). A large set of parameters influence which of the two approaches will produce a higher mould index value in a given scenario, including details of the construction, and the distribution of outdoor vapour pressure and air temperature conditions through the simulated period.

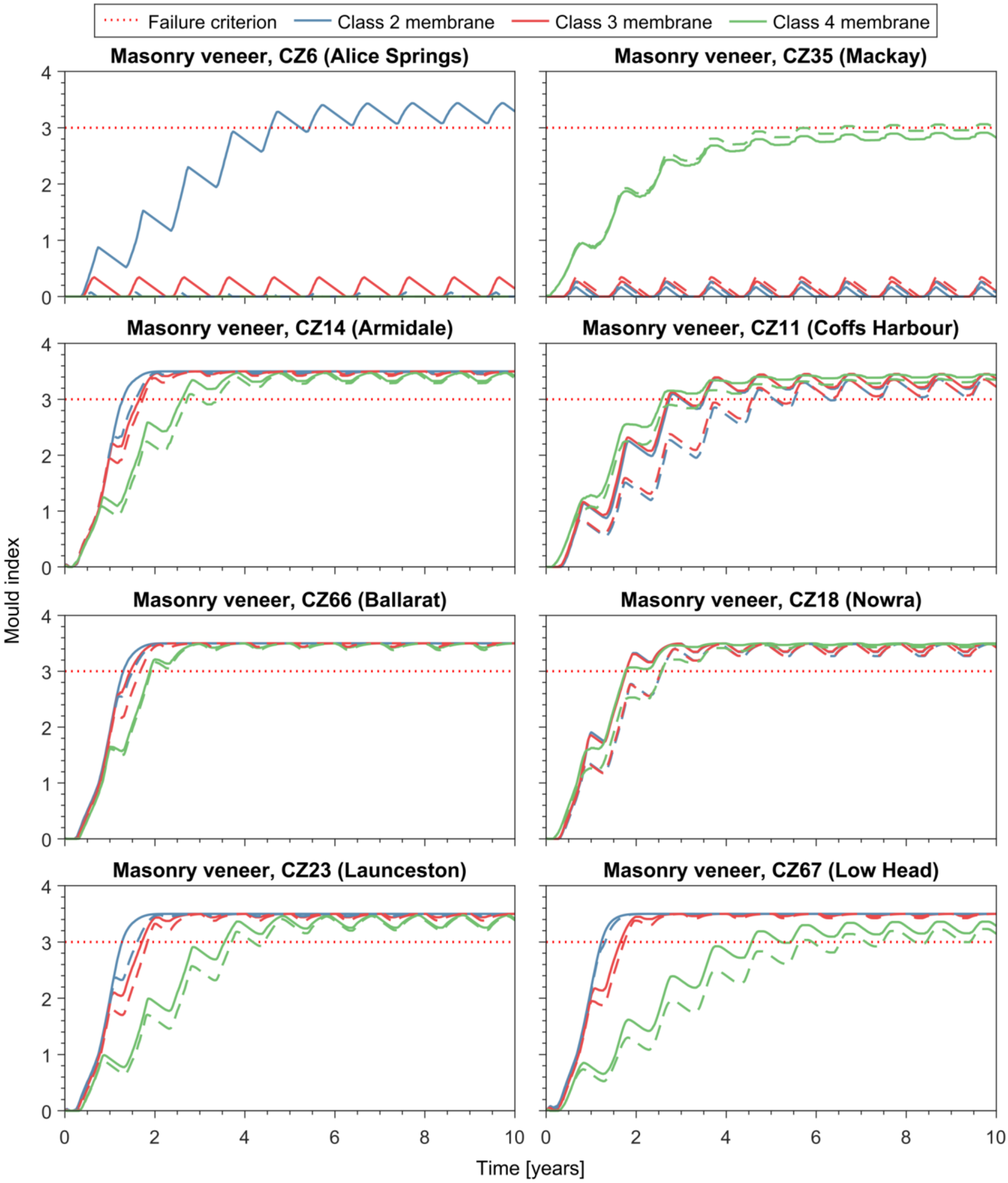


Figure 6-8: Comparison of mould index time series simulated with indoor humidity conditions generated using the standard AIRAH DA07 intermediate method with 70 % relative humidity cap (solid lines), and those generated using the hybrid method (broken lines). Results in this figure are from simulations of the masonry veneer wall with three different membranes in the 8 selected locations.

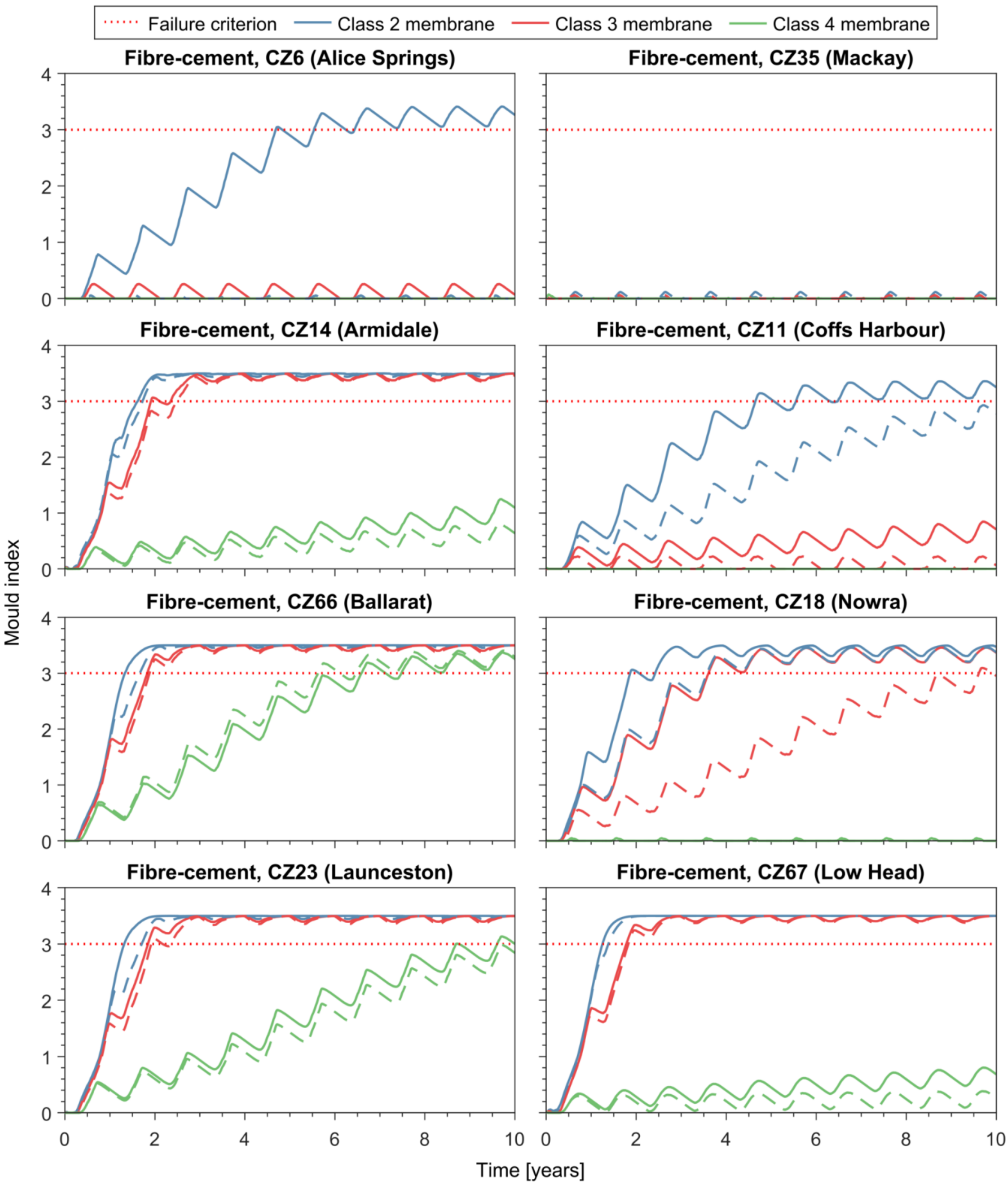


Figure 6-9: Comparison of mould index time series simulated with indoor humidity conditions generated using the standard AIRAH DA07 intermediate method with 70 % relative humidity cap (solid lines), and those generated using the hybrid method (broken lines). Results in this figure are from simulations of the fibre-cement-clad wall with three different membranes in the 8 selected locations.

6.5 CONCLUSION

Whilst the results presented here provide some valuable insights into differences between the three approaches to generate indoor humidity boundary conditions described in Section 6.1, they do not provide a complete justification for choosing one approach over another. The pros and cons of each method can be summarised as follows:

- The standard AIRAH DA07 intermediate method with 70 % relative humidity cap:
  - Is consistent with AIRAH DA07, and therefore also with verification methods specified in clauses H4V5 and F8V1 of NCC 2022; but
  - Does not model conditions that could be expected to occur in typical Australian buildings (i.e. those without dedicated mechanical dehumidification equipment); and
  - Produces negative indoor vapour pressure excess values for a significant proportion of the time in some cases, even at times that air conditioning is not active (occurring for up to a maximum of 11 % of the year, and an average of 2 % of the year across the 69 NatHERS climate zones)—such conditions do not match measured data that we are aware of.
- The AIRAH DA07 intermediate method with 95 % relative humidity cap:
  - Avoids creating negative indoor vapour pressure excess values when applied to the 69 NatHERS climate zones; but
  - Produces indoor relative humidity values of 95 % for a significant proportion of time in the 8 climate zones selected for detailed analysis, corresponding to indoor vapour pressure excess values far in excess of measured data from residential buildings that we are aware of; and
  - Is not consistent with AIRAH DA07 and NCC 2022 verification methods.
- The hybrid method described in this report:
  - Avoids creating negative indoor vapour pressure excess values when applied to the 69 NatHERS climate zones; and
  - Creates indoor humidity levels that correspond relatively closely to measured data we are aware of from other jurisdictions, as well as the ‘indoor climate classes’ outlined in BS 5250, ISO 13788 and CIBSE Guide A; but
  - Is not yet an established method; and
  - Is not consistent with AIRAH DA07 and NCC 2022 verification methods.

Discussion of these points with the ABCB Office and Condensation TRG eventually led to the decision to use the standard AIRAH DA07 intermediate method, with 70 % relative humidity cap, to generate indoor humidity boundary conditions in this study.

Future studies should establish a reliable dataset of conditions measured inside existing Australian buildings, to support the development of indoor boundary conditions that are more realistic for use in future simulation studies.

7 Impact of Thermal Bridges

7.1 BACKGROUND

Simulations run in the primary simulations study were one-dimensional, and therefore did not include any thermal bridges. In reality, most building envelope constructions include a variety of thermal bridges, including those typically classified as 'repeating' (such as studs in walls, and joists in floors and ceilings), and those classified as 'linear' or 'point' thermal bridges (such as wall/ceiling junctions, wall/floor junctions, and service penetrations).

However, the two-dimensional hygrothermal simulations needed to model such building features require much more time and computational resources to run than the one-dimensional simulations run in the primary simulation study. Therefore, it was not feasible to include thermal bridges in the primary simulation study. Instead, a thermal bridging study was undertaken to investigate the impacts of thermal bridging in a relatively small set of cases. The aims and scope of the study are described in Section 2.1.5, but are also summarised here for convenience.

The study included 12 simulations, modelling the masonry veneer and fibre-cement-clad walls, in Climate Zones 1 and 7, and in three thermal bridging scenarios:

i) With no thermal bridges (to act as a 'baseline' against which scenarios 2 and 3 could be compared);
ii) With a 90 mm × 35 mm timber stud modelled as if it were installed at 450 mm centres; and
iii) With a 90 mm × 40 mm × 0.75 mm BMT steel stud modelled as if it were installed at 450 mm centres.

Climate Zones 1 and 7 were included so as to capture two different modes of potential 'failure' (i.e. inwards vapour drive and mould risk on the indoor side of the insulation in Climate Zone 1, and outwards vapour drive and mould risk on the outdoor side of the insulation in Climate Zone 7).

Both walls were simulated with Class 4 membranes (with vapour permeance of 1.1403 µg N^{-1} s^{-1}), and with a ventilated reflective cavity (created by a membrane with low-emittance surface facing outwards).

Results from these simulations were analysed to investigate the impact of these typical 'repeating' thermal bridges on the risk of mould growth in the two walls. If the thermal bridges were found to have a significant impact on mould index values in the walls, that would impact how results from the primary simulation study should be interpreted. Such a result would also indicate the need for further investigation.

Three mechanisms were identified by which thermal bridges could potentially impact mould index values in simulated walls:

1. Impacts of the thermal bridges on surface temperatures within the walls would modify the local relative humidity, which is the primary input to the mould index model;
2. Hygric 'buffering' by the timber thermal bridge could dampen of humidity fluctuations within the walls; and
3. Within the mould index model, timber has a higher sensitivity class than most other materials in the walls, so could be at higher risk of mould growth.

The combined impact of these three mechanisms could not be predicted at the outset of the study, since they could have opposing impacts on the maximum mould index value.

7.2 RESULTS

Results from the two-dimensional simulations of walls with no thermal bridge, a timber stud thermal bridge, or a steel stud thermal bridge are presented in Figure 7-1 and Table 7-1 (covering Climate Zone 1), and Figure 7-2 and Table 7-2 (covering Climate Zone 7).

It should be noted that these results are not directly comparable to the one-dimensional simulation results presented in Section 4, since the membranes in the two-dimensional simulations were modelled with reflective (i.e. low-emittance) surfaces, producing cavities with higher effective thermal resistance than was modelled in the one-dimensional simulations. Moreover, we have so far been unable to produce matching results for the masonry veneer wall using the one- and two-dimensional versions of the WUFI software, even when the cavities in both models are modelled with the same thermal resistance. The discrepancy in results from the masonry veneer wall does not appear to be caused by convergence failures, differences in the computational grid, or other common issues, and we are currently in communication with the WUFI developers to investigate possible causes. Evidence we have so far appears to point to the absorption of wind-driven rain at the outer surface of the wall as being different between the two software packages, although our understanding is that it is not supposed to be different.

Overall, the mould index values obtained in simulations with thermal bridges were of similar magnitude to those obtained in the corresponding case without any thermal bridge. However, there were significant spatial variations of mould index in cases with thermal bridges, and the overall impact of thermal bridges varied between the two wall types, two bridge types, and two climates.

Table 7-1: Maximum 10-year mould index reached in two-dimensional simulations of walls in Climate Zone 1.

Type of wall		**Location in wall**					
		Indoor surface of membrane			**Outdoor surface of plasterboard**		
		Aligned with centre of stud	**Aligned with edge of stud**	**Between studs**	**Aligned with centre of stud**	**Aligned with edge of stud**	**Between studs**
Masonry veneer	No thermal bridges	0.00			0.71		
	Timber studs	0.24	0.06	0.00	0.00	0.07	0.35
	Steel studs	0.07	0.00	0.00	0.00	0.00	0.23
Fibre-cement-clad	No thermal bridges	0.00			0.28		
	Timber studs	0.02	0.00	0.00	0.00	0.04	0.24
	Steel studs	0.00	0.00	0.00	0.00	0.00	0.22

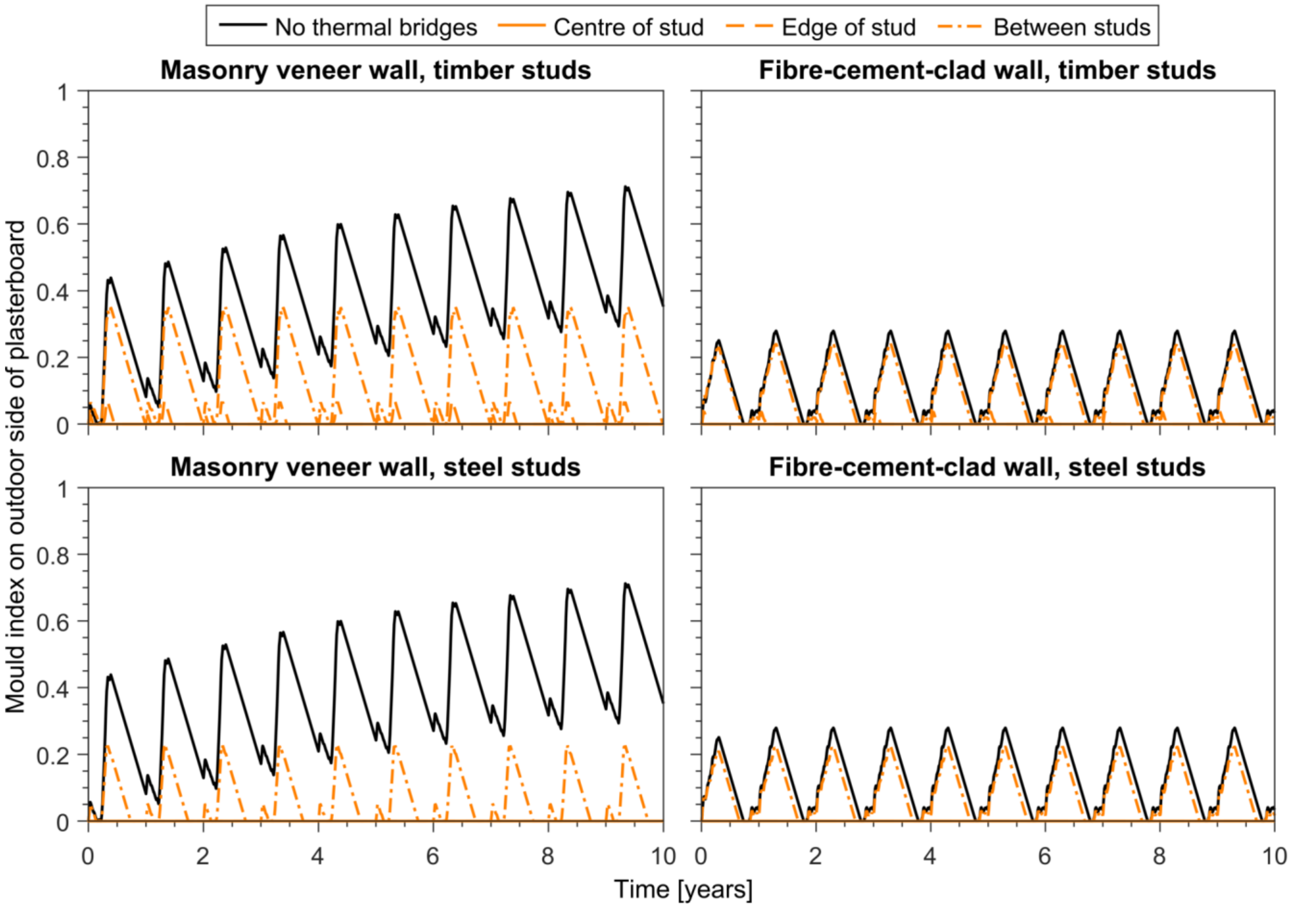


Figure 7-1: Comparison of mould index values simulated in Climate Zone 1 in two-dimensional wall geometries containing no thermal bridges, a timber stud thermal bridge, or a steel stud thermal bridge. These mould index values were simulated near the outdoor-facing surface of the plasterboard.

Table 7-2: Maximum10-year mould index reached in two-dimensional simulations of walls in Climate Zone 7.

Type of wall		**Location in wall**					
		Indoor surface of membrane			**Outdoor surface of plasterboard**		
		Aligned with centre of stud	**Aligned with edge of stud**	**Between studs**	**Aligned with centre of stud**	**Aligned with edge of stud**	**Between studs**
Masonry veneer	No thermal bridges	0.21			0.00		
	Timber studs	0.00	0.62	0.17	0.00	0.00	0.00
	Steel studs	0.00	0.00	0.19	0.00	0.00	0.00
Fibre-cement-clad	No thermal bridges	1.57			0.00		
	Timber studs	0.00	0.41	0.38	0.00	0.00	0.00
	Steel studs	0.00	0.00	0.91	0.00	0.00	0.00

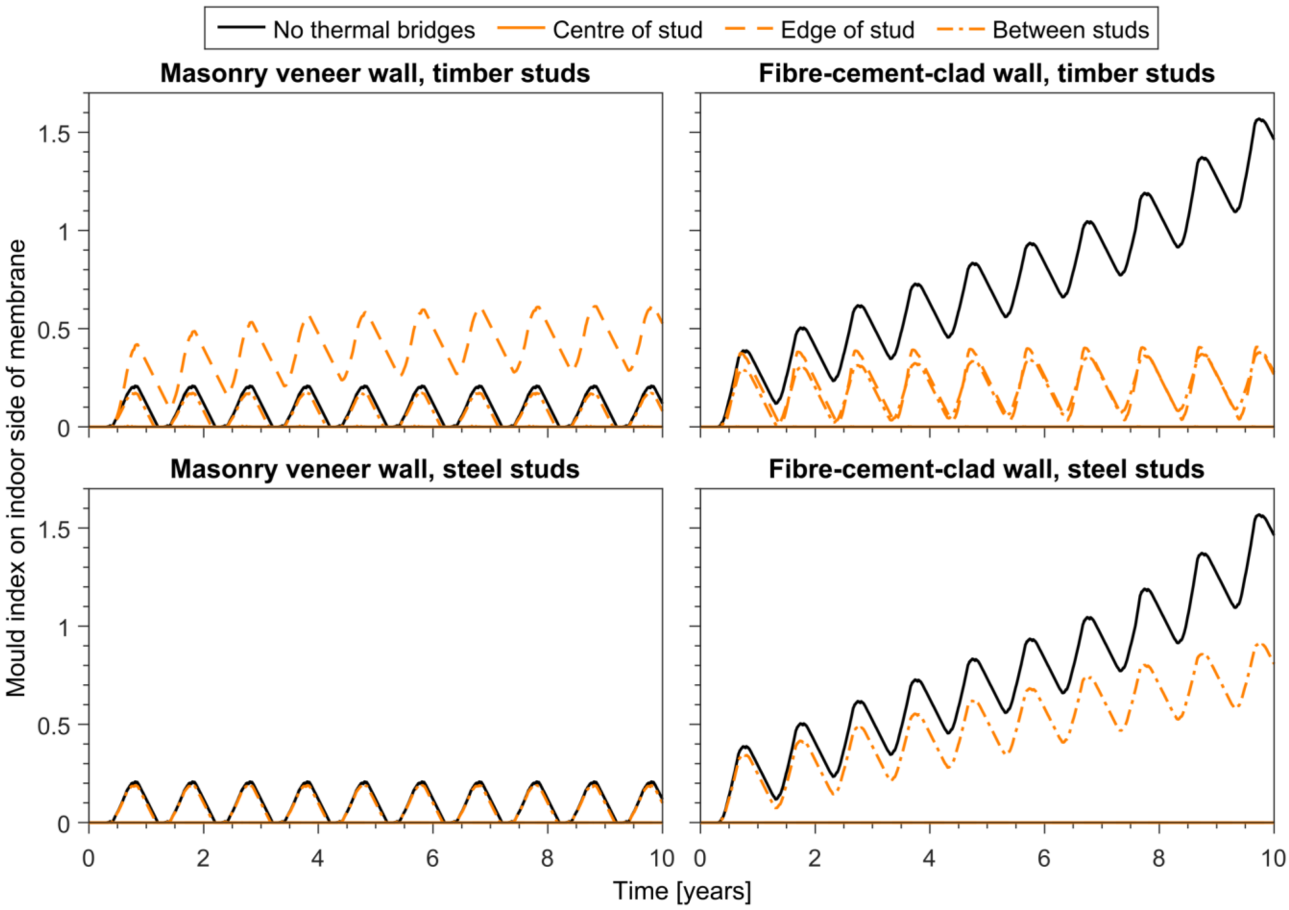


Figure 7-2: Comparison of mould index values simulated in Climate Zone 7 in two-dimensional wall geometries containing no thermal bridges, a timber stud thermal bridge, or a steel stud thermal bridge. These mould index values were simulated near the indoor-facing surface of the membrane.

In all cases simulated with a thermal bridge, the relative humidity near the cold side of the bridge was reduced, and the relative humidity near the warm side of the bridge increased, due to the localised influence of the thermal bridge on temperature. These effects even influenced relative humidity values in locations half-way between studs, albeit to a much smaller extent. Given that the location at which the mould index reached its highest value was on the cold side of the insulation layer in all cases (i.e. at the membrane/insulation interface in Climate Zone 7, and at the plasterboard/insulation interface in Climate Zone 1), these thermal effects of the thermal bridges helped to reduce the risk of mould growth.

The second effect of thermal bridges on the simulated mould index was through 'hygric buffering', as the timber bridge adsorped and desorped moisture; the steel thermal bridge did not provide any significant hygric buffering. The impact of hygric buffering was evident in the relative humidity fluctuations through diurnal cycles. However, it did not appear to have a substantial impact on seasonal humidity fluctuations, which could be expected given the time scales involved and total moisture capacity of the timber stud. The mould index was influenced much more strongly by seasonal humidity fluctuations than it was by diurnal humidity fluctuations, with higher relative humidities during winter leading to an increase in the mould index and dryer periods during summer leading to a decrease in the mould index. Therefore, hygric buffering did not appear to play a major role in the effects that the thermal bridges had on the maximum mould index reached during each 10-year simulation.

The third effect of thermal bridges on the simulated mould index was the classification of the timber thermal bridge as 'sensitive' within the mould index model, whereas the membrane and mineral wool insulation were classified as 'medium resistant'. This effect did not apply to cases with the steel thermal bridge, since it too was classified as 'medium resistant', nor did it apply to locations on the indoor side of the insulation layer, since the paper-faced plasterboard was already classified as 'sensitive'. Therefore, the change in classification from 'medium resistant' to 'sensitive' only applied to locations at the interface between the timber stud and membrane, aligned with the centre or edge of the timber stud.

The combined impact of the three effects described above on the simulated 10-year maximum mould index varied between cases.

Cases with steel thermal bridges were only impacted by the first effect (i.e. the modification of local relative humidity due to thermal effects), and therefore the mould index in cases with steel thermal bridges was always lower than in the corresponding case with no thermal bridge. At locations aligned with the centre or edge of the bridge, the mould index was effectively kept equal to zero in both climate zones, and in both wall types. In locations between studs, the mould index reached values closer to those reached in the 'no bridge' cases, but the thermal effects of the steel thermal bridge still reduced the level of risk to some degree.

Cases with timber thermal bridges were impacted by all three effects described above, so the net effect on mould index values was more varied. In locations aligned with the centre of the timber stud, the maximum mould index was effectively reduced to zero. However, at the edge of the timber stud, where the material was classified as 'sensitive' but the thermal impacts of the bridge were somewhat weaker, the combination of thermal effects and material sensitivity effects led to decreased mould index values in three cases (masonry veneer in Climate Zone 1, and fibre-cement in Climate Zones 1 and 7) and increased mould index values one case (masonry veneer in Climate Zone 7). In locations between studs, a small decrease in the mould index was observed in all cases.

These results have implications relevant to the interpretation of one-dimensional simulation results presented in other sections of this report, as well as for the selection of appropriate modelling assumptions for future studies. The results indicate that typical one-dimensional simulations, which ignore thermal bridges, are likely to over-predict the risk of mould growth in constructions with metal thermal bridges, and may under- or over-predict mould risk in cases with timber thermal bridges.

We understand that some practitioners choose to assign the 'sensitive' material classification to additional materials within a one-dimensional simulation, to account for the relatively high sensitivity of a timber frame even though the frame itself cannot be modelled within the one-dimensional domain. That approach was not adopted in this project. Results from this thermal bridging study indicate that such an approach is likely to produce strongly conservative predictions of mould risk in many cases.

For example, if the membrane or mineral wool batts were classified as 'sensitive' in the case involving the masonry veneer wall with no thermal bridges in Climate Zone 7 (Figure 7-2 and Table 7-2), the mould index at the membrane/insulation interface would reach a value of 3 in the 3rd year of the simulation. This result is clearly much further from the values obtained through two-dimensional analysis than the value obtained by simply assigning each material with its own sensitivity class (i.e. with the membrane and mineral wool set as 'medium resistant').

However, the advantage of assigning materials in a one-dimensional simulation higher sensitivity classifications to account for timber frame members is that the results are more likely to be conservative than they would if each material were assigned its correct sensitivity class. While the risk of mould growth is likely to be strongly over-predicted following such an alternative approach, the risk that it is under-predicted would be reduced substantially.

8 Thermal Impacts of Ventilated Cavities

8.1 BACKGROUND

A question arose late in the present study regarding the potential impact of ventilated cavities on the thermal performance of walls, should ventilated cavities be included in the DTS provisions for NCC 2025.

As explained in Section 3.3.2, a growing body of evidence has demonstrated that, under realistic conditions including solar irradiance and long-wave radiant heat exchange with the outdoor environment, cavity ventilation can actually increase the effective thermal resistance (R-value) of building assemblies, rather than decreasing it as several standard R-value calculation methods would suggest (e.g. methods in AS/NZS 4859.2).

Data from the primary simulation study presented in this report are well-suited to provide insights into the actual thermal impacts of ventilated cavities on Australian wall systems, since they were generated through transient simulations of typical Australian wall constructions under realistic Australian conditions, and heat exchange with the outdoor environment and cavity ventilation rates were both modelled in relatively high fidelity.

In this section of the report, heat flux data from the primary simulation study have been analysed to investigate the effects of ventilated cavities on the thermal performance of walls. Where available, average annual heat gains and losses to/from the indoor space have been compared between walls with: (i) 'direct-fixed' cladding, and (ii) drained and ventilated cavities behind the cladding.

8.2 RESULTS

The average annual heat gains/losses to/from the indoor space in simulations of walls with timber, fibre-cement, metal and AAC cladding are presented in Figures 8-1, 8-2, 8-3 and 8-4, respectively. The graphs in these figures compare heat gains and losses simulated through walls with 'direct-fixed' cladding and those with drained and ventilated cavities, where all other model settings are identical. The results presented here only include cases with the 'baseline' indoor boundary conditions (i.e. Indoor Humidity Risk Rating of 10), and with a membrane permeance of 1.1403 $\mu g\ N^{-1}\ s^{-1}$ (i.e. at the threshold between Class 3 and Class 4).

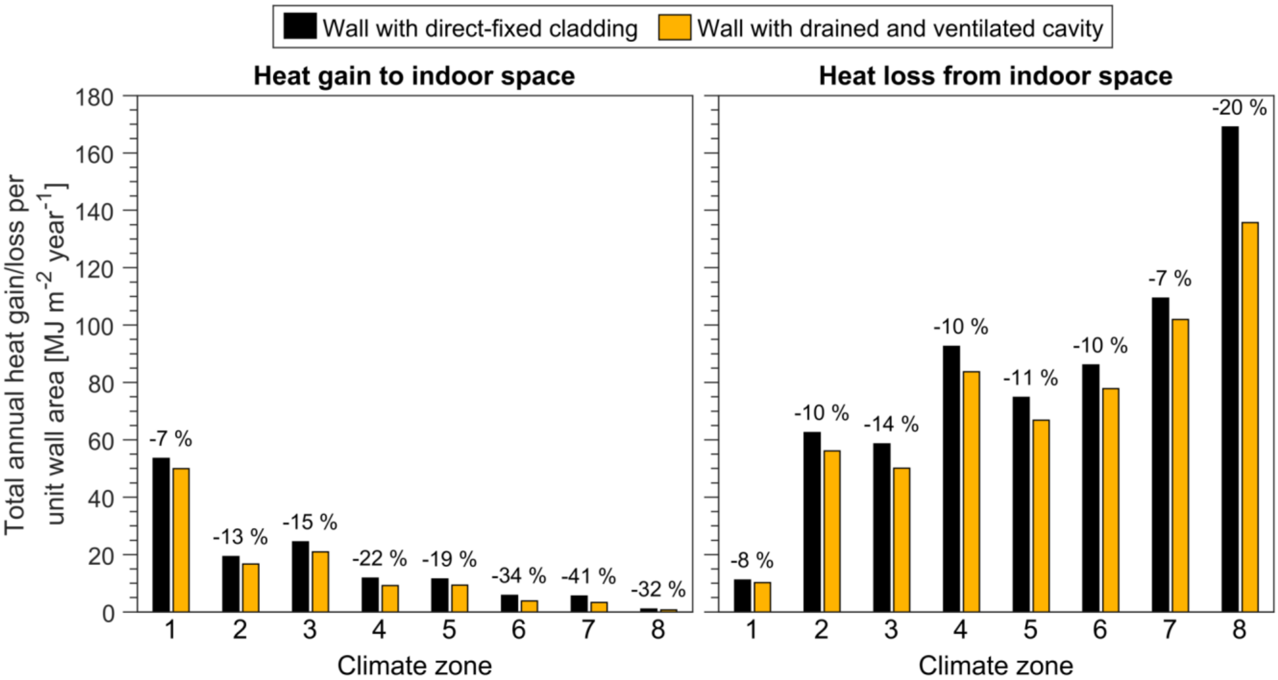


Figure 8-1: Simulated total annual heat gains and losses per unit area through walls with timber cladding and either (i) direct-fixed cladding or (ii) drained and ventilated cavities.

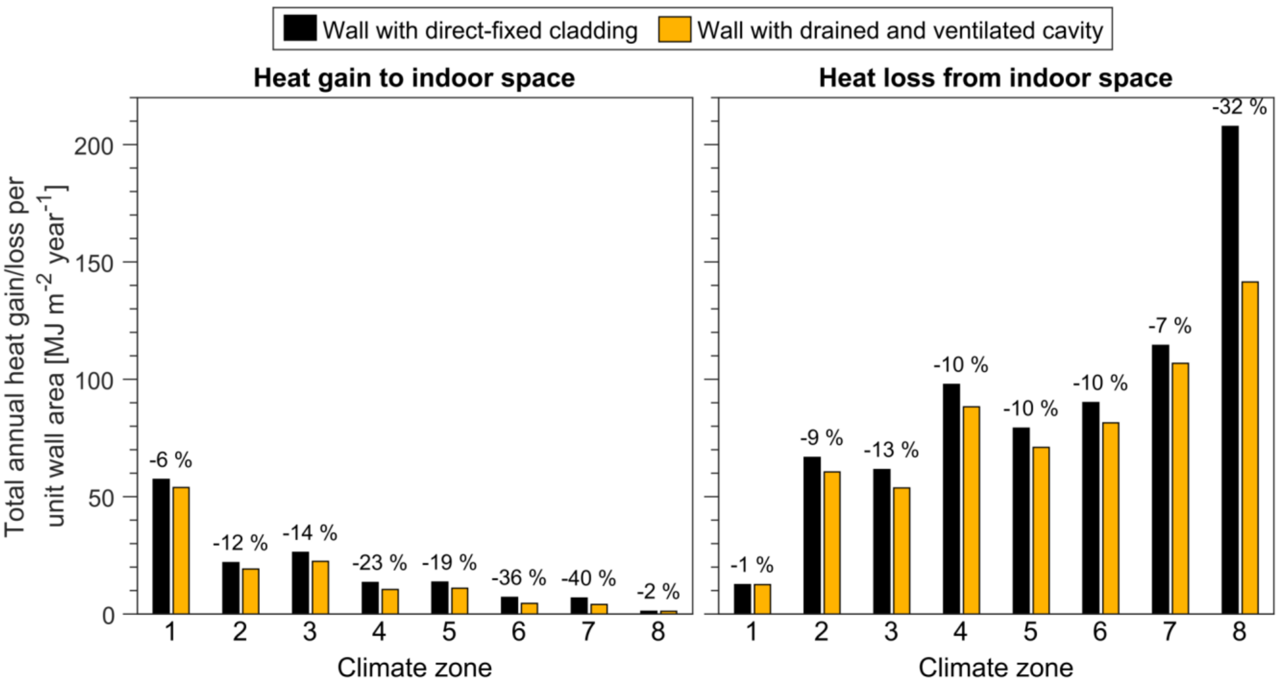


Figure 8-2: Simulated total annual heat gains and losses per unit area through walls with fibre-cement cladding and either (i) direct-fixed cladding or (ii) drained and ventilated cavities.

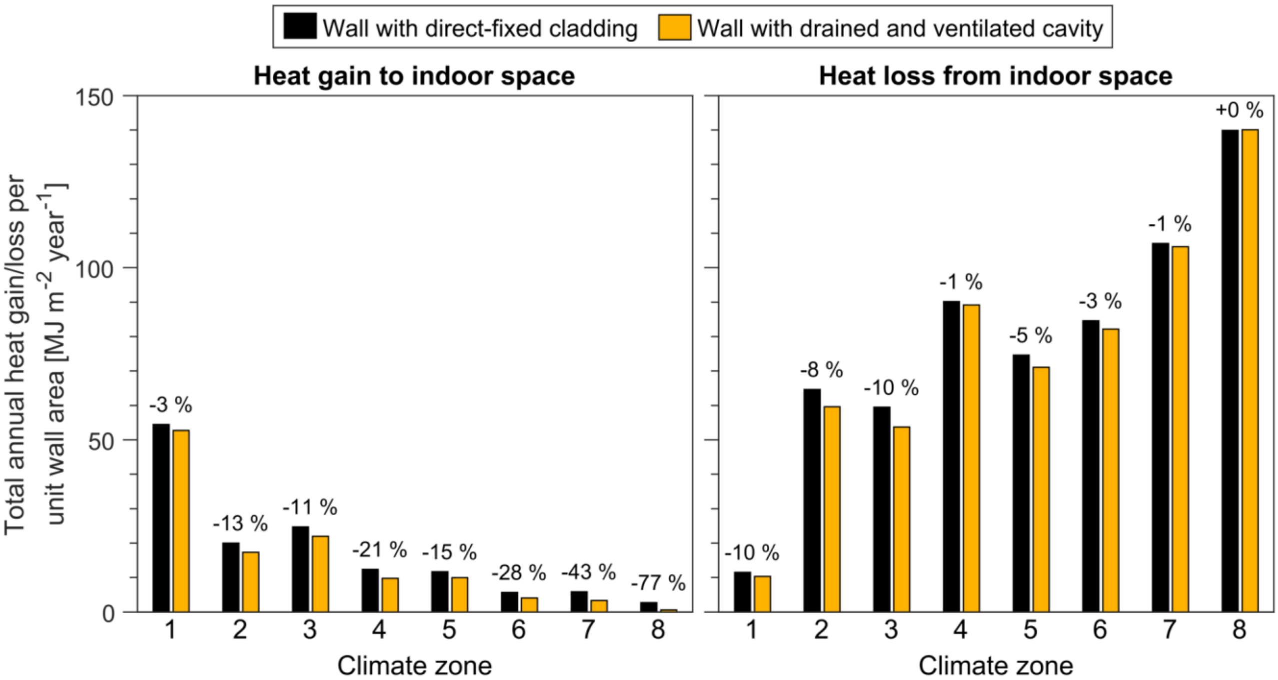


Figure 8-3: Simulated total annual heat gains and losses per unit area through walls with metal cladding and either (i) direct-fixed cladding or (ii) drained and ventilated cavities.

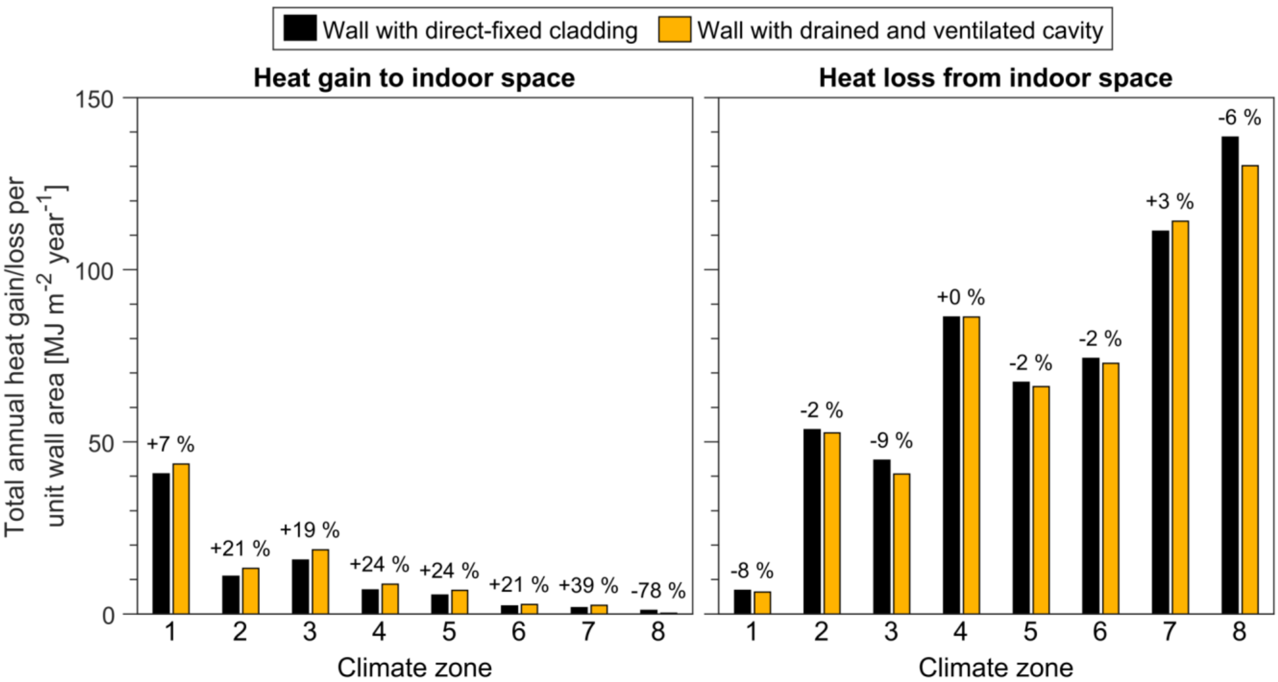


Figure 8-4: Simulated total annual heat gains and losses per unit area through walls with AAC cladding and either (i) direct-fixed cladding or (ii) drained and ventilated cavities.

Simulated heat gains and losses through the walls with timber, fibre-cement and metal cladding were reduced by the addition of a ventilated cavity in all 8 climate zones. The magnitude of reduction varied, but was in the order of 10 % in the majority of cases.

The reduction of heat losses through the metal-clad wall was typically less significant—ranging from 0 % to 10 % across the 8 climate zones, whereas corresponding cases with timber or fibre-cement walls ranged from 1 % to 32 %. This is likely to be a result of the metal-clad wall with 'direct-fixed' cladding being modelled with a narrow, weakly ventilated cavity (created by the profiled cladding) while the other walls with 'direct-fixed' cladding were modelled with no cavity at all (since those cladding materials could sit flush against the membrane). It appears that the narrow, weakly ventilated cavity modelled in the metal-clad wall with 'direct-fixed' cladding was able to provide a significant proportion of the reduction in heat losses that the larger 'drained and ventilated' cavity could, and therefore the performance of those two walls was not as different as it was in walls with other cladding types.

Results from the wall with AAC cladding were significantly different to the other cases, with a net increase in heat gains in all climate zones except Climate Zone 8, and with relatively small changes in heat losses—increasing slightly in some climate zones and decreasing slightly in others. The primary reason that the AAC-clad wall responded so differently to the introduction of a drained and ventilated cavity is likely to be the relatively high R-value of the AAC cladding itself. In the other walls studied, the vast majority of the wall's thermal resistance was provided by materials on the indoor side of the cavity (i.e. the bulk insulation), whereas in the AAC wall the thermal resistance of the cladding (0.52 m^2 K W^{-1}) was significant relative to the thermal resistance of the bulk insulation (2–2.5 m^2 K W^{-1}). Therefore, ventilation airflow in the AAC wall was effectively bypassing a significant proportion of the wall's overall thermal resistance, leading to a decrease in the effective R-value of the wall under some conditions.

It is important to note that the specific scenarios modelled in this study were designed to produce relatively severe mould and condensation risks, and several of the model settings that were chosen for this purpose are likely to influence the thermal data presented here. In particular, the following settings create scenarios in which very little solar radiation is absorbed by the walls:

1. The walls all face south;
2. The walls all have a solar absorptance of 0.33 (representing a colour close to white); and
3. The solar radiation incident on the walls was reduced to mimic the impact of shading by eaves.

Therefore, the results presented here correspond to cases where the potential thermal benefits of cavity ventilation, in terms of reducing solar heat gains, are relatively low. Heat gains through walls with other orientations, with higher solar absorptance, and/or with narrower eave overhangs, could be expected to be reduced by a greater margin than is indicated here when ventilated cavities are introduced.

9 Conclusion

The hygrothermal simulations undertaken in the primary simulation study were intended to provide a technical basis for condensation provisions in the NCC 2025. The graphical summaries of simulation results in Section 4 have been developed for that purpose.

Moreover, the literature review, and results from the climate sensitivity study, indoor boundary conditions sensitivity study, thermal bridging study, and analysis of thermal impacts of ventilated cavities, provide useful insights into the context, implications and limitations of the results in this report.

This study has demonstrated that the mitigation of mould risk in Australian dwellings can often require a multi-faceted approach, including measures that address the construction details (e.g. cavity ventilation and membrane vapour permeance) as well as the indoor environment (e.g. indoor ventilation). The effectiveness of such risk mitigation measures varies between the different climate zones and construction types, and the data presented in this report provide a basis for selecting and prioritising those that will have the greatest effect.

This study has also demonstrated the relatively high risk that dwellings with high occupant densities and/or low levels of ventilation can present. While the DTS provisions in the NCC may continue to apply the same requirements to all dwellings in each climate zone for the sake of simplicity, the reality is that dwellings with certain features will be at much higher risk of mould growth than others.

While the data presented in this report do provide a quantitative basis for the development of condensation provisions for NCC 2025, they should be interpreted with care for the reasons explained in Section 2.1.7. Each simulated mould index value is a result of the specific assumptions and settings applied in its simulation, so data presented here should be treated as theoretical values within that context rather than definitive indications of absolute risk.

Through the course of this project, several topics have been identified that require further investigation. Future studies with any of the following aims are likely to further advance our understanding of mould and other condensation-related issues in Australian buildings, which could lead to further strengthening of the relevant codes and standards:

- Generate reliable statistical evidence showing the prevalence of mould in existing Australian buildings, to allow meaningful comparison with results from simulation studies such as those presented here. Ideally, this work should:
  - Investigate interstitial mould as well as mould on exposed surface;
  - Diagnose the cause(s) of mould in each case; and
  - Collect comprehensive metadata on each dwelling, including orientation, building use, ventilation usage, etc.
- Develop reliable experimental data and models to allow air flows to be modelled accurately in hygrothermal simulations of Australian envelope constructions, including cavity ventilation and other fugitive air flows.
- Collect existing and/or new data on the indoor vapour pressure excess in Australian buildings, together with comprehensive metadata on the building characteristics, usage, etc.
- Build on the indoor boundary condition sensitivity study in this report to develop an improved method to specify indoor boundary conditions in AIRAH DA07 and/or the NCC.
- Develop standard weather data files for hygrothermal analysis in Australia.
- Build on the thermal bridging study in this report by investigating a broader set of thermal bridging cases, including linear and point thermal bridges and additional climate zones.
- Develop a comprehensive database containing the hygrothermal properties of typical Australian building materials.

The work presented in this report, together with the substantial body of literature that already exists, can serve as a foundation on which to develop the knowledge and data that is needed to comprehensively and effectively address mould and condensation issues in Australian buildings over the coming decades.

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Appendices

APPENDIX A: EVALUATION OF WINDOW FRAMES AND GLAZING

Standard procedures for the rating of window thermal performance in Australia are set by the Australian Fenestration Rating Council (AFRC), and are modelled closely on procedures set by National Fenestration Rating Council (NFRC) in the USA. The thermal transmittance (U-value) of glazed assemblies is typically quantified through steady-state finite-element thermal simulations of the glazing system in isolation (to obtain a 'centre-of-glazing' U-value), and of a cross-section through the frame (to obtain 'edge-of-glazing' and 'frame' U-values).

NFRC procedures also include a condensation risk assessment procedure [124]. The finite-element simulation results described above provide an estimate of surface temperatures likely to arise on the glazing and frame. The minimum simulated surface temperature that would be exposed to the indoor environment can be normalised by the simulated indoor-outdoor temperature difference, to provide a standard measure of the potential for condensation:

$$T^* = \frac{T_s - T_o}{T_i - T_o} \quad (5)$$

where:

T^* is the dimensionless surface temperature, which can vary from 0 (high condensation risk) to 1 (low condensation risk);

T_s is the minimum simulated surface temperature on the indoor side of the fenestration component;

T_{i} is the simulated indoor boundary temperature; and

T_{o} is the simulated outdoor boundary temperature.

An almost identical method for condensation risk assessment is specified for building envelope assemblies more generally (i.e. not just fenestration) in ISO 10211 [125].

The primary disadvantages of such methodologies are that they:

a) Do not provide an assessment of hygrothermal performance in a specific set of conditions (i.e. climate and indoor conditions); and
b) Do not assess whether the quantity of condensation predicted is likely to cause damage (i.e. rot, corrosion or mould growth)—they simply rate the risk that condensation could form.

In this study, a hybrid methodology was adopted for the assessment of window systems, taking the standard NFRC condensation risk assessment and applying it within the AIRAH DA07 mould risk assessment framework. The involved the following steps:

1. Calculate/simulate the minimum dimensionless surface temperature (i.e. condensation index) of each glazing system and window frame using the software WINDOW v7.8, and THERM v7.8, respectively, in accordance with NFRC procedures [6,7].
2. For each case of interest (i.e. each combination of indoor and outdoor boundary conditions) simulate the accumulation and drying of a film of condensate on the indoor surface of the window component through 1 year of operation. This process involved the following steps, applied to each 1 h timestep sequentially:
    a. Start with an ‘initial guess’ of the internal and external surface temperatures of the window component.
    b. Based on the indoor humidity boundary condition and the minimum surface temperature, calculate the rate at which condensate would evaporate or condense during that timestep.
        i. If evaporation is predicted and any condensate existed on the surface at the end of the previous timestep, allow it to be evaporated at the calculated rate but limit any evaporation to avoid a negative condensate load on the component, and
        ii. If condensation is predicted, allow it to occur at the calculated rate.
    c. Calculate the minimum surface temperature on the component, adopting a quasi-steady assumption (i.e. assuming that the component is at hygrothermal equilibrium with its surroundings), and including any latent heat absorption or release due to condensation or evaporation.
    d. Iteratively loop through steps b and c above, until convergence is reached (i.e. until a quasi-steady thermal equilibrium is reached and a condensation/evaporation rate is established for the timestep.
    e. Track the accumulation and drying of condensate through time by marching through the set of 8760 timesteps, but wherever the condensate load is predicted to exceed 30 g m^{-2}, assume that runoff has occurred and set the condensate mass load to 30 g m^{-2} at the start of the next timestep.
3. The performance criterion used to compare the different glazing and frame components was the number of hours during which condensate runoff was predicted during a year.

Wherever possible in these simulations, the same models and assumptions applied in the primary simulation study (using WUFI Pro) were adopted. For example, the same equations for radiant and convective exchanges with the outdoor and indoor environments were used.

This approach relies on several assumptions, most importantly the assumption that the temperature and moisture content of window systems can be treated as 'quasi-steady'. The glass, aluminium, u-PVC, and sealants that comprise window systems are not hygroscopic (i.e. they do not absorb and store moisture when exposed to water vapour), do not allow significant transfer of liquid water or vapour, and their thermal capacitance (i.e. thermal mass) typically has a negligible impact on their temperature at any given point in time—they are much more strongly driven by the temperature of their surroundings and solar irradiance. Therefore, they can be characterised as 'quasi-steady' in hygrothermal simulations without a significant loss of accuracy.

APPENDIX B: OVERVIEW OF CLIMATE DATA

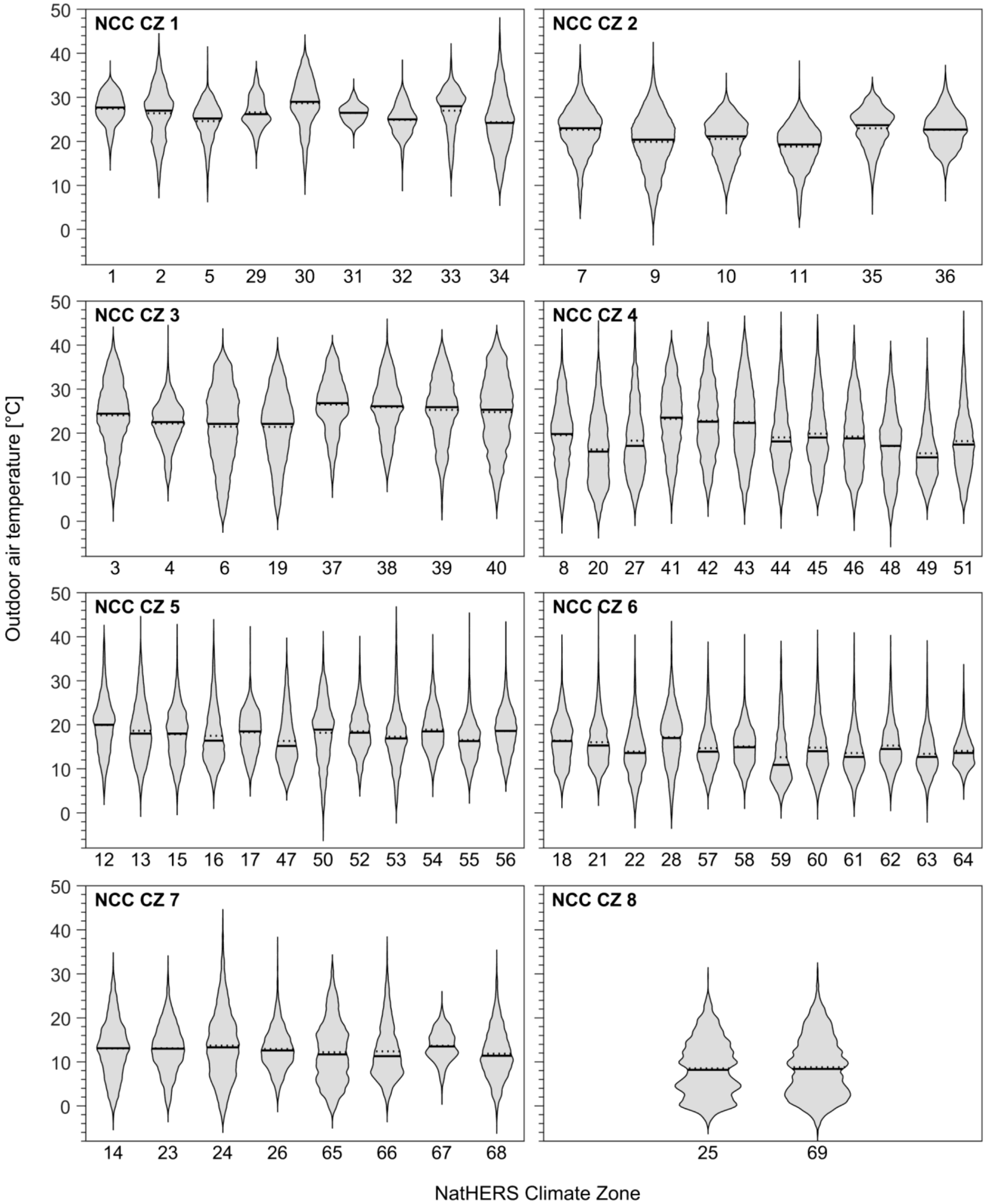

Figure 0-1: Distribution of outdoor air temperature in the climate files used to represent each of the NatHERS Climate Zones.

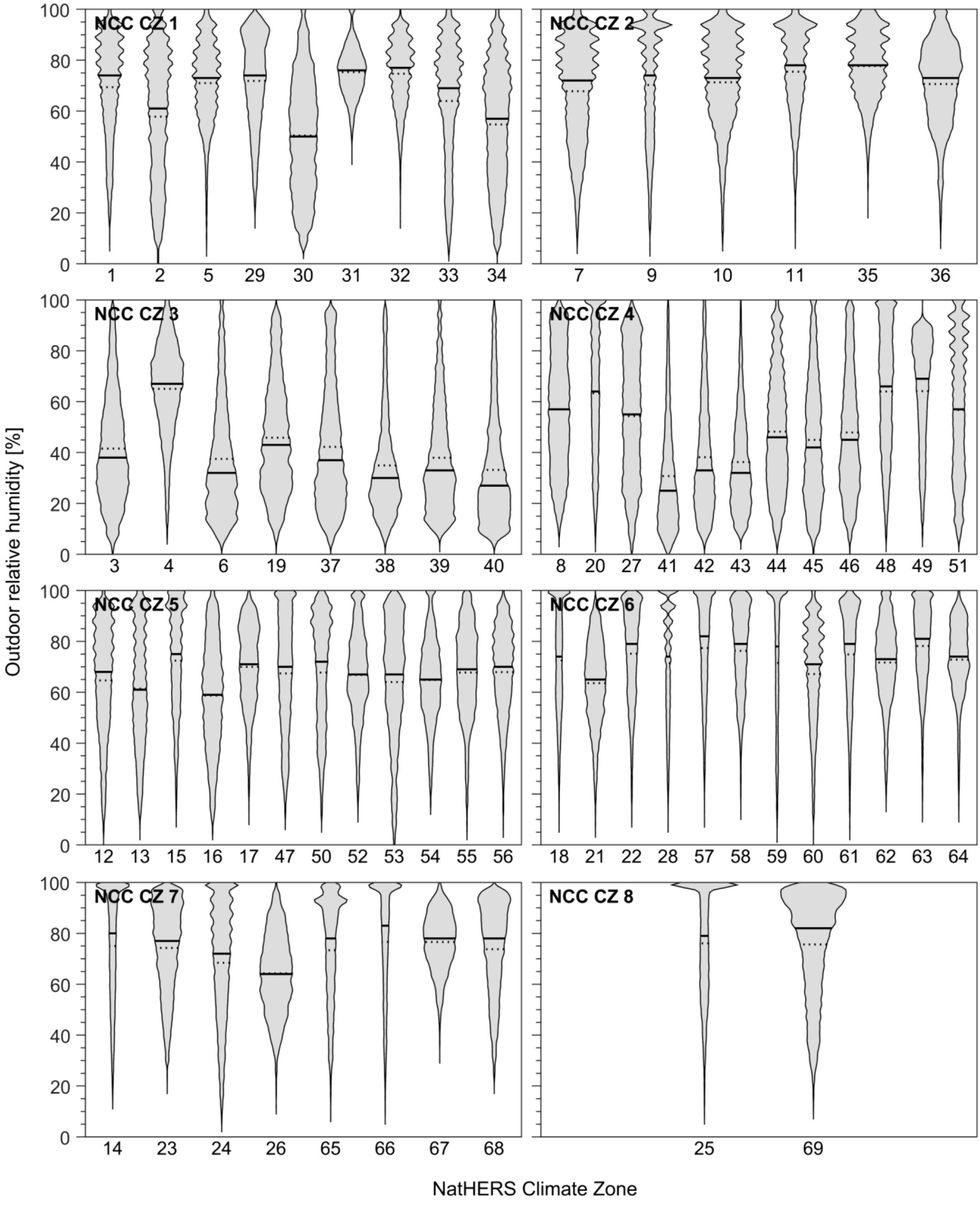

Figure 0-2: Distribution of outdoor relative humidity in the climate files used to represent each of the NatHERS Climate Zones.

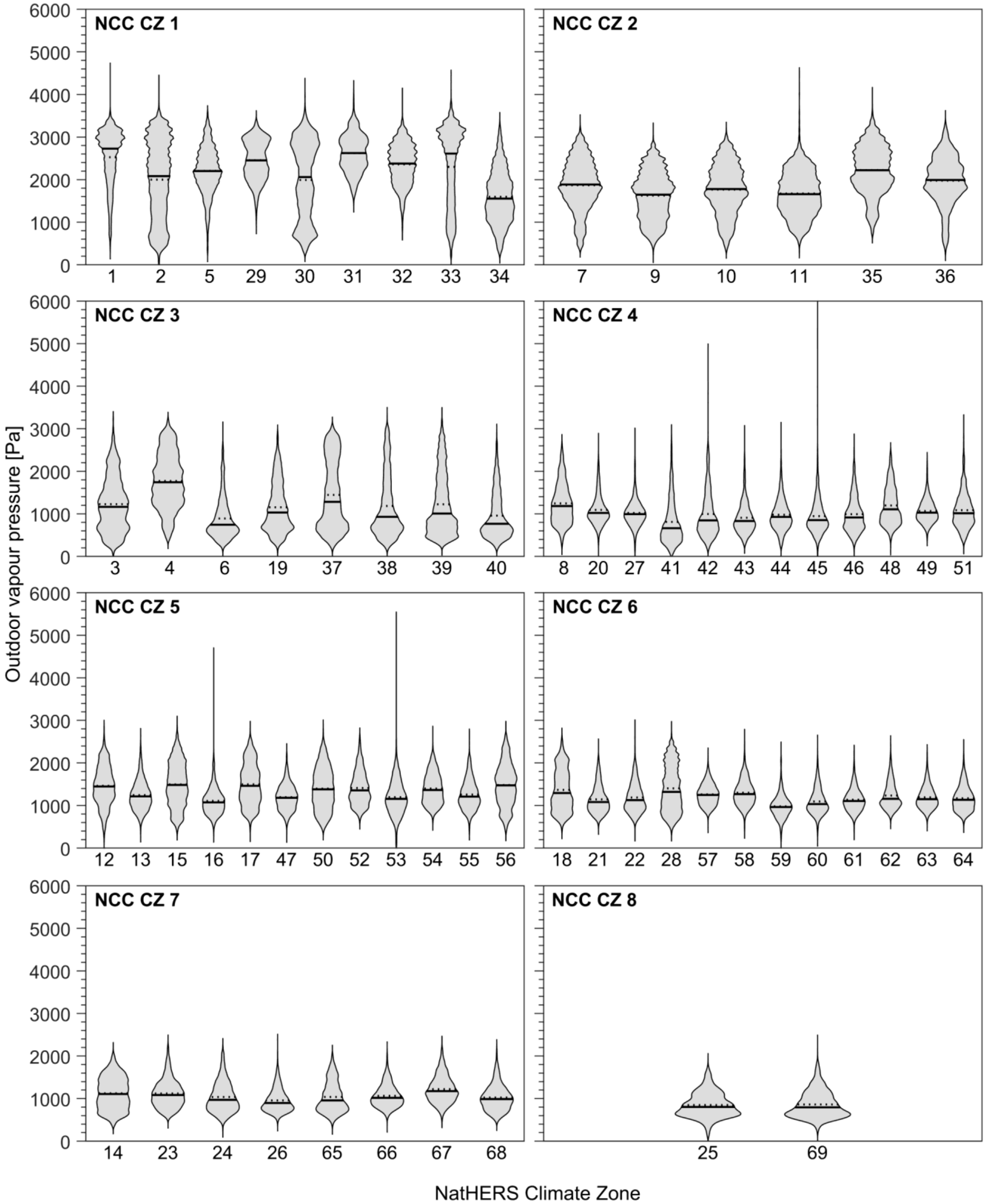

Figure 0-3: Distribution of outdoor vapour pressure in the climate files used to represent each of the NatHERS Climate Zones.

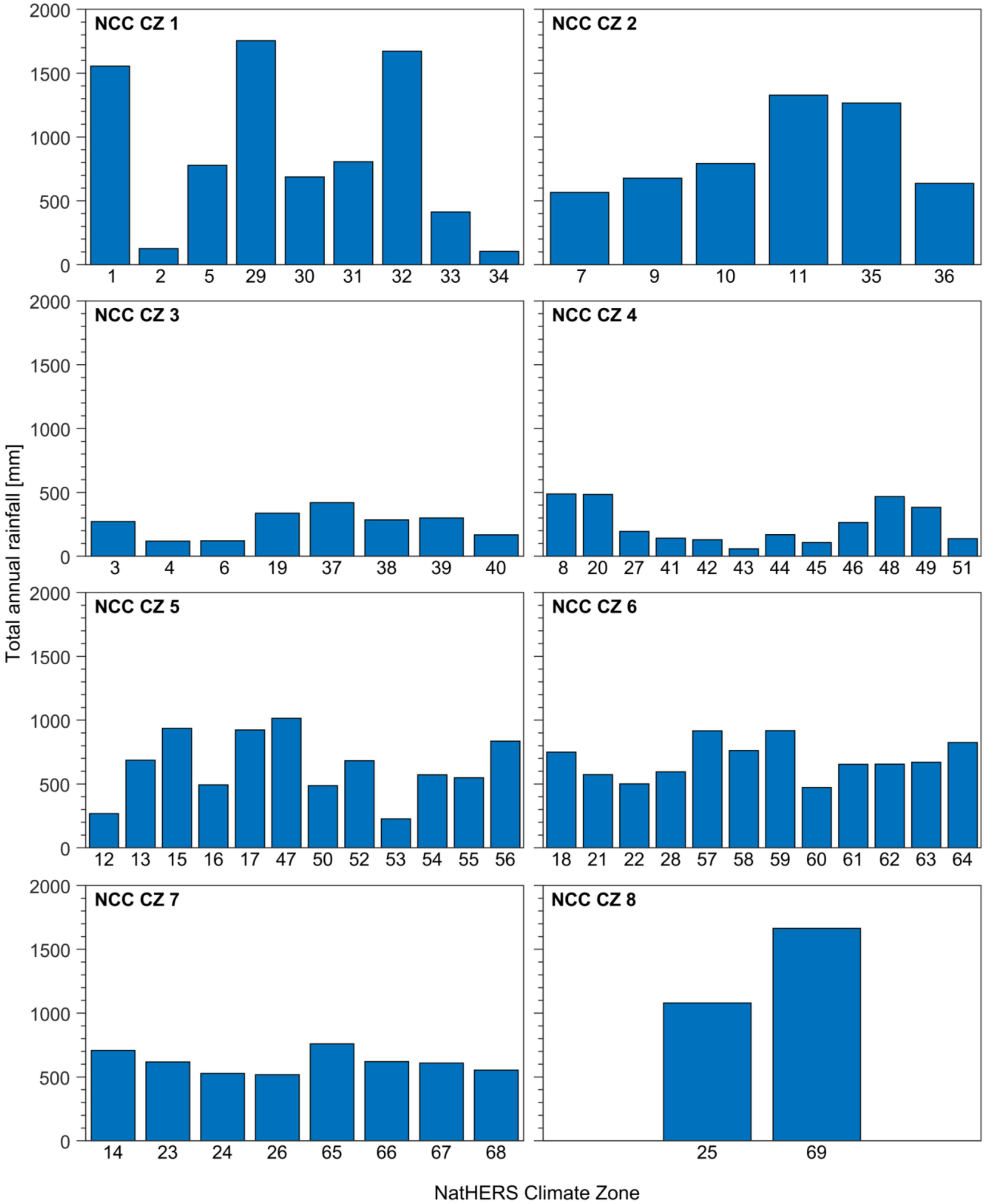

Figure 0-4: Total annual rainfall in the climate files used to represent each of the NatHERS Climate Zones.

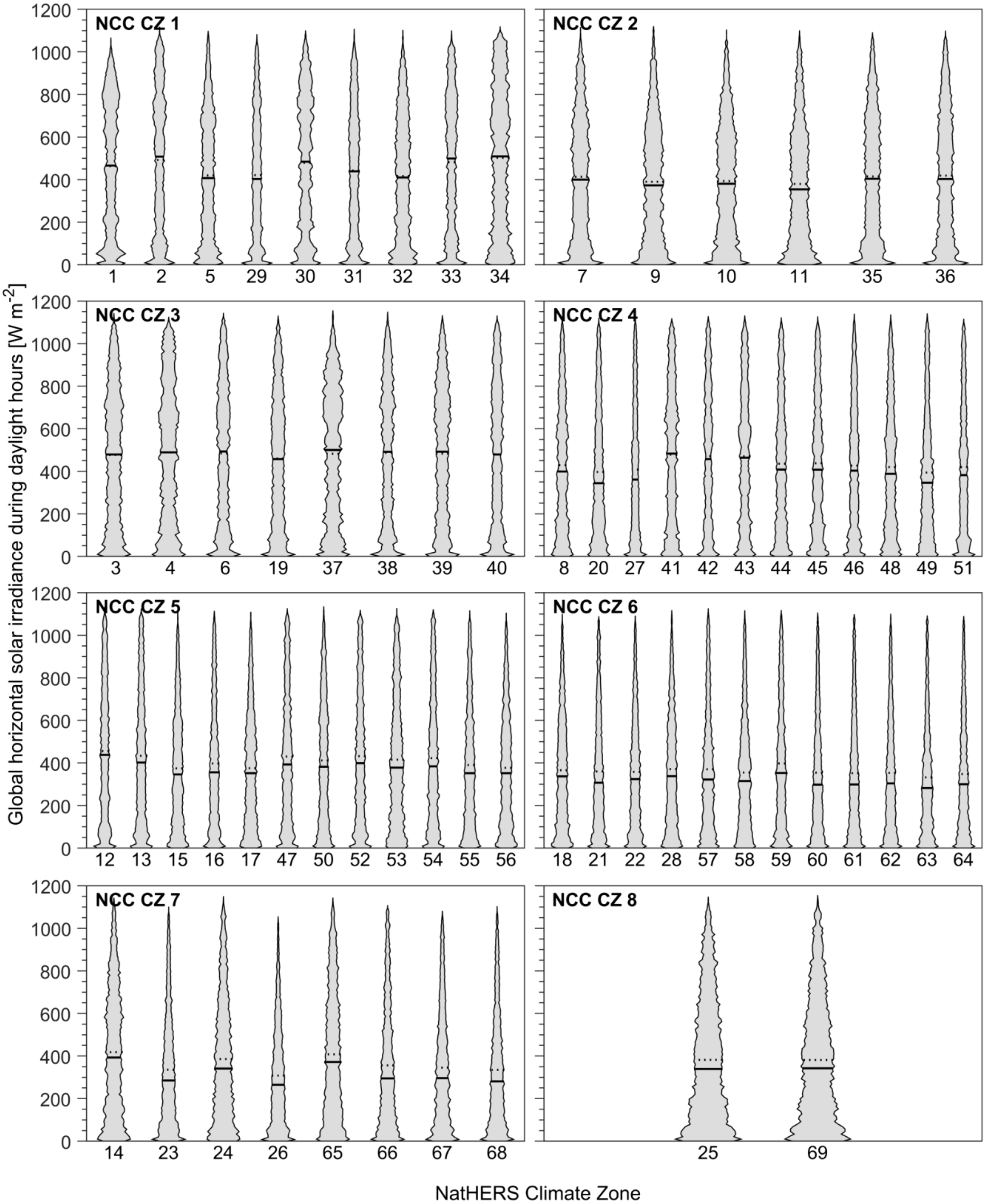

Figure 0-5: Distribution of global horizontal solar irradiance during daylight hours in the climate files used to represent each of the NatHERS Climate Zones.

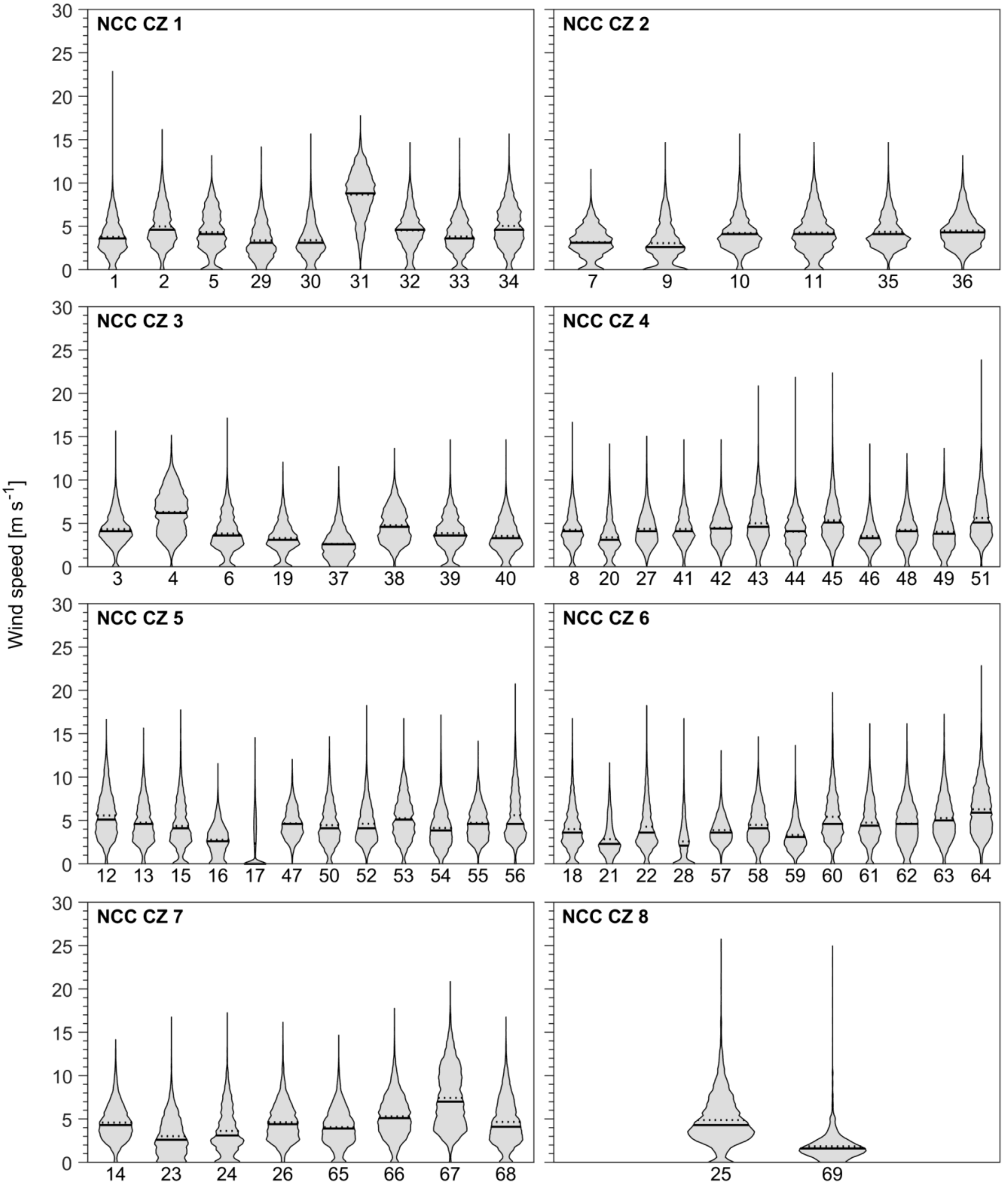

Figure 0-6: Distribution of mean hourly wind speed in the climate files used to represent each of the NatHERS Climate Zones.