A climate-based moisture index approach for hygrothermal analysis in Australia

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Abstract. In Australia, one-third of new constructions are affected by condensation and about 50% of buildings suffer from mould risk, mainly due to inappropriate design and management strategies. Despite the potential structural damage and serious health hazards, there is a lack of preventive moisture management strategies at the legislative level. The first hygrothermal management provisions were adopted in the National Construction Code only in 2019, with very general indications that correlate the breathability of the membranes with the climate zone. However, the building code identifies only eight zones for the entire Australia, which were originally developed for thermal analysis and energy efficiency provisions. The result is a coarse climate grid that clusters locations with highly variable humidity conditions. This paper undertakes a semi-empirical approach to identify whether the current climate zones are suitable for hygrothermal purposes. This research represents the first step towards an Australian-specific moisture risks management framework, and it advances the discussion about the suitability of the current hygrothermal design and construction policy and practices. The outcomes reveal the highly variable moisture indices obtained for the different representative cities, affirming the inappropriate use of existing climate zone clustering for hygrothermal assessment purposes.

1. Background

Moisture accumulation on building surfaces and within the walls is a widespread condition which, if not adequately managed, can lead to structural degradation by causing decay, deformity of materials and elements [1]. Furthermore, damp buildings pose a serious risk to indoor environmental quality and occupant health through dust mite proliferation, mould growth, and condensation [2].

At present, one-third of new Australian constructions suffer from surface and interstitial condensation, with up to 50% of buildings affected by dampness, which might eventually lead to mould growth [3]. The main cause lies in the existing knowledge gap within the construction and design industry about effective strategies to mitigate moisture risk [3], combined with a lack of a coherent body of research.

Condensation risk has only recently been introduced to the “Health and Amenities” section of the National Construction Code 2019 [4]. However, the code faces a fundamental problem of specifying appropriate climate zones in terms of moisture-related risk, mainly due to a lack of consensus on the use of climate input parameters and methodology, and a conclusive means to evaluate results obtained [1]. Currently, the code specifies eight climate zones as input for moisture management strategies, which were originally developed for energy efficiency provisions and thermal analysis, resulting in clusters of locations not refined enough for hygrothermal uses, as the same climate zone comprises areas with
highly variable humidity conditions [1]. Moreover, all recommendations are based on foreign research, in particular ASHRAE standard [5], without proper contextualization nor validation for Australian conditions.

This research responds to the compelling need of understanding whether the proposed climate zones can be suitable for hygrothermal assessments. It determines the most befitting methodology for developing a climate-based ranking system to assess hygrothermal performance and moisture risk potential of buildings in different locations throughout Australia. This research constitutes the first step towards the development of a new hygrothermal climate clustering for Australia as a basis for a robust hygrothermal risk mapping of the country. The outcomes of the study are intended to aid in the formulation of a design framework for moisture management with respect to local climate conditions.

2. Hygrothermal analysis and climatic input

Hygrothermal analysis is used to identify building service life and degradation expectancy, with a focus on heat and moisture movement through the building envelope [6]. Currently, there are two main approaches for undertaking a hygrothermal assessment, the first being construction dependent methods, while the second relies on construction independent methods.

Construction dependent methods investigate hygrothermal risks in relation to a specific construction type, simulating moisture movements within the building envelope. Although the results obtained are highly reliable, they are also particularly specific to the construction typology evaluated, making it difficult to extend the results to a broader framework which limits the scope of assessment [7].

Construction independent methods, on the contrary, characterize climate in terms of the potential risk of moisture-related issues for the building envelope, such as condensation risk and mould growth potential [5]. These climate-based methods are suitable for preliminary assessments and as a first indicator of potential moisture risk. Their potential lies in the possibility to highlight more risk-prone areas, where particular attention to hygrothermal assessment must be given [8]. The results can further scaffold the knowledge necessary to develop moisture management that comprises climate-specific indications.

This study uses a construction independent method to formulate a climate zoning system for Australia. Its ultimate goal is to identify whether the current climate zoning system is suitable to generate general moisture management provisions.

3. Methodology

Construction independent methods rely on the definition of a moisture reference year (MRY) as the key parameter. The MRY is the year most representative of moisture conditions of a specific location, and it considers the critical moisture loads on the building envelope, which sets a base requirement against damage caused by moisture. [6]

Several research methods have been implemented over the years to calculate MRY:

i. Geving simplified approach [9] which proposes the consideration of annual mean relative humidity to develop MRY.

ii. PI-factor method [10] which investigates the drying potential of wall construction through vapour pressure difference.

iii. ANK/ORNL-approach [11] which considers hygric potential and impact of airflow through a structure.

iv. Moisture Index method [12] which is the only method to implement both wetting and drying potential as indices.

v. Damage function method [5] which incorporates relevant damage indices, subject to change based on climate type, to show severity of the weather in relation to the durability of the structure.

Most of these methodologies require a certain construction type to be specified to measure the potential for damage. Based on the specific definition of each method, the Moisture Index approach [12] is identified as the most suitable for the purpose of this paper. Developed by Cornick et al., it uses both
wetting and drying indices to determine the MRY. The wetting index (WI) represents the impacts of annual wind-driven rain loads (WDR), while the drying index (DI) constitutes the annual potential evaporation based on vapor ratio differential between saturated and actual ambient air [12].

3.1. Site selection
To identify whether the current climate classification established by the NCC is suitable for hygrothermal purposes, at least two locations per climate zone have been selected. The locations have been identified based on population density and data availability. Climate data has been retrieved from the Bureau of Meteorology [13], which collects climate data within Australia. As shown in Table 1, a total of 15 cities spread across the country have been analysed in this study, after cross-referencing data collection with selected cities. The selection allows for comparison both across the continent and within the same climate zones.

| Zone | Climate type                        | City                      |
|------|-------------------------------------|---------------------------|
| 1    | High humidity summer, warm winter   | Broome, Darwin, Cairns    |
| 2    | Warm humid summer, mild winter      | Brisbane, Rockhampton    |
| 3    | Hot dry summer, warm winter         | Alice Springs, Tennant Creek |
| 4    | Hot dry summer, cool winter         | Kalgoorlie Boulder, Wagga Wagga |
| 5    | Warm temperate                      | Perth, Adelaide, Sydney   |
| 6    | Mild temperate                      | Melbourne, Mount Gambier  |
| 7    | Cool temperate                      | Canberra                  |

3.2. Data evaluation
As there was significant variation in hourly data availability prior to the 21st century, a 21-year dataset from 2000 to 2020 was compiled for all locations to maintain consistency. The data provided by the Bureau of Meteorology is original raw monitored data, consisting of sub-hourly and daily values for the relevant climatic parameters, including air and dewpoint temperature, relative humidity, air pressure, precipitation, wind speed and wind direction. The datasets have been analysed and converted to the required format through the appropriate methods, further discussed in the following sections.

3.2.1. Simple average. Parameters such as temperature, relative humidity, wind speed and air pressure have been averaged from sub-hourly to hourly values.

3.2.2. Vector resultant. For wind direction, the sub-hourly steradian values have been decomposed into two-directional vector components, with the resultant steradian as the hourly value. This allows to account for specific impacts of wind speed on corresponding wind direction per sub-hour.

3.2.3. Cumulative precipitation. Precipitation data was received as a cumulative sub-hourly format which reset every 24 hours. This data has been extracted as hourly values, and further reduced to precipitation amount per hour.

3.2.4. Interpolation. Missing hours in the dataset have been filled in by interpolation of existing data, and by referencing to daily values provided by BOM. It is worth noticing that the missing data amounted to less than 4% in any location, which allows for a statistically acceptable gap.

3.3. Wetting Index
The wetting index is calculated as wind-driven rain (WDR) load, which is the amount of rain striking a vertical surface, according to the following equation specified in ASHRAE 160-P [14]:

\[ R_{WDR} = F_E \times F_D \times 0.2 \times R_h \times V_{10} \times \cos \theta \]
where $R_{\text{WDR}}$ is the rain deposition on a vertical wall surface (kg/m$^2$.h); $F_E$ is the rain exposure factor; $F_D$ is the rain deposition factor; 0.2 is an empirical constant (kg.s/m$^3$.mm); $R_h$ is rainfall intensity on a horizontal surface (mm/h); $V_{10}$ is the hourly average wind speed at 10 m height (m/s); and $\theta$ is the angle between wind direction and normal to the wall.

As the exposure factor $F_E$ is dependent upon surrounding topography and height of the building, these two variables were established for each location. Height of the building has been fixed as below 10m for all locations, as low-rise building represents the majority of the building typology in Australia [15]. To represent real world conditions in a more accurate manner, the type of exposure is selected as either severe or medium with reference to the wind regions allocated in NCC Volume II [16], which classifies areas in Australia according to cyclonic wind exposure.

| Building height (m) | Type of Exposure category |
|---------------------|---------------------------|
| <10                 | Severe | Medium | Sheltered |
|                     | 1.4    | 1.0    | 0.7       |

For the deposition factor $F_D$, the maximum value according to ASHRAE 160-P [14] has been used to simulate the most severe condition, representing walls subject to rain runoff, which is $F_D = 1.0$.

The annual WDR is determined as the sum of the hourly $R_{\text{WDR}}$, calculated separately for the 8 wall orientations, both cardinal and ordinal. To propagate the worst-case scenario, the orientation with the maximum annual WDR is selected to represent the Wetting Index of that particular year. As a result, the worst wetting potential for each year is taken forward to determine the Moisture Index.

### 3.4. Drying Index

The Drying Index is a measure of potential evaporation, which is calculated as the difference between humidity ratio at saturation and humidity ratio of ambient air, as mentioned in Cornick et al. [12]

$$\Delta w = w_{\text{sat}} (1 - \mu)$$

where $\Delta w$ is the hourly differential (kg water/kg air); $w_{\text{sat}}$ is the humidity ratio at saturation; and $\mu$ is the degree of saturation. Furthermore:

$$\mu = w_{\text{ambient}} / w_{\text{sat}}$$

The annual Drying Index is simply a sum of $\Delta w$ for that year (kg water/kg air year), as follows:

$$DI = \sum_{h=1}^{k} \Delta w$$

where $k$ is the number of hours in that year.

To establish the drying potential, vapor pressure at ambient air level and saturation levels had to be extracted from the available climate data. As hourly dry-bulb temperature, dewpoint and air pressure were known, these have been used to determine the required humidity ratios, as per calculations mentioned by NOAA [17]:

$$w = 0.622 \times \frac{V_{p}}{(P - V_{p})}$$

where $w$ is the humidity ratio of interest, ambient or saturation; $V_p$ is the corresponding vapor pressure; and $P$ is the air pressure.

$$V_{p} = 6.11 \times 10^{0.002374 T}$$

where $T$ is dewpoint temperature for ambient $V_p$; and air temperature for saturation $V_p$. 
3.5. Moisture Index

The wetting and drying indices are calculated independently and therefore have different units, which are then normalized according to the following function:

\[
I_{\text{normalized}} = \left( I - I_{\text{min}} \right) / \left( I_{\text{max}} - I_{\text{min}} \right)
\]

(7)

where \( I \) represents the index of interest.

The Moisture Index is then calculated for each year as follows:

\[
MI = \sqrt{W_{I_{\text{normalized}}}^2 + (1 - D_{I_{\text{normalized}}})^2}
\]

(8)

This calculation process is performed for 21 years of the hourly climate dataset for each location. The resulting Index is then ranked, from highest to lowest value based on its severity, to determine the MRY that corresponds to the 10th-percentile year for each city. This is considered to be the most representative year for severe moisture stress on a building envelope.

4. Results and discussion

Results show that the different representative cities are characterized by highly variable indices. Fig. 1 reports the drying and wetting indices as maximum, minimum and mean values for each. Alice Springs, Tennant Creek, Kalgoorlie-Boulder, have a higher drying potential and low wind-driven rain, making them less vulnerable to moisture damage. Clearly, these reflect a climate analysis only, as a primary indicator for hygrothermal risks. Occupancy patterns, design and construction quality may influence the mould occurrence probability and would require a thorough analysis during the design stage, when assumptions related to construction technology and building use are known.

Tropical climates, such as Broome, Darwin and Cairns show a higher range of WDR distribution, indicated by the difference between the maximum and minimum values. As WI values are from all 8 orientations, high variability in its range indicates a strong directionality of wind-driven rain. This ultimately influences only certain orientations, resulting in a greater disparity among values. Contrarily, for other locations, the WDR direction is more evenly distributed, leading to a greater susceptibility to damage from precipitation across multiple orientations.

Figure 1. Drying (left) and Wetting (right) maximum, mean and minimum index distribution across cities.
Figure 2. WDR Roses depicting magnitude and direction for selected MRY, worst case WDR, and mean WDR. Units: kg/m².h x 10³.
Fig. 2 shows the WDR roses for the worst-case scenario, the selected 10th percentile year (MRY), and the mean WDR for each city. Results significantly differ based on the orientations, which indicates that WDR may be a useful tool in determining risk-prone orientations for the design phase, which may possibly be essential in preventing moisture damage. The figure clearly shows the impacts of the surrounding topography, especially for coastal cities, where the predominant orientation faces the respective coastal wind.

The results also highlight the significant contribution of the drying potential for determining the most severe year for moisture damage, as it allows for years with less severe Wetting Index to become highly vulnerable and be selected as MRY. This is true for a few locations, where MRY is also the worst WDR year. This further confirms the importance of considering drying potential for hygrothermal analysis.

An important aspect of determining potential evaporation is the solar radiation and wind influence. It can be inferred that the North orientation will generally have the highest drying potential given the solar exposure, however, this is a conclusion with limitations and might not portray on-ground conditions accurately. Zhou et al. [18] introduce an alternate method using Penman’s equation [19] which incorporates radiation values. However, as calculations were carried out on a daily instead of hourly timeframe, the benefits need to be examined in more detail. Additionally, The WDR calculation does not consider recurrence or impact of the previous year, which may significantly alter the results.

Table 3 lists the three worst-ranked years for each city with reference to the Moisture Index, where the 10th percentile year is represented by the 2nd ranked year.

| City            | Rank | Year | MI  | City            | Rank | Year | MI  |
|-----------------|------|------|-----|-----------------|------|------|-----|
| Broome          | 1    | 2000 | 1.1486 | Cairns         | 1    | 2010  | 1.3018 |
|                 | 2    | 2018 | 1.1009 |                | 2    | 2004  | 1.1464 |
|                 | 3    | 2004 | 0.9108 |                | 3    | 2006  | 1.1263 |
| Cairns          | 1    | 2010  | 1.3018  | Brisbane       | 1    | 2013  | 1.3032 |
|                 | 2    | 2004  | 1.1464  |                | 2    | 2008  | 1.1754 |
|                 | 3    | 2006  | 1.1263  |                | 3    | 2010  | 1.1425 |
| Rockhampton     | 1    | 2010  | 1.4070  | Alice Springs  | 1    | 2010  | 1.4142 |
|                 | 2    | 2014  | 1.1426  |                | 2    | 2000  | 1.1419 |
|                 | 3    | 2013  | 1.0410  |                | 3    | 2001  | 1.0568 |
| Tennant Creek   | 1    | 2010  | 1.3125  | Kalgoorlie-Boulder | 1    | 2000  | 1.3663 |
|                 | 2    | 2001  | 1.2348  |                | 2    | 2011  | 1.1355 |
|                 | 3    | 2011  | 1.2340  |                | 3    | 2014  | 1.1114 |
| Wagga Wagga     | 1    | 2011  | 1.3427  | Perth           | 1    | 2005  | 1.2423 |
|                 | 2    | 2012  | 1.2862  |                | 2    | 2003  | 1.1463 |
|                 | 3    | 2010  | 1.2000  |                | 3    | 2007  | 1.0978 |
| Adelaide        | 1    | 2016  | 1.4142  | Sydney          | 1    | 2011  | 1.2799 |
|                 | 2    | 2001  | 1.0254  |                | 2    | 2001  | 1.1494 |
|                 | 3    | 2003  | 1.0150  |                | 3    | 2015  | 1.1397 |
| Melbourne       | 1    | 2010  | 1.2288  | Mount Gambier   | 1    | 2016  | 1.3619 |
|                 | 2    | 2020  | 1.1012  |                | 2    | 2011  | 1.0555 |
|                 | 3    | 2011  | 1.0762  |                | 3    | 2020  | 0.9443 |
| Canberra        | 1    | 2010  | 1.3242  |                | 1    | 2010  | 1.3242 |
|                 | 2    | 2012  | 1.1167  |                | 2    | 2012  | 1.1167 |
|                 | 3    | 2020  | 1.0718  |                | 3    | 2020  | 1.0718 |

The results illustrate the variability and extent of moisture damage, indicating that the current climate zoning system is unable to capture the hygrothermal stress differences, misrepresent the risk severity across Australia, and therefore fail to provide a consistent and robust climate clustering. A refined hygrothermal mapping may aid in the definition of provisions that can be tailored to the gravity of the risks, rather than generalized indications based on thermal zones.
5. Conclusion

Australian hygrothermal standards and codes currently fall far behind any other developed country, with only a few general provisions about membrane breathability [4]. This paper demonstrates that the climate zones at the basis of these provisions are unsuitable for their purpose, failing to provide a robust design framework. On the other hand, the proposed climate index does not intend to substitute case-specific hygrothermal assessments or simulations, but rather generate an Australian hygrothermal risk map aimed to identify areas of high moisture-related risks as a basis, with the ultimate goal to provide clustering for tailored hygrothermal policies.

Furthermore, this paper unveils a systematic failure in the way climate data is collected, which threatens the development of a robust hygrothermal mapping. Indeed, the dataset utilized was incomplete and not available for the preferable 30-year range. Satellite data from NOAA could serve as an alternative, to assemble a more complete dataset.

In past years, much attention has been given to energy efficiency factors, highlighted by the accuracy in both the data capture and documentation of climatic parameters usually used in thermal calculations, while overlooking factors key for hygrothermal assessments, such as wind speed, wind direction, rainfall and solar radiation. This finding calls for an urgent update of the way we currently monitor climate parameters, necessary for the definition of robust climate clustering based on moisture risk severity.

This paper scaffolds the knowledge for future research steps, aimed at establishing a moisture-risk based climate clustering system that can be validated and supplemented by hygrothermal simulations, which would aid in establishing specific indices for mould growth and condensation potential by considering construction systems and internal environment conditions.

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