The evaluation of real-time indoor environment parameters measured in 297 Chilean dwellings

Constanza Molina[1,2], Amy Jackson[1] and Benjamin Jones[*1]

1 Department of Architecture and Built Environment,
University of Nottingham
Nottingham, NG7 2UH, UK.
**Corresponding author:*
benjamin.jones@nottingham.ac.uk

2 Escuela de Construcción Civil,
Pontificia Universidad Católica de Chile
Avda. Vicuña Mackenna 4860, Santiago,
7820436, Chile

ABSTRACT

People spend the majority of their time in their own homes and so the indoor environmental conditions are an important determinant of population health and wellbeing and have economic consequences. Chile is undergoing rapid economic growth and is managing its national energy demand to minimize its greenhouse gas emissions. Its housing stock is growing rapidly, and is responsible for 15% of national energy demand. Accordingly, there is a need to understand the performance of the stock by measuring parameters that indicate air quality, thermal comfort, and energy demand. This study is a preliminary examination of real-time indoor and outdoor measurements of air temperature made in 297 dwellings during 2016 and 2017 as part of the Red Nacional de Monitoreo de Viviendas (ReNaM) program, implemented by The Ministry of Housing and Urbanism of Chile. Indoor temperatures are generally found to be cold when compared to the European adaptive model of thermal comfort, EN 15251. However, they are above temperature thresholds found to affect negatively the health of vulnerable groups for 78% of the time. There are significant seasonal differences in indoor air temperature but modest differences between day and night time temperatures. The winter temperatures are low, indicating limited effective heating, and households of low socio-economic status are colder than those of mid and high status. There is no evidence of mechanical cooling in the summer.

KEYWORDS

Thermal comfort, adaptive comfort, houses

1 INTRODUCTION

People spend around 70% of time within their own home (Koehler *et al.*, 2018) and so the quality of the indoor air is important. Controlling the indoor air temperature is important for the thermal comfort of occupants, and although varying temperatures may provide thermal alliesthesia (Cabanac, 1971), significant winter variability is associated with respiratory mortality and hospitalizations (Sun *et al.*, 2018), and summer overheating is linked to increased mortality of vulnerable sub-populations, such as the elderly and the very young (Taylor *et al.*, 2018). Therefore, it is important to manage the thermal environment to simultaneously satisfy the occupants, preserve their health, and save energy and corresponding greenhouse gas (GHG) emissions. Many developed countries are implementing retrofitting programs to help meet GHG reduction targets. For example, investments in heating and insulation in three large communities of houses in New Zealand showed that occupants had fewer cold-related health problems, and that the houses were more energy efficient (Howden-Chapman *et al.*, 2012). However, in countries that are industrializing and increasing their technological infrastructure, their national energy demand and GHG emissions tend to increase over time (González-Eguino, 2015) and so it is important to manage them and decouple them from economic growth using a regulatory framework.

Chile is a South American country whose economy is ranked 42nd largest in the world (World Bank, 2016) and had an average annual growth rate of 4.65% (OECD, 2018) between 2003 and 2013. Its houses are responsible for 15.4% of the total final consumption of national energy demand (IEA, 2014), although the contribution of specific services, such as space heating or cooling, is currently unknown. The Chilean housing stock comprises 6.5 million dwellings, where 80% are houses and 18% are apartments (INE, 2018). The majority are located in urban areas, with 57% in and around the capital city of Santiago. They have high occupancy densities when compared to international norms, and 20% are overcrowded. Dwelling energy demand is often correlated with floor area, and over the last 27 years the mean floor area of new dwellings has increased by around 40%, from 57m^2 in 1990 to 82m^2 in 2015 (INE, 2016). In order to understand the performance of its stock, The Ministry of Housing and Urbanism of Chile (MoH) has implemented a monitoring program of houses known colloquially as the Red Nacional de Monitoreo de Viviendas (the National Network of Housing Monitoring), or ReNaM. Real-time sensors are located in 299 houses in five towns and cities measuring air temperature, relative humidity, sound pressure level, and CO_2.

This paper evaluates the outputs of ReNaM's to evaluate the indoor environment in Chilean houses. The focus is restricted to the impacts of temperature on thermal comfort and its relationship with the socioeconomic status of Chilean households. Section 2 describes the ReNaM monitoring network, its equipment, and dataset. Section 3 assesses the thermal conditions found in the monitored dwellings using a model of thermal comfort, any seasonal variability, and relationships between temperatures and groups of dwellings and households, such as dwelling location and household socio-economic status. Section 4 discusses the results.

2 METHOD

2.1 Measurement Locations

Chile is a continental territory with a north to south length of 4,300km and an average width of 177km. Its mean annual air temperature varies by up to 6°C laterally and by more than 15°C longitudinally, and differences in relative humidity are similarly well defined (Castillo, 2001). Five locations were chosen by the MoH to reflect this climatic variation (see Figure 1) and real-time sensors (see Section 2.2) are currently installed and operational in 299 houses located in the north (n=28), south (n=60), and centre (n=211) of the country. Most are located in the metropolitan and capital region of Santiago de Chile (n=150). The sample is not statistically representative of the housing stock (Molina *et al.*, 2017), but statistical methods can be applied to generalise findings. Therefore, the data are expected to identify broad trends in indoor environment quality and highlight areas worthy of more detailed investigations.

Figure 1: Chile (red) and the five ReNaM monitoring locations.

The northern city of Antofagasta lies on the Tropic of Capricorn and has mean daily dry bulb air temperatures, $\bar{T}_o$ (°C), between $12.73 \leq \bar{T}_o \leq 21.75$ (Meteotest, 2017). Valparaiso & Viña del Mar are coastal towns located in the centre of the country with $4.58 \leq \bar{T}_o \leq 26.23$. Santiago is the national capital city. It is inhabited by 41% of the population, its stock is comprises 2.4 million houses (INE, 2018), and $4.08 \leq \bar{T}_o \leq 24.41$. Temuco is located 700km south of Santiago where $1.28 \leq \bar{T}_o \leq 21.49$. Coyhaique is a small town located 1400km south of Santiago in the Patagonia region where $-8.13 \leq \bar{T}_o \leq 26.23$. All five locations are polluted (MMA, 2017; Jorquera & Berraza, 2013; Toro *et al.*, 2014; Koehler *et al.*, 2019). Antofagasta is contaminated with NOx and SO_2 from local foundries, and the other locations have ambient $PM_{2.5}$ (particulate matter with a diameter of $\leq$2.5μm) concentrations that exceed WHO thresholds attributable to vehicles, industries and wood burning. Santiago's urban density and meteorological conditions also contribute to its pollution.

The monitoring was preceded by a survey that provides information about the location (region, town/city, and commune), the dwelling (type, construction year, storeys, floor area, orientation, envelope materials, number of windows, glazing properties, and heating system), the householders (income (see Table 1), energy bills, health issues), and behaviours (heating months, weekday and weekend occupancy, smoking).

Table 1: Classification of Socio Economic Level. Sources: Renam, 2018; INE, 2003.

Family monthly income* **(Chilean Pesos, CLP)**	**Socio-economic level (ReNaM)**	**Corresponding socio-economic decile (National classification)**
>CLP 1 450 000	high	10
CLP 550 000 – CLP 1 450 000	medium	8-9
< CLP 555 000	low	1-7

**1 UK Pound ≡ 872 Chilean Pesos; 1 US Dollar ≡ 666 Chilearn Pesos.*

2.2 Equipment

The *Netatmo* weather station (Netatmo, 2018) is a *consumer* grade device that comprises indoor and outdoor modules, and requires little or no maintenance by the host. Both record dry bulb air temperature and relative humidity, but the indoor module also measures noise, and CO_2. They are factory calibrated. The sensors are located away from direct heat sources in the living room, although some are located in a bedroom. They sample and upload the data to an online database every 30 minutes. Measurements started in 2016 and are ongoing. The platform is accessible online (ReNaM, 2018) to registered users and contains the approximate location of each sensor and all surveyed and measured data.

2.3 Assessing Occupant Comfort

Thermal comfort is not solely determined by the indoor air temperatures and can be influenced by personal and environmental factors (ASHRAE, 2010), making it subjective. Chilean dwellings generally use windows for ventilation, and are *free running* during the summer. Therefore, occupants are expected to take adaptive measures to maintain their comfort. During the winter, the most common heating system is a stove (INE, 2003).

Perez-Fargallo *et al.* (2018) investigated the application of international adaptive models of thermal comfort, including EN 15251 (BSI, 2007), to low income families in the south of Chile (14 dwellings; 121 occupants). The dwellings were monitored for 7 months during the winter and occupant thermal preferences were surveyed. The measurements were compared to EN 15251 and showed that the occupants of these dwellings were more tolerant to cold temperatures than the model predicts. They then propose a model of adaptive thermal comfort that solely applies to social dwellings located in the south of Chile. Section 2.1 shows that only 60 ReNaM dwellings are located in the south and so we apply the European adaptive model described by EN 15251 (BSI, 2007) to all dwellings. The thresholds of comfort (°C) are given by

$$T_{C_{max,min}} = 0.33T_m + 18.8 \pm X \tag{1}$$

where $X = 2$°C is appropriate for a free running naturally ventilated spaces, and T_m is the running mean of the ambient air temperature where

$$T_m = (1 - \alpha_{rm})T_{E-1} + \alpha_{rm}T_{rm-1} \tag{2}$$

Here, $\alpha_{rm} = 0.8$ is used as the running mean constant, T_{E-1} (°C) is the previous day's daily mean ambient temperature, and T_{rm-1} (°C) is the previous day's running mean temperature.

Many households are in energy poverty, where they spend more than 10% of their income on heating to achieve a satisfactorily warm environment (Boardman, 1991). This is particularly problematic in the south of the country where 61% of households are in energy poverty (Reyes *et al.*, 2019). Therefore, this is assessed in Section 3.

2.4 Data Processing and Statistical Analyses

To date, over 100 million data entries have been recorded. The raw dataset comprises measurements from all houses and was parsed using bespoke MATLAB® code (Mathworks, 2018) to allocate it to individual dwellings, and to remove duplicate entries. The statistical tool *R* (R Core Team, 2018) was used to interrogate the data and provide summary statistics. In 45% of dwellings data was either corrupted or missing for some periods of time. Dwellings were removed from the analysis if they had missing data for the entire monitoring period, leaving a sample of 297 dwellings.

To test the integrity of the measured data and to choose appropriate statistical tests, tests of normality are applied to the dataset in Section 3. Analysis of Variance (ANOVA) or Kruskal-Wallis (*ks*) tests were applied performed to normally and non-normally distributed data, respectively. When there is a large quantity of data the West reference criteria for a substantial departure from normality are used rather than a *ks*-test (West *et al.*, 1995). A *post hoc* analysis tested the nature of any differences. All tests use a 5% significance threshold.

A coefficient of variance, CV, is the standard deviation value of interest of a group divided by its mean. It is used to compare difference parameters and consistency in the results. A value CV>1 shows that it is highly variable.

3 RESULTS

3.1 Indoor Thermal Conditions

Figure 2 is cumulative distribution function (CDF) of internal and external air temperatures measured inside and outside of all 297 dwellings. It shows that the ambient air temperatures varied between 0-35°C and indoor temperatures varied between 5-30°C. Median temperatures for winter day and night times are 17.0°C and 16.3°C, respectively, and 24°C and 23.5°C for summer day and night times, respectively.

Collins (1993) suggests that, for vulnerable groups, temperatures below 16°C increase the risk of respiratory diseases; below 12°C may cause cardiovascular strain from cold; and below 6°C may cause the failure of thermoregulation and hypothermia. The WHO recommends indoor temperatures of 18-21°C for clothed sedentary occupants to avoid potential health risks (WHO, 2007). These thresholds are mapped onto Figure 2 and show that Collin's thresholds are achieved around 78% of the time. The WHO limits are met around a third of the time.

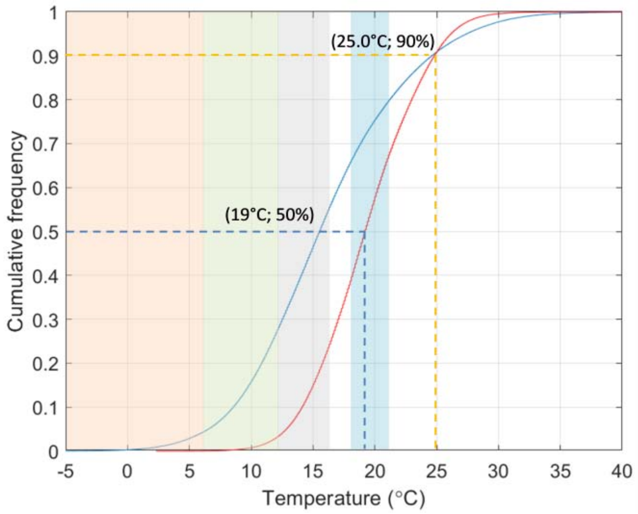

Figure 2: CDF of internal (red) and external (blue) air temperatures for all dwellings. Orange, green and grey areas correspond to Collins's (1993) health risk thresholds. The blue area shows WHO limits. The dashed blue line shows the median of 15°C and the dashed orange line shows that indoor median of 90% of the time the indoor air temperature is higher than the outdoor air temperature.

The CIBSE (CIBSE, 2015) recommends an upper limit of 25°C and 23°C in the living rooms and bedrooms respectively, of naturally ventilated dwellings in the UK. It defines an overheating dwelling as one where the indoor operative temperature is 3°C above these limits. Here, this only occurs around 10% of the time, by considering the operative temperature equivalent to the air temperature. Figure 3 illustrates how using a daily mean temperature as a key indicator can disguise both the extremes of temperatures and variance between them. A knowledge of occupant exposures to low and high temperatures may help to identify adverse conditions and health consequences.

3.2 Seasonal and daily variability

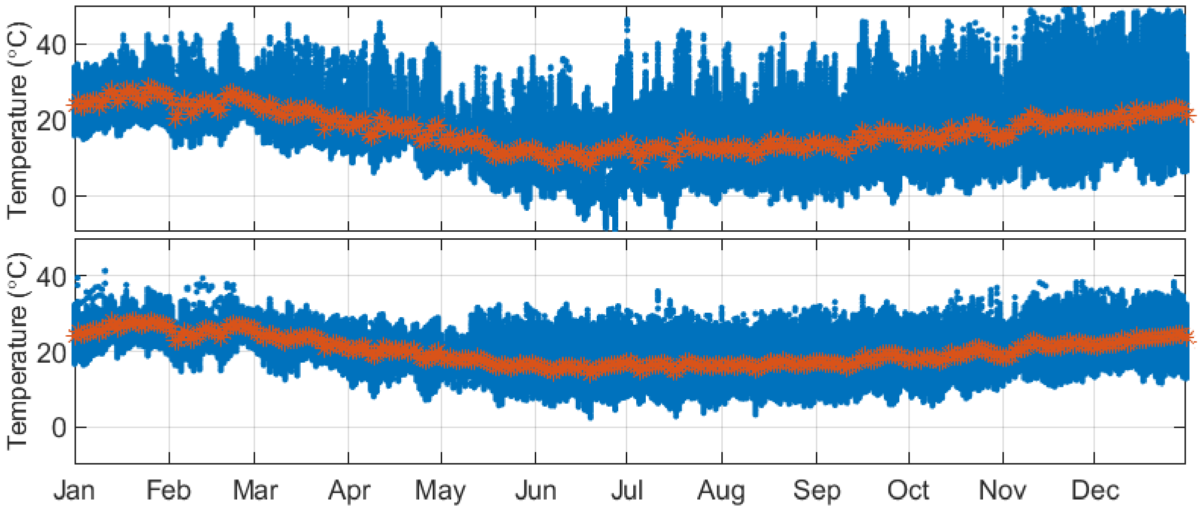

Figure 3: Sampled air temperatures (blue) outside (top) and inside (bottom) with daily average temperatures (orange) in all 297 houses during 2017.

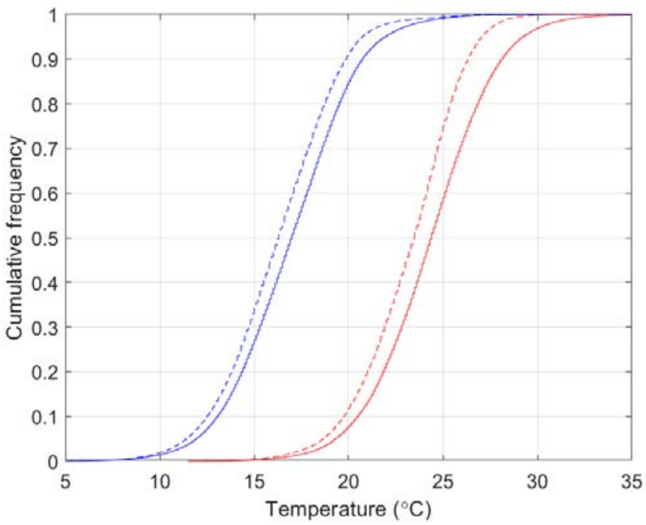

Figure 4: Internal temperatures (continuous) and ambient (dashed) in winter (blue) and summer (red).

Analysis of the summer and winter temperatures shows seasonal differences and highlights their impact on thermal comfort. Winter is considered to be between 21st June and 21st September. The data is divided further into day and night times where a day starts at 7am and finishes at 10pm. Figure 4 shows that the seasonal variation is large, but Figure 5 shows that day and night temperatures differences for each season are small. The low temperatures in the winter suggest that there is limited effective winter heating in the dwellings. Heating only when dwellings are occupied should be reflected by bi or multi-modal distributions. A West reference criterion indicates that the groups of indoor temperatures are each moderately normal, except for the summer night time data and so it is likely that heating was either continuous or non-existent and the dwellings are free running. Further analysis is required.

The low night time air temperatures may help the occupants sleep; for example, CIBSE (2015) shows that temperatures as low as 12°C can improve sleep quality, although occupants require appropriate bed-clothing.

3.1 Socio-Economic Differences

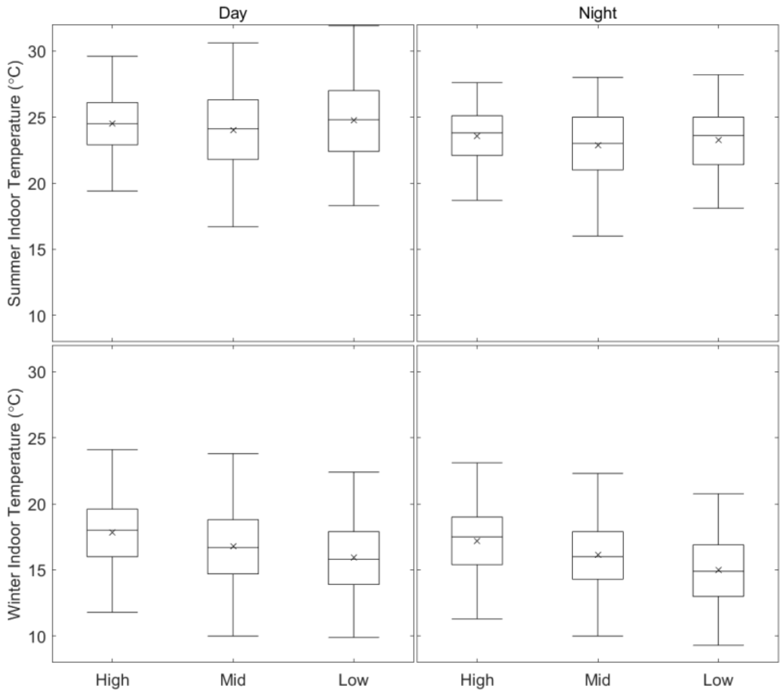

Figure 5: A comparison of winter and summer, day and night, indoor air temperatures by socio-economic status.

To investigate whether the socio-economic status of each house has an impact on thermal comfort, the data was further divided into the three socio-economic level categories given in Table 1; see Figure 5. An ANOVA test is used to determine if the results obtained for thermal conditions from different socio-economic classes are significantly different from each other. It shows that there is a casual inference that different socio-economic levels result in different mean indoor air temperatures, especially for winter days and nights (all *p*-values <<0.05). A further *post hoc* test highlights the exact nature of the difference. In the summer day time, the high socio-economic class is significantly different to the low and middle classes, but the middle and low classes are not significantly different from each other. In the summer time there is no difference between the classes, whereas during the winter, all socio-economic classes are significantly different from each other. The magnitude of this significance were calculated using the means of the two variables being compared and contrasted with *Cohen's r* thresholds (Cohen, 1977). Between high and low socio-economic classes, medium and high effects are found for winter days and nights respectively.

3.2 Analysis of Groups

Thermal comfort boundaries are calculated as a function of the running mean using Equation (1). The outdoor running mean is calculated using Equation (2) and measured outdoor air temperatures. Figure 6 shows the indoor air temperatures in a single ReNaM dwelling during 2017. House 39 is a new heavy weight apartment located in Santiago occupied by a household with high socio-economic status. It is used for illustrative purposes because it is one of two dwellings that has the highest percentage of measurements within the thermal comfort boundaries. Coloured dots show day and night indoor temperatures.

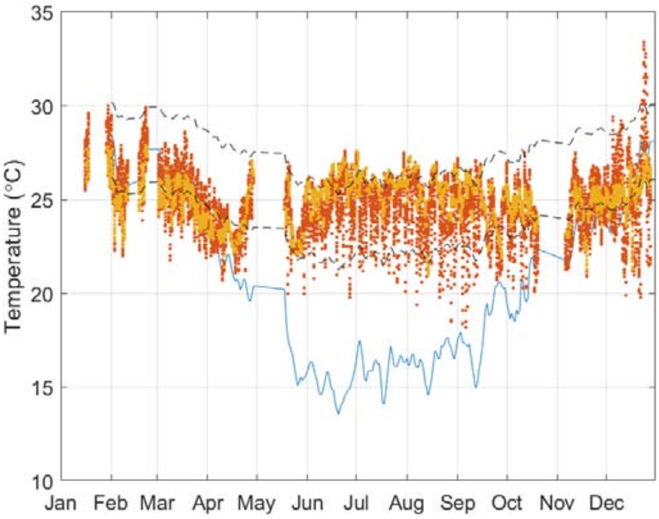

Figure 6: House 39 indoor temperatures for 2017 during the day (red), at night (orange), thermal comfort limits (black dashed), and outdoor running mean temperature (blue).

The percentage of time each measurement of temperature falls inside and outside the thermal comfort boundaries are calculated for all 297 dwellings individually. The median time the indoor air temperature falls within the thermal comfort boundaries is 12%; see Figure 7. A median of 86% temperature measurements fell below the comfort zone, and a median of 0.2% were above. This indicates that the dwellings are cold and do not require mechanical cooling in the summer.

The data now aggregated by the three ReNaM socio-economic classes; see Table 1. The median time the temperature measurements fall within the comfort zone is between 10% (for low status) and 15% (for high status), below the comfort zone is between 87% (low) and 82% (high), and the time above the comfort zone is<1%. Figure 8 (left) shows that a significant majority of dwellings in the three groups spend more time below the comfort zone. Kruskal-Wallis tests show that the differences in the time spent in the thermal comfort zone are significantly affected by socio-economic class ($p = 0.02$). Focused comparisons of the medians between socio-economic classes (using a Mann-Whitney test as the *post hoc* test) shows that the proportion of time spent in the thermal comfort zone is only significantly different when the low class was compared to high ($p < 0.05$). The variability of this percentage within each of the groups can be considered *low* for the High and Mid socio-economic classes ($CV_{High} < CV_{Mid} < 1$) and *large* for the Low class group ($CV_{low} > 1$) (see Figure 8 right).

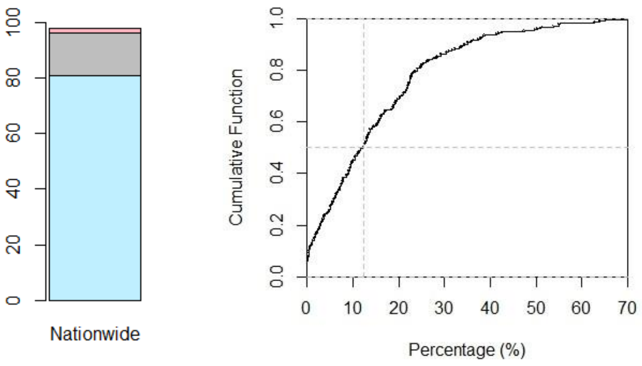

Figure 7: Left: Proportion of the time in each zone (*below comfort* in blue, *comfortable* in grey, and *above comfort* in pink) Percentages correspond to the means and so they do not add up to 100%. Right: Empirical cumulative distribution function of the proportion of recorded data in the comfort zone nationwide (grey area on the left). Only 12% of the houses considered are comfortable for >50% of the recorded time.

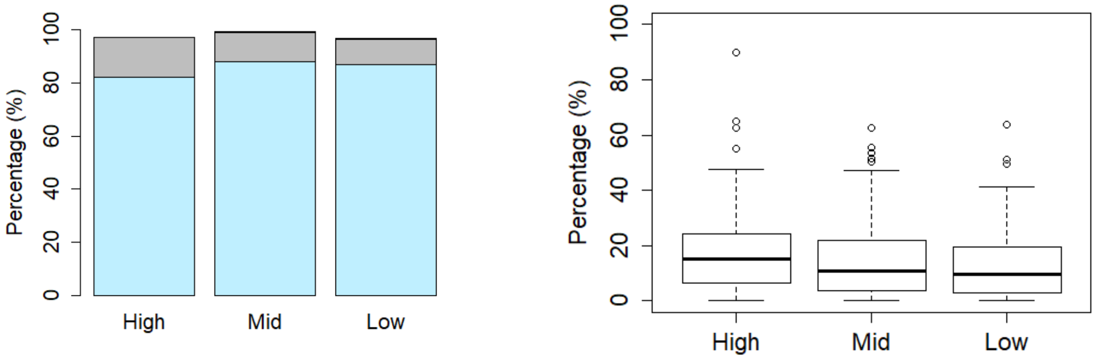

Figure 8: Left: Proportion of the median time within each comfort area by each socio-economic (SE) group (*below comfort* in blue, *comfortable* in grey, and *above comfort* in pink). Percentages correspond to the means and so they do not add up to 100%. Right: Boxplot of the percentage of the time within the thermal comfort zone (grey area on the left figure) for houses categorised in each of SE class.

A similar analysis can analyse the thermal comfort variability within and between each location. The variability of the time the measurements fall within the comfort zone within each location can be considered as low except for Antofagasta ($CV_{Coyhaique} < CV_{Santiogo} < CV_{Temuco} < CV_{Valparaiso} <$

1 $< CV_{\text{Antofagasta}}$) the northern most location; see Section 2.1 for locations and Section 2.4 for test statistics. The Kruskal-Wallis test showed a significant difference between the groups of locations, ($p \ll 0.05$). Focused comparisons of the medians showed that the proportion in the thermal comfort zone were only significantly different when Valparaíso's dwellings were compared to those of the other locations ($p < 0.05$).

Finally, both a Kruskal-Wallis test (here reported using H(degrees of freedom) and a p value) and *post-hoc* multiple comparison tests showed no significant differences when applying other grouping categories. For example, dwellings are classified by the weight of their construction materials (subjectively recorded as *heavyweight*, *lightweight*, or *mid-weight*) where $H(2) = 5.592$ and $p = 0.13$, by year of construction (periods: *< 2000*, *2000-2007*, *>2007*) where $H(1) = 2.351$ and $p = 0.31$, and by geometry (recorded as *detached*, *one* or *two shared walls*, or *flat*) where $H(3) = 10.811$ and $p = 0.14$, showing that none are significant. The latter analysis may have been affected by the way geometry was recorded. Some dwellings were not categorized and were only classified as *house*.

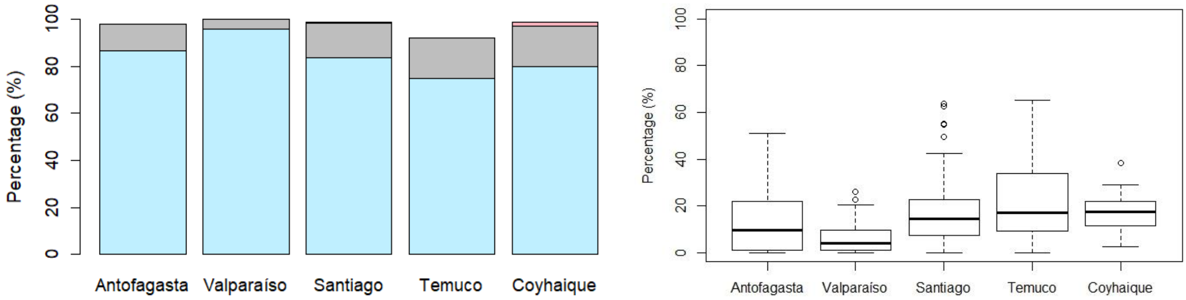

Figure 9: Left: Proportion of the median time within each comfort area (*below comfort* in blue, *comfortable* in grey, and *above comfort* in pink) by each ReNaM location arranged from North to South. Percentages correspond to the means and so they do not add up to 100%. Right: Boxplot of the percentage of the time within the thermal comfort zone for houses located in each of the five locations. Variability of the time in the comfort zone (grey area on the left figure) for each group of houses.

4 DISCUSSION

Chile has highly variable weather and environmental conditions, energy demands, socioeconomic status (the socioeconomic composition of each region and available economical resources), social gaps, lifestyles and habits. Therefore, obtaining a representative sample of houses that encapsulates this variation is a significant challenge. Misunderstanding or ignoring the variability in the stock and their probability of occurrence could lead to the inaccurate quantification of problems or to the inaccurate characterization of the *status quo*. Nevertheless, the ReNaM contains highly valuable information that can inform our understanding of the current stock, the way people use it, and how it might be modelled. Therefore, its analysis will provide guidance on future data gathering and areas of research.

There are a large number of missing data points in the dataset. This could be a function of sensor malfunction, poor internet accessibility, or power failure. In addition, there is little information about the specific location of each sensor within individual dwellings. The integrity of the analysis of the dataset is dependent on the quality of its data. Therefore, it is important that the location of all sensors is as consistent as possible. The large number of dwellings, participating in the survey (around 300) makes it likely that there is variation in their locations and some may be suboptimal; for example, they may be in direct sunlight or close to heat sources and sinks. Figure 3 shows that there are clear issues with this both inside and out. However, hosting households were advised on appropriate locations for their sensors and, giving the sheer quantity of measurements, it is hoped that confounded data appear as outliers in the analysis. There are also known limitations of *consumer-grade* IAQ monitors; see Singer *et al.* (2018). All sensors require periodic calibration, but the ReNaM devices are not routinely examined. Therefore, the outputs of these devices can be considered indicative rather than exact.

It is important to be cautious when interpreting the ReNaM data because there is little information on occupancy patterns, clothing, activities, personal preferences, or thermal satisfaction, making it difficult to assess the actual risk of exposures to low temperatures and thermal comfort. Accordingly, it is too early to make firm judgments or to draw conclusions on the state and issues of the housing stock and further work is required.

Future work should consider the appropriateness of the European comfort model EN 15251 in a Chilean context. Perez-Fargallo *et al.* (2018) also found that dwellings were cool when compared against EN 15251 criteria and proposed modifications to a limited type of dwellings. Section 3 confirms that EN 15251 find dwellings are cool and so this work should be continued to apply it to the majority of Chilean dwellings. It is possible that Chileans like their dwellings cold, and although this may be good for moderating the national energy demand, Collins (1993) shows that they may adversely affect health and quality of life. It is important to note that high socio-economic households are cold. They could be because they are empty during the day and so the data from these houses needs to be tested individually for multimodality.

An analysis of comfort should be combined with an assessment of domestic heating systems and dwelling airtightness and insulation. Most dwellings use *ad hoc* decentralized heaters, such as wood burners, which also decrease the quality of the ambient air quality. Any improvement in heating systems should be combined with energy efficiency measures to minimize *take back*, the reduction in expected gains from technologies that increase energy efficiency attributable to behavioural or other systemic responses.

Future analyses should also consider the other measured parameters; see Section 2.2. Sound pressure levels and CO_2 concentrations could indicate occupant presence and patterns. Steady state CO_2 concentrations and their decay over time could indicate ventilation rates, albeit with uncertainty. Indoor relative humidity could identify the risk of mould growth, especially in the south of the country.

5 CONCLUSIONS

Indoor temperatures in Chilean dwellings are generally found to be cold when compared to the European adaptive model of thermal comfort, EN 15251, even in the northern city of Antofagasta. However, they are above temperature thresholds found to affect negatively the health of vulnerable groups for 78% of the time.

There are significant seasonal differences in indoor air temperature but modest differences between day and night time temperatures. The winter temperatures are low and suggest that there is limited effective heating in dwellings.

The socio-economic status of householders significantly affects indoor temperatures during winter days and nights, and the time spent in within EN 15251 thermal comfort boundaries. Low socio-economic status households are colder than those of mid and high households in the winter. There is no difference between economic groups during the summer.

When dwellings are grouped by their location, the median time indoor temperatures were in the comfort zone were found to be broadly similar, except in the coastal towns of Valparaiso & Viña del Mar. The greatest variability was found in the northern city of Antofagasta. Comfort is not found to be a function of dwelling type, construction materials, or construction period.

6 ACKNOWLEDGEMENTS

The authors acknowledge DITEC-MINVU for granting academic access to ReNaM database.

Constanza Molina is funded by the CONICYT-Chile (Commission of Scientific and Technologic Research of Chile) “Becas Chile” Doctoral Fellowship Programme, 2015; Grant No. 72160504.

7 REFERENCES

Abdi, H. Coefficient of variation. Encyclopaedia of research design, 1, 169-171. 2010

ANSI/ASHRAE, Standard 55 Thermal Environmental Conditions for Human Occupancy. 2010.

Boardman, B., Fuel poverty: from cold homes to affordable warmth. 1991, London: Bellhaven Press.

BSI. EN 15251. Indoor Environment Input Parameters for Design and Assessment of Energy Performance of Buildings Addressing Indoor Air Quality, Thermal Environment, Lighting and Acoustics. London. 2007.

CIBSE, TM52: The limits of thermal comfort: avoiding overheating in European buildings. 2013: London.

CIBSE. Guide A - Environmental Design. London, UK. 2015.

Cabanac, M., Physiological role of pleasure. 1971. 173(4002): p. 1103-7.

Castillo, C. Estadística climatológica. Dirección meteorológica de Chile. Santiago, Chile. 2001.

Cohen, J., Statistical power analysis for the behavioral sciences. 1977, Academic Press.

Collins, K.J., 1993. Cold-and heat-related illnesses in the indoor environment. Unhealthy housing: research, remedies and reform. London: E and FN Spon.

González-Eguino, M., Energy poverty: An overview. Renewable and Sustainable Energy Reviews, 2015. 47: p. 377-385.

Howden-Chapman, P., et al., Tackling cold housing and fuel poverty in New Zealand: A review of policies, research, and health impacts. Energy Policy, 2012. 49(C): p. 134-142.

METEOTEST. 2017. Meteonorm. In: METEOTEST (ed.) Version 7 ed. Switzerland: Meteotest.

MMA, Ministerio del Medio Ambiente., Tercer Reporte del Estado del Medio Ambiente. 2017.

IEA. Energy Efficiency Indicators: Essentials for Policy Making. International Energy Agency. 2014.

INE. 2003. Censo de Población y Vivienda 2002. Instituto Nacional de Estadísticas, Santiago, Chile.

INE. 2016. Demografía nacional y regional. Instituto Nacional de Estadísticas. Santiago, Chile.

INE. 2018. Censo de Población y Vivienda 2017. Instituto Nacional de Estadísticas, Santiago, Chile.

Jorquera, H. and Barraza, F., 2013. Source apportionment of PM10 and PM2. 5 in a desert region in northern Chile. Science of the Total Environment, 444, pp.327-335.

Kavouras, I.G., *et al.* 2001. Source apportionment of PM10 and PM25 in five Chilean cities using factor analysis. Journal of the Air & Waste Management Association, 51(3), pp.451-464.

Koehler, K., *et al.* 2019. The Fort Collins commuter study: Variability in personal exposure to air pollutants by microenvironment. Indoor air, 29(2), pp.231-241.

Molina, C. *et al.* 2017. The Development of Archetypes to Represent the Chilean Housing Stock. 38th AIVC Conference, Nottingham, UK.

Netatmo. 2015. Personal weather station https://www.netatmo.com/en-GB/product/weather/weatherstation (accessed 02 July 2018).

Perez-Fargallo, A., *et al.*, Development of a new comfort model for low income housing in the central-south of Chile. 2018, Energy and Buildings. p. 94-106.

R Core Team. 2018. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. URL https://www.R-project.org/.

ReNaM (Red Nacional de Monitoreo de Viviendas). National Housing Monitoring Network. http://renam.cl/site/acerca-de [Access date: 15/03/2018]

Reyes R, *et al.* Controlling air pollution in a context of high energy poverty levels in southern Chile: Clean air but colder houses?. Energy Policy. 2019 Jan 1;124:301-11.

Singer B. Delp, W. Response of consumer and research grade indoor air quality monitors to residential sources of fine particles. Indoor Air 28(4) 34-639. 2018.

Sun, S. *et al.* 2018. Seasonal temperature variability and emergency hospital admissions for respiratory diseases: a population-based cohort study. Thorax, 73:951-958. 2018.

Taylor, J., et al., Estimating the Influence of Housing Energy Efficiency and Overheating Adaptations on Heat-Related Mortality in the West Midlands, UK. 2018.

Toro, R., *et al.* 2014. Inhaled and inspired particulates in Metropolitan Santiago Chile exceed air quality standards. Building and Environment, 79, pp.115-123.

West, S., J. Finch, and P. Curran, Structural equation modeling: concepts, issues and applications. 1995, Sage: Newbury Park, CA. p. 56-75.

World Bank. Chile Overview. 2018 [cited 2018 19 December]; Available from: https://www.worldbank.org/en/country/chile/overview.

WHO. Housing, energy and thermal comfort: a review of 10 countries within the WHO European Region. Copenhagen: WHO Regional Office for Europe; 2007.